

2021.04.23



LUND  
UNIVERSITY

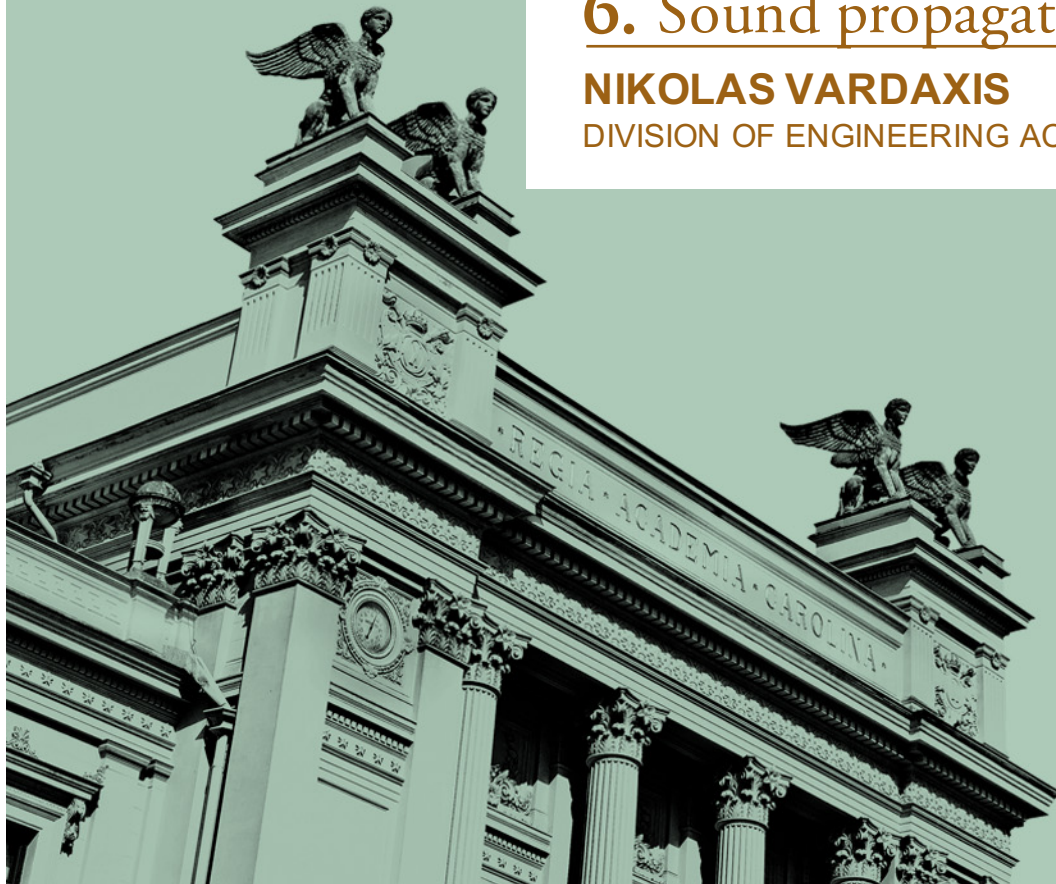
## VTAF 01 – Sound in Buildings and Environment

### 6. Sound propagation

---

**NIKOLAS VARDAXIS**

DIVISION OF ENGINEERING ACOUSTICS, LTH, LUND UNIVERSITY



# Standing waves – Velocity profile

---

Recap from Lecture 5...

©2011, Dan Russell



# Standing waves – Pressure profile

---



©2011, Dan Russell



# Standing waves – Velocity profile

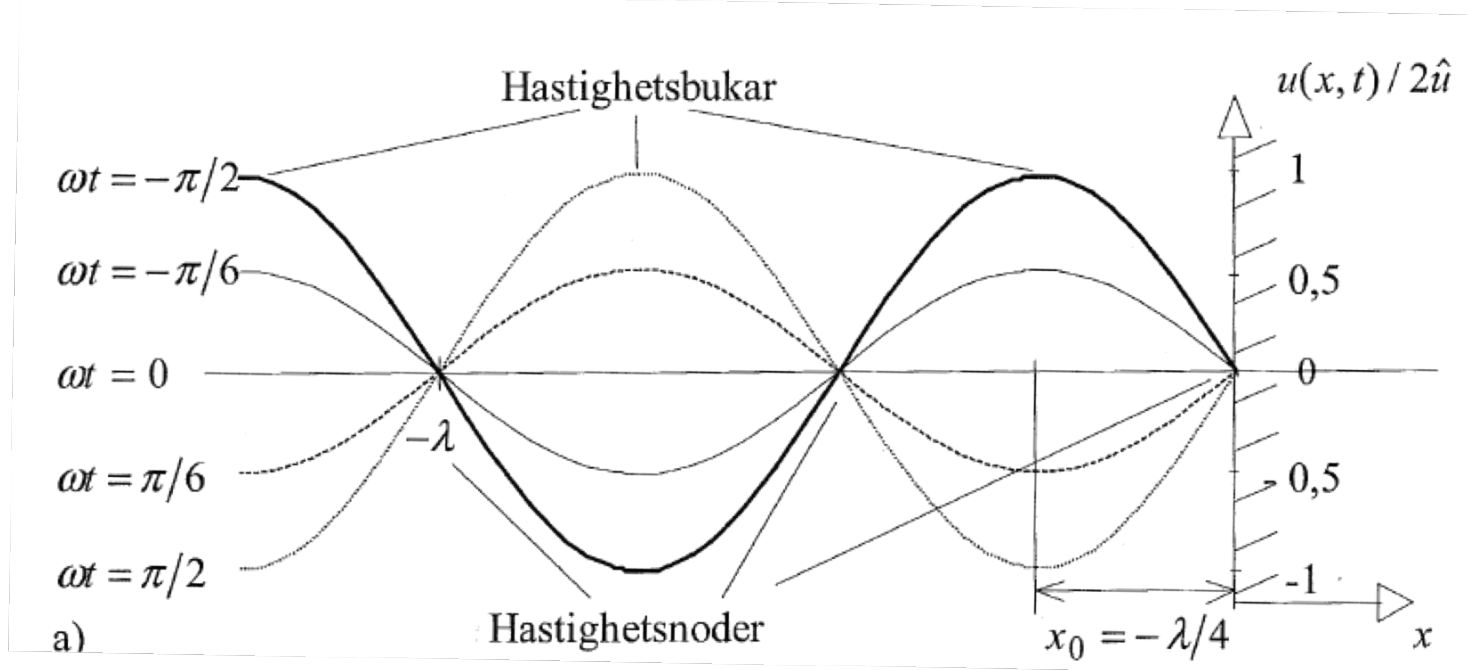
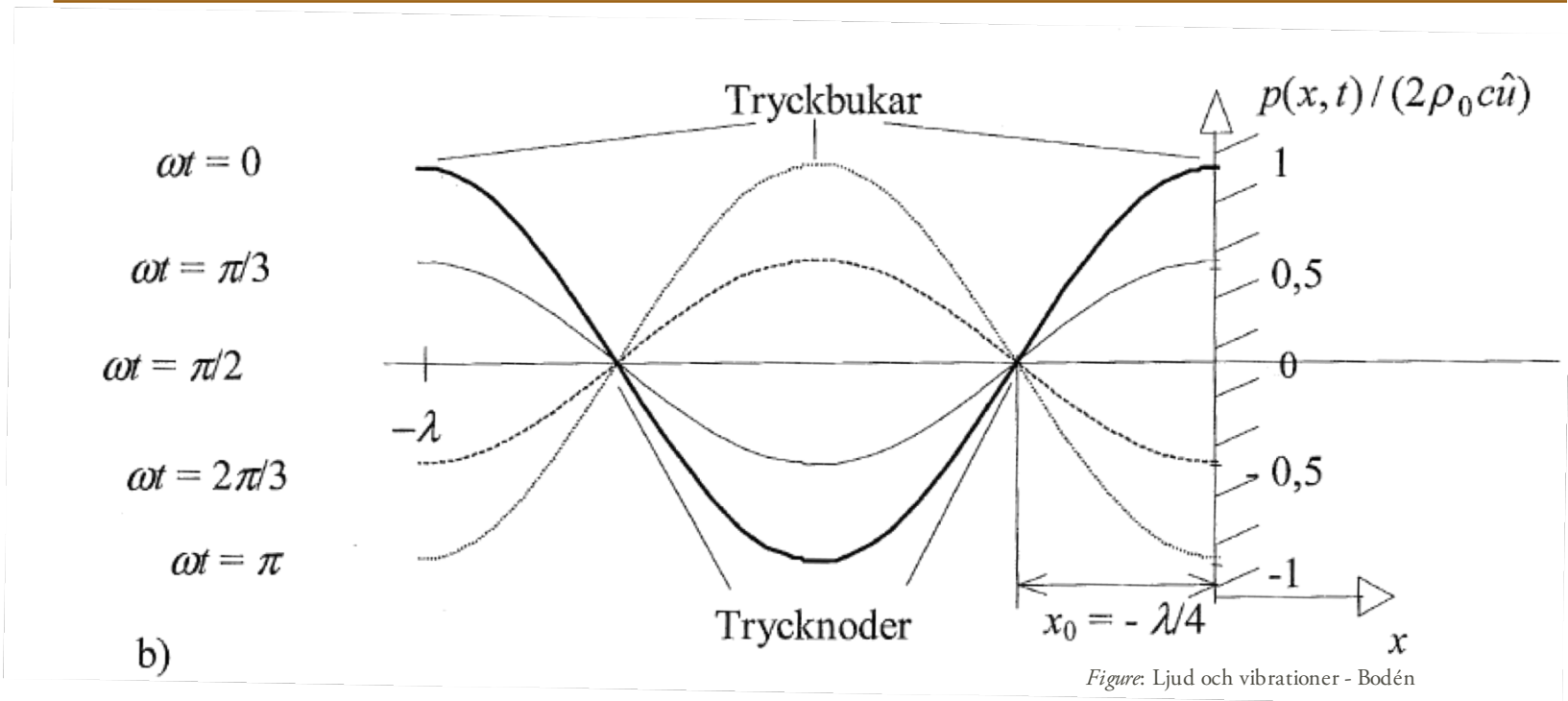


Figure: Ljud och vibrationer - Bodén

- Velocity profile:  $v(x, t) = 2\hat{v}_+ \sin(kx) \cdot e^{i(\omega t - \pi/2)}$ 
  - Minimum if:  $\sin(kx) = 0, (x < 0) \rightarrow x = -\frac{n\lambda}{2}$
  - Maximum if:  $x = -\frac{\lambda}{4} - \frac{n\lambda}{2} \rightarrow$  Insulation



# Standing waves – Pressure profile

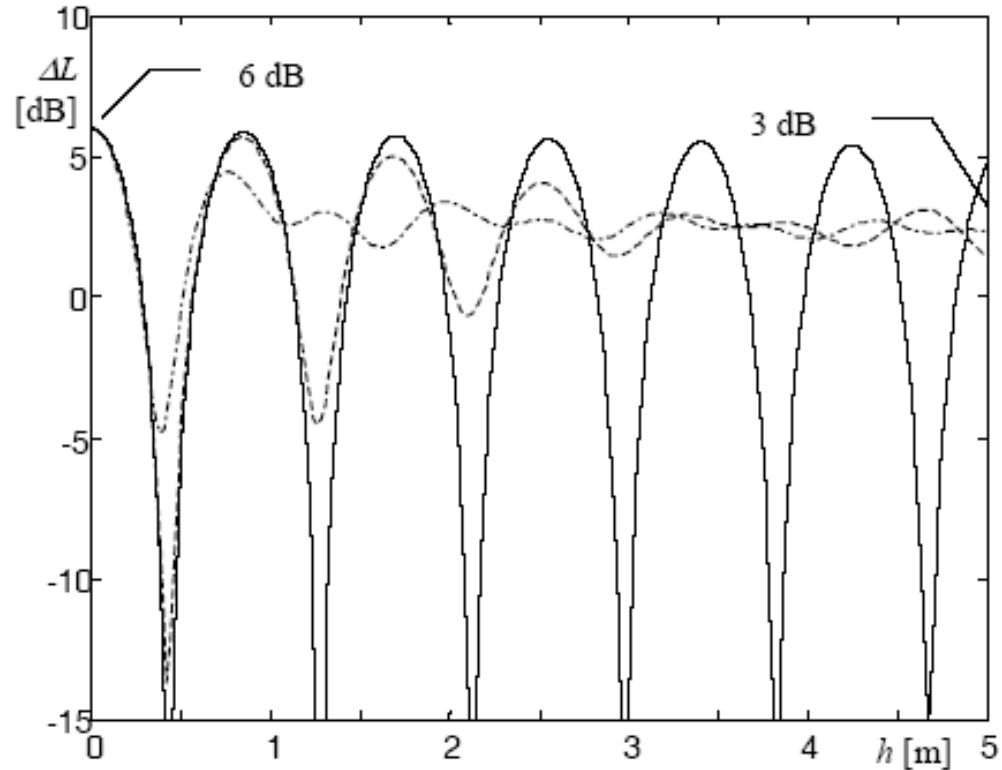


- Pressure profile:  $p(x,t) = 2\hat{p}_+ \cos(kx) \cdot e^{i\omega t}$ 
  - Nodes if:  $\cos(kx) = 0, (x < 0) \quad x = -\left(\frac{1}{2} + n\right) \frac{\lambda}{2}$
  - Maximum if:  $x = -\lambda/2, -\lambda, -3\lambda/2$  osv.  $\rightarrow$  Measurement by a hard wall



# Measurement of SPL close to a hard surface

---



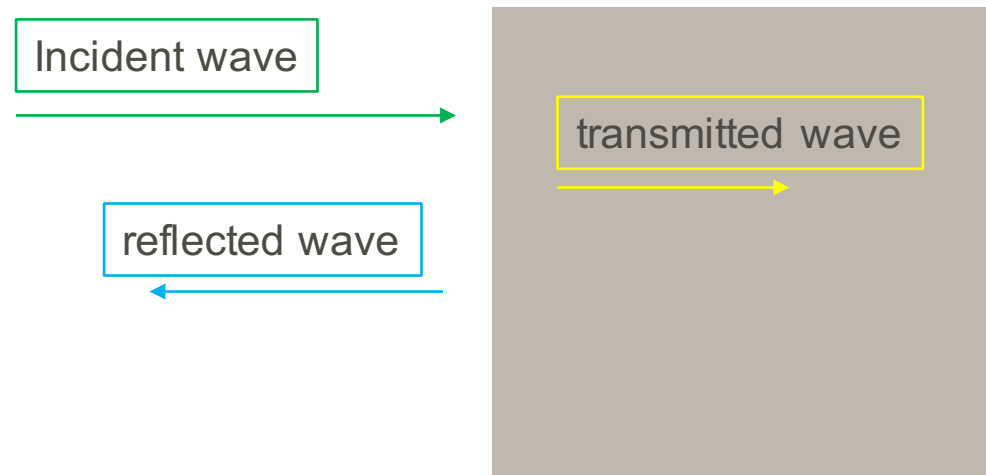
Interference by a facade for narrow band (solid line), third octave band (dashed line) and octave band (dotted/dashed line). Midfrequency: 200 Hz (wavelength 1.7 m).



# Transmission and reflection

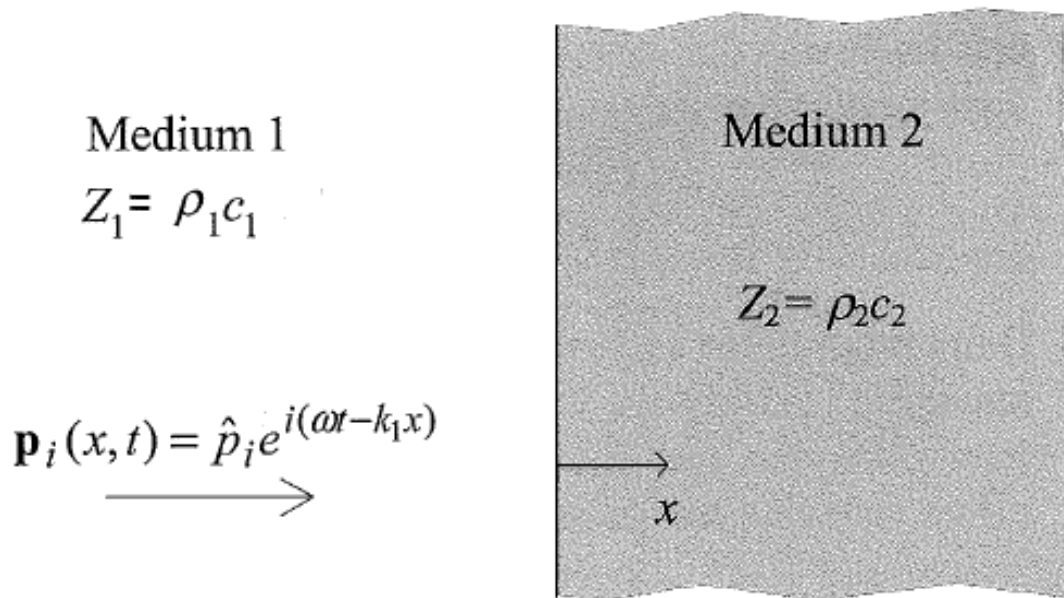
---

- In general sound waves may impinge on partitions that are not *hard*.
- Our hard wall example is a simplification – nonetheless a very good and useful one that all acoustician use.
- In general, a sound wave meeting another medium will experience reflection (as we saw) and transmission into the next medium – air/structure; structure/structure; hot air/warm air.



# Transmission and reflection

---



$$r = \frac{\hat{p}_r}{\hat{p}_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

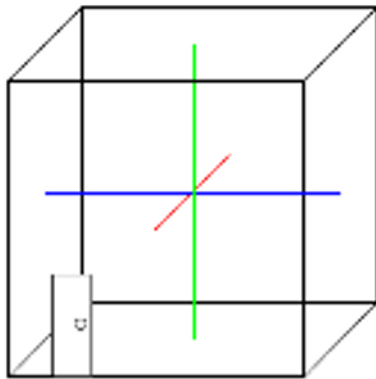
$$t = \frac{\hat{p}_t}{\hat{p}_i} = \frac{2Z_2}{Z_2 + Z_1}$$



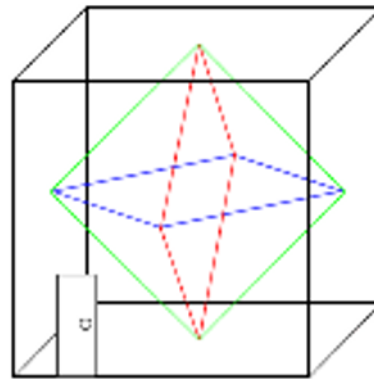
# Room eigenfrequencies and eigenmodes

---

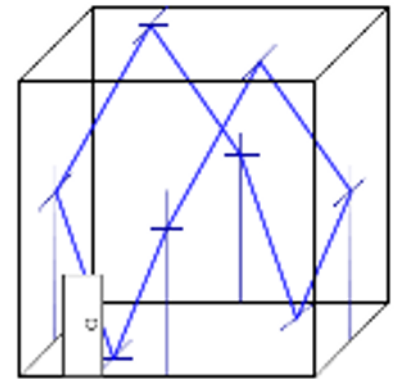
- Eigenfrequencies of a 3D room  $f_{n_x, n_y, n_z} = \frac{c}{2} \sqrt{\left(\frac{n_x}{L}\right)^2 + \left(\frac{n_y}{B}\right)^2 + \left(\frac{n_z}{H}\right)^2}$
- Types of modeshapes. [Link](#).



Axial modes 1D  
Two n-indexes are 0



Tangential modes 2D  
One n-index is 0



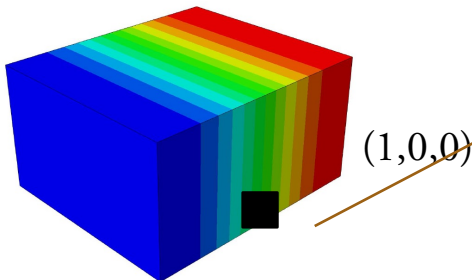
Oblique modes 3D  
No n-index is 0

Eigenmode: different ways air in a room can vibrate generating standing waves



# Forced response and modes

- Depending on the spatial location of the driving loudspeaker, different modes are excited.
- E.g. modes that are not excited by the loudspeaker in the middle position have a node in that point.
- All modes have a peak or a valley at a corner (hard walls).



Source: Carl Hopkins, *Sound Insulation*

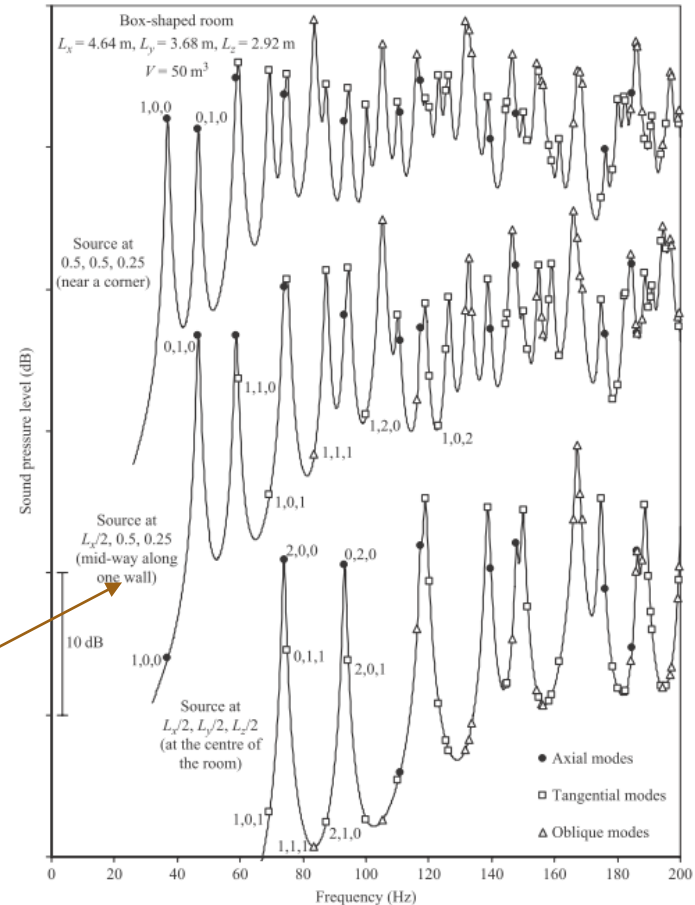


Figure 1.37

Excitation of room modes with three different source positions. Curves for the sound pressure level in the corner position ( $L_x, L_y, L_z$ ) are shown along with the axial, tangential and oblique mode frequencies to assess which modes are, and which modes are not excited by the source position. Note that the curves have been offset from each other; this allows the relative levels along each individual curve to be assessed, but not the relative levels between different curves.



# Eigenmodes count in a room

- How many modes do we have in a room?

Source: Carl Hopkins, *Sound Insulation*

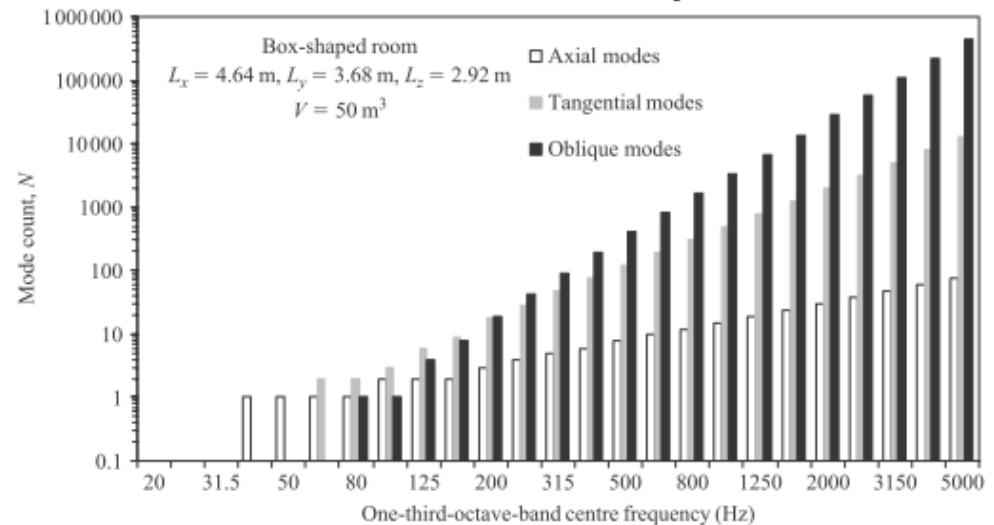
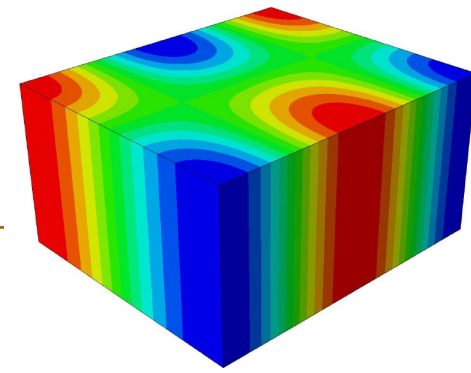


Figure 1.14

Mode count for axial, tangential, and oblique modes in a 50 m<sup>3</sup> box-shaped room.

- About modes in solids? Think: Beam, string, plates?
  - Each structure has its own eigenfrequencies (modes) – like the string.
  - In particular each kind of wave motion has its own eigenfrequencies.
  - At lower frequencies only bending modes are present.
    - And not so many modes either.





# Diffuse field & Non-diffuse field

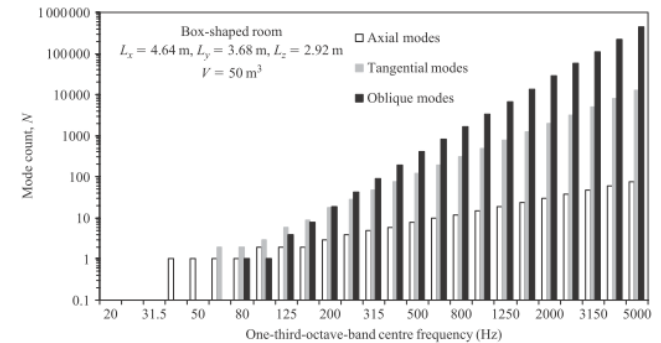
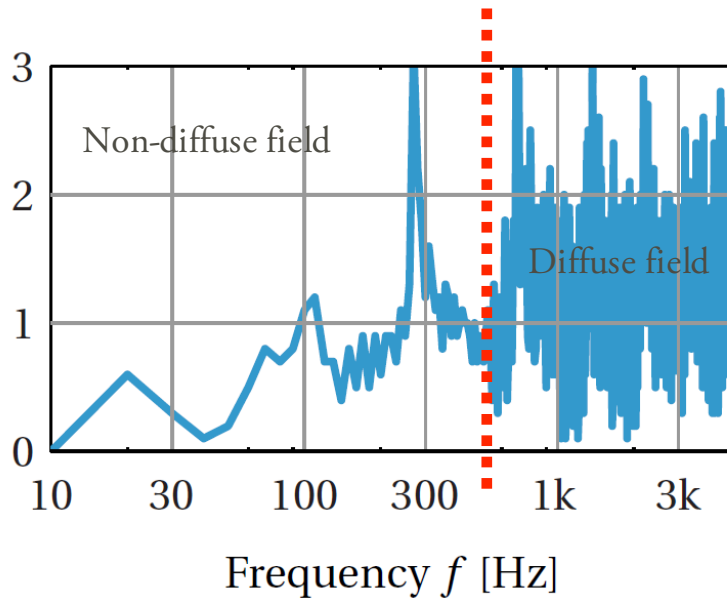
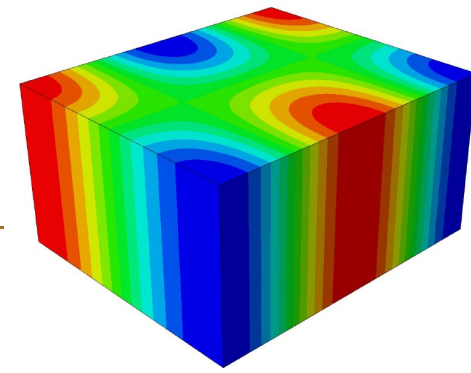


Figure 1.14

Mode count for axial, tangential, and oblique modes in a 50 m<sup>3</sup> box-shaped room.

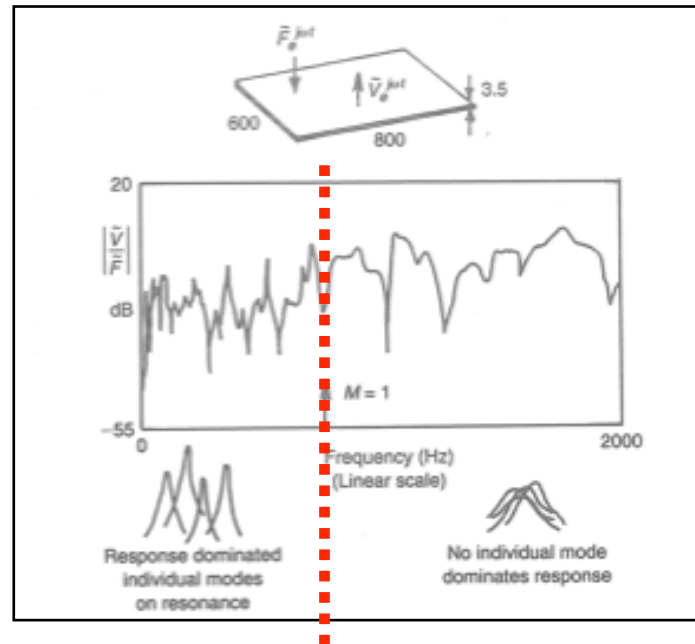
- Low modal density in the low frequency range → measurement problems
- Higher modal density in high-frequency range
- Limit between both “behaviours” → Schroeder frequency
  - We examine this in Room acoustics





# Diffuse field & Non-diffuse field

- Go back to transfer functions...



- Clear peaks i.e. clear modes
- Characteristic of the structure
- Detailed precise description attempted

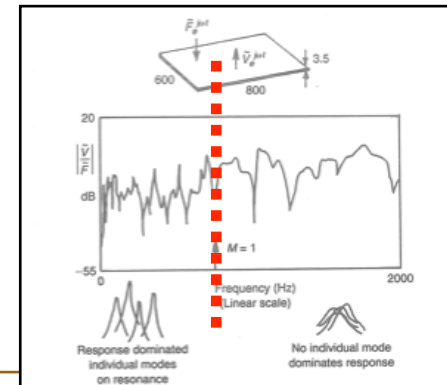
- Confused peaks i.e. cannot distinguish single modes
- Small variations determining for single modes
- Gross overall description attempted



# Low and high frequencies

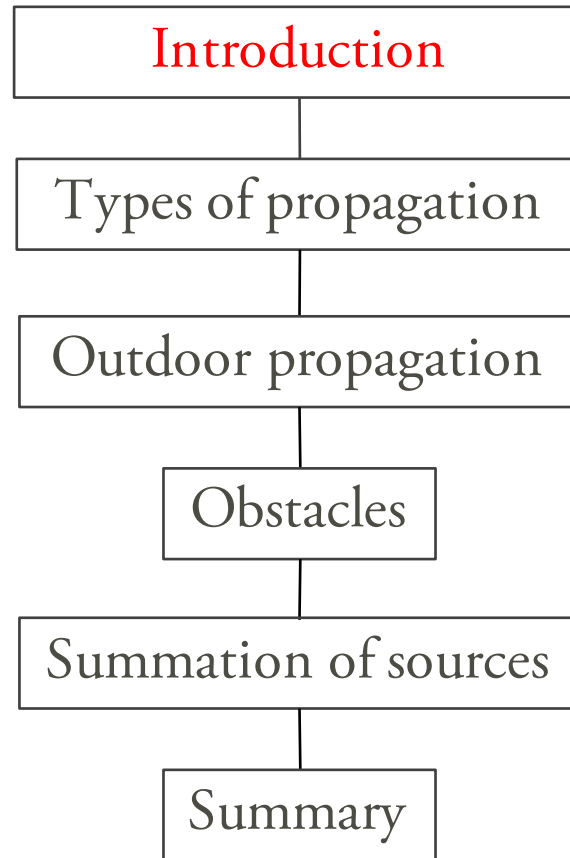
---

- Low frequencies:
  - Few distinct modes
  - Modes depend on boundary conditions and geometry of structure
  - Little sensible to details in the structure
  - Deterministic response
- High frequencies
  - Many indistinguishable modes
  - Modes depend on gross properties of the structure – volume and material properties
  - Much sensible to details in the structure
  - Chaotic response



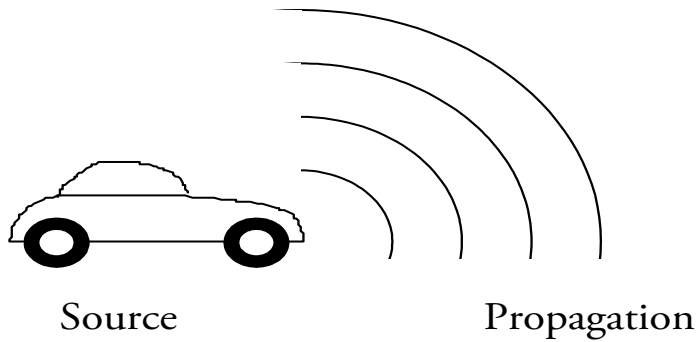
# Outline

---



# How does sound propagate?

---



# Sound power and sound intensity

---

- Introduce key concepts to describe sound sources and the propagation of sound from them – sound power and sound intensity.
  - Already seen in exercises?
  - Besides their definition we can also see why these concepts are useful tools for an acoustician.
- In the end we look at some phenomena outdoors and with propagating waves in general.
- But first how sound propagates? Let's define *where* sound may propagate!



# Definitions

(check: <http://www.acoustic-glossary.co.uk>)

---

- **Direct field:** the region in which the measured sound can be attributed to the source alone without reflections.
  - Early reflections that reach the listener within 50 ms integrate with the direct sound and can improve speech clarity.
  - Later reflections may have a negative effect on speech clarity. More during room acoustics.).
- **Free field:** a sound field region with no adjacent reflecting surfaces. In practice a free-field can be said to exist if the direct sound is 6 dB or preferably 10 dB greater than the reverberant or reflected sound.
- **Diffuse field:** the region in a room where the Sound Pressure Level (SPL) is uniform i.e. the reflected sound dominates, as opposed to the region close to a noise source where the direct sound dominates. Same as Reverberant Field.
- **Non-diffuse field:** SPL is dependent on the position one measures, i.e. the direct sound dominates. Typical from low frequencies in a room, where modal density is low.



# Free field

---

Outdoors open space



Anechoic room

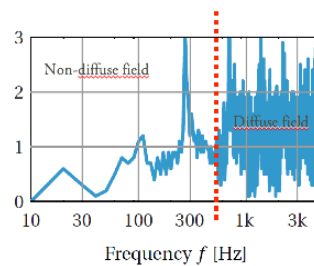


# Diffuse field

---



**Acoustic laboratory:  
Reverberation room**



# Sound propagation measures in dB levels

---

Different aspects of sound, and the decibels for each represent different measurement quantities.

**Sound Pressure in Pascals [Pa] → SPL:**

- » Amplitude level of sound at a specific location in space (scalar)
- » Dependent on the location and distance to the source



**Receiver**

**Sound Intensity in [W/m<sup>2</sup>] → SIL :**

- » Sound power flow per unit of area



**Path**

**Sound Power in Watts [W] → SWL :**

- » Rate at which sound is emitted from an object
- » Independent of location or distance



**Source**

---

# Sound power and sound intensity

---

- A loudspeaker consumes electrical power [W] just like a lamp.
- The loudspeaker changes the electric power into acoustic power [W].
  - Just a small bit of electrical power is changed into acoustic power.
- A talking person produces a sound power of  $50e-6$  W.
- A complete symphonic orchestra 10-20 W.
- The sound power produced by the sound source is preserved in the sound wave and is distributed in the surrounding medium – conservation of energy.
- If one places a fictitious surface perpendicular to the wave's wave front, then the amount of power passing through that surface is a measure for the strenght of the sound source at that point.
- This quantity is called Intensity I [W/m<sup>2</sup>].

- For a free propagating wave with planar form,  $\bar{I} = \frac{\tilde{p}^2}{\rho c}$

- For a free propagating wave with spherical form (r radial distance),  $\bar{I} = \frac{\tilde{p}^2}{r^2 \rho c}$



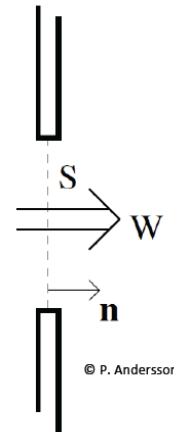
# Sound (acoustic) power – definition

---

- Rate of energy transported through a surface [W=J/s]
  - Scalar quantity
  - Instantaneous value:  $W(t) = \vec{F}(t) \cdot \vec{u}(t)$ .
  - Time average:  $\bar{W} = \frac{1}{T} \int_0^T W(t) dt$

- In decibels...

$$L_W = 10 \log \left( \frac{\bar{W}}{W_{\text{ref}}} \right); \quad W_{\text{ref}} = 10^{-12} \text{W}$$



NOTE: the power ratios in decibels (e.g. acoustic power, intensity) are calculated as: 10 times base 10 logarithm of the ratio; whereas amplitude quantities (e.g. acceleration, pressure) in decibels are calculated as ratio of squares (i.e. 20 times base 10 logarithm of the ratio of amplitudes).



# Sound (acoustic) intensity – definition

---

- Sound power (i.e. rate of energy) per unit area [ $\text{W}/\text{m}^2$ ]
  - Instantaneous value:  $\vec{I}(t) = p(t)\vec{v}(t)$
  - Vector quantity: energy flow and direction:  $\vec{I} = \langle p\vec{v} \rangle = \frac{1}{T} \int_0^T p(t)\vec{v}(t) dt$
  - In a free field (plane waves):  $\bar{I} = \frac{\widetilde{p^2}}{\rho c}$ ;  $\bar{I} \propto p^2$
- In decibels...  $L_I = 10 \log \left( \frac{\bar{I}}{I_{\text{ref}}} \right)$ ;  $I_{\text{ref}} = 10^{-12} \text{W}/\text{m}^2$

NOTE 1:  $\bar{I}$  is the magnitude of the time average  $\vec{I}$

NOTE 2:  $p(t)$  is the particle pressure and  $\vec{v}(t)$  the particle velocity

NOTE 3: Free field occurs when the sound field is not influenced by any surrounding object or close surfaces

NOTE 4: In a perfectly diffuse sound field the sound intensity is zero



# Relation between SPL, SWL, SIL

---

- For plane waves with harmonic motion (See course material for detailed derivations),

- $\bar{I} = \frac{1}{T} \int_0^T p(t)v(t)dt = \frac{1}{\rho c T} \int_0^T p^2(t)dt = \frac{\tilde{p}^2}{\rho c}$  (squared rms value of pressure).

- $$L_I = 10 \log_{10} \left( \frac{I}{I_{ref}} \right) = 10 \log_{10} \left( \frac{\tilde{p}^2}{\rho c I_{ref}} \right) = 10 \log_{10} \left( \frac{\tilde{p}^2 \cdot p_{ref}^2}{p_{ref}^2 \rho c I_{ref}} \right) =$$
$$10 \log_{10} \left( \frac{\tilde{p}^2}{p_{ref}^2} \right) + 10 \log_{10} \left( \frac{p_{ref}^2}{\rho c I_{ref}} \right) = L_p - 0,008\text{dB} \approx L_p.$$

- Numbers in decibel may be similar but they are two very different quantities!



# Relation between SPL, SWL, SIL

---

- The amount of power passing through that surface is a measure for the strength of the sound source at that point and is called intensity.

- For a point source radiating with power  $W$  the intensity at distance  $r$  is:

$$I = \frac{W}{4\pi r^2}.$$

- In decibel:  $L_I = 10 \log\left(\frac{W}{W_{ref}} \frac{1}{4\pi r^2}\right) = L_W + 10 \log\left(\frac{1}{4\pi r^2}\right).$

- If  $L_I \approx L_p$  then:  $L_W = L_p - 10 \log\left(\frac{1}{4\pi r^2}\right).$

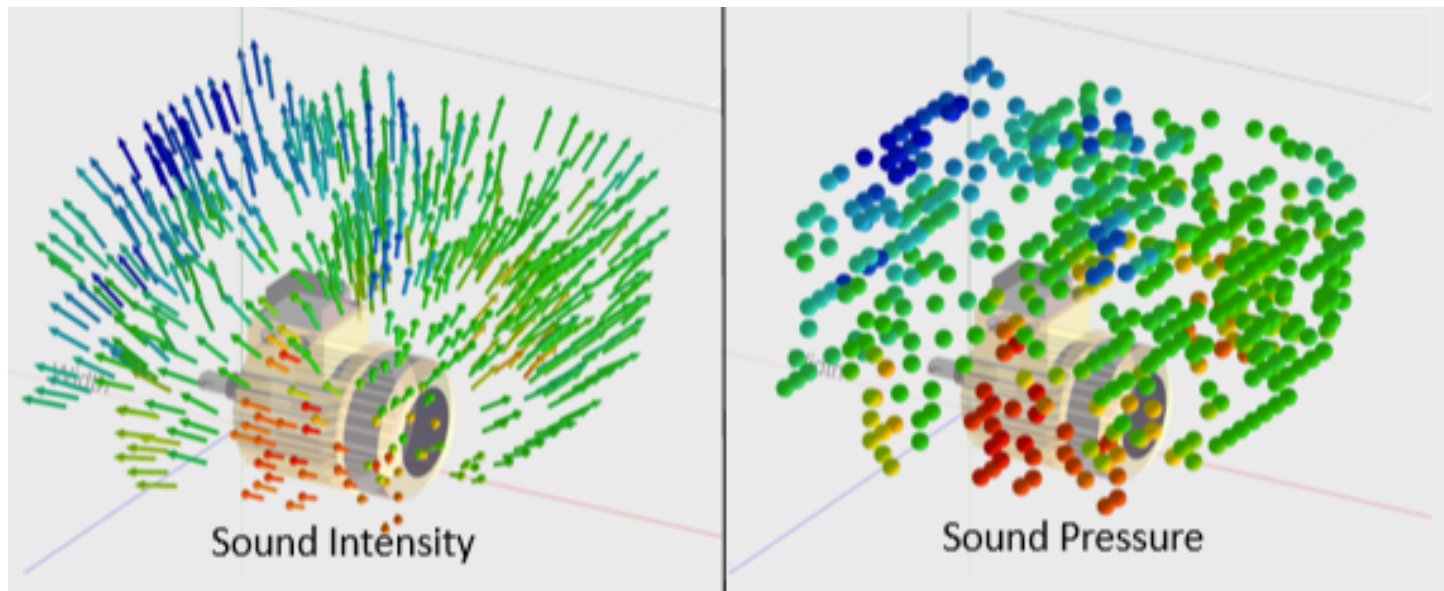
- At 1 m:  $L_W = L_p - 11$  dB.

- $L_I = L_W$  for  $r=0.2821$  m. ( $4\pi 0.2821^2 = 1$ ).



# Relation between SPL, SWL, SIL

---



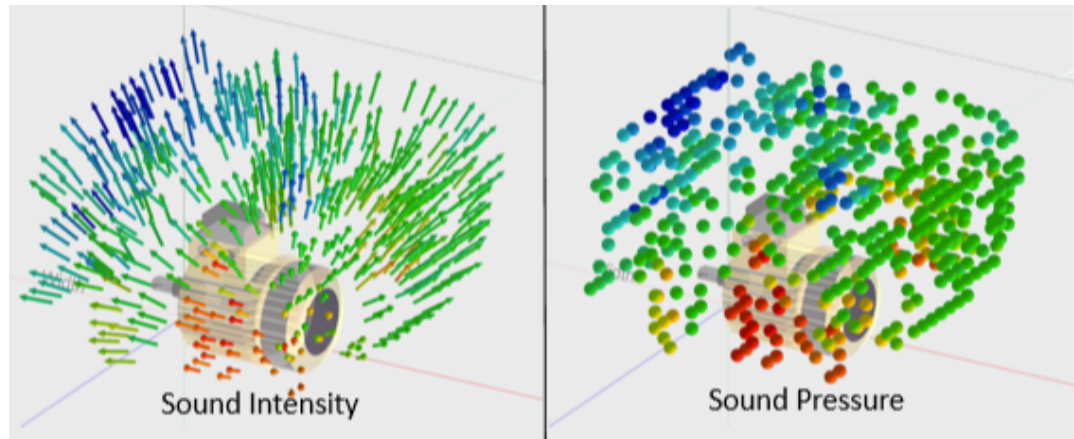
Amplitudes are the same / Directions are the difference (easier to troubleshoot with SI)



# Do not mix up concepts (II)...

---

- Zero levels...
  - SPL:
    - Threshold of hearing:  $p_0=20 \mu\text{Pa} \rightarrow L_p(f = 1 \text{ kHz})=0 \text{ dB}$
  - SIL:
    - Threshold of hearing:  $I_0=1 \cdot 10^{-12} \text{ W/m}^2 \rightarrow L_I(f = 1 \text{ kHz})=0 \text{ dB}$



Amplitudes are the same / Directions are the difference (easier to troubleshoot with SI)



# Relation between SPL, SWL, SIL

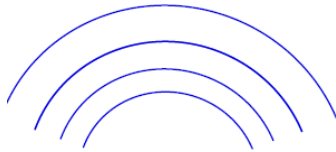


Receiver  $\longleftrightarrow$  Sound Pressure Level

$$L_p = 10 \log_{10} \frac{p^2}{p_o^2}$$

$$p_o = 2 \times 10^{-5} \text{ N/m}^2$$

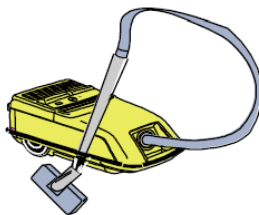
$$= 20 \mu\text{Pa}$$



Path  $\longleftrightarrow$  Sound Intensity Level

$$L_i = 10 \log_{10} \frac{I}{I_o}$$

$$I_o = 1 \text{ pW/m}^2$$



Source  $\longleftrightarrow$  Sound Power Level

$$L_w = 10 \log_{10} \frac{W}{W_o}$$

$$W_o = 1 \text{ pW}$$

www.bksv.com, 2

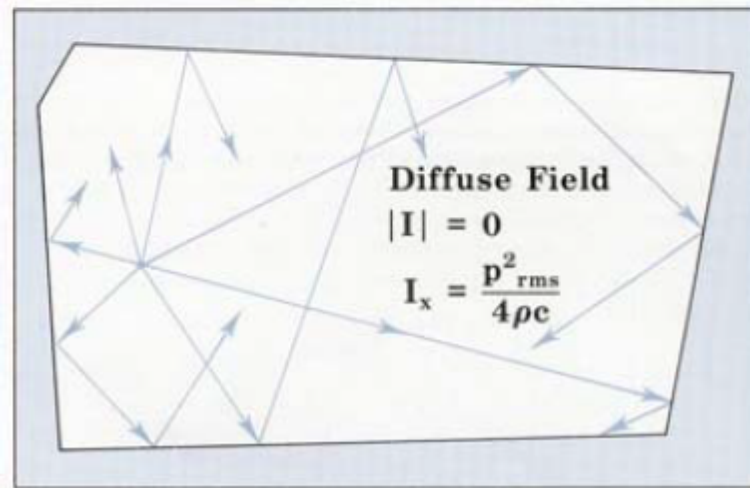
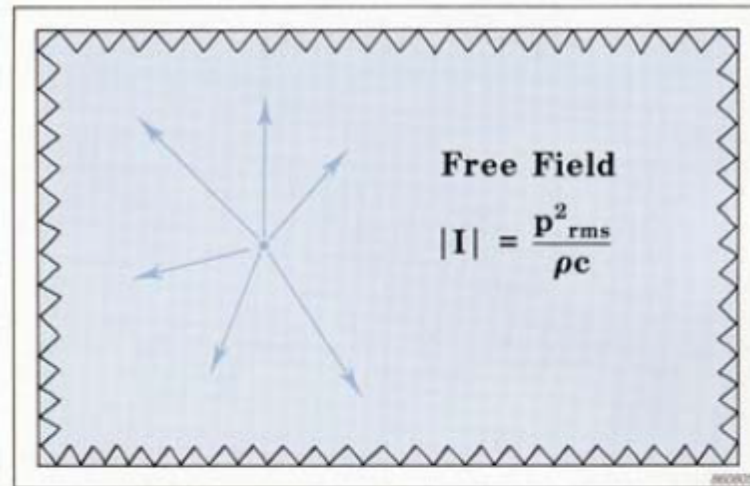
Brüel & Kjær   
BEYOND MEASURE



LUND  
UNIVERSITY

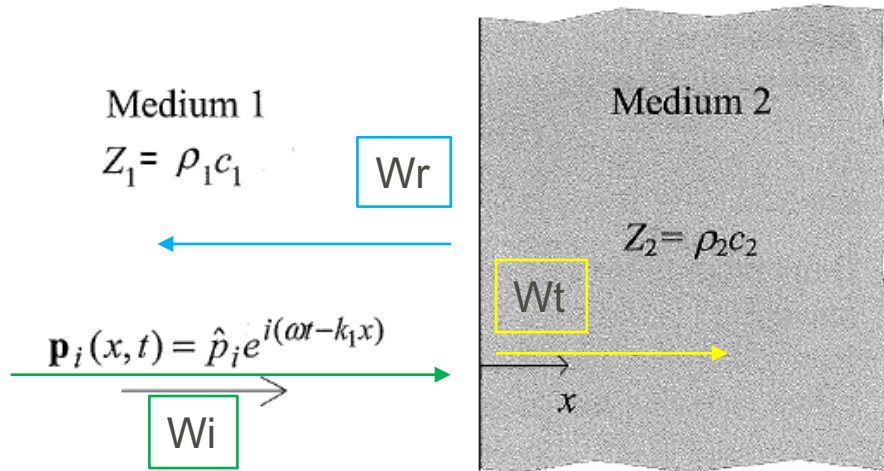
# Intensity in diffuse and free fields.

---



# Transmission and reflection – power-related quantities

- Digression: Now we can introduce a couple of quantities that we left aside during F5.



$$r = \frac{\hat{p}_r}{\hat{p}_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

$$t = \frac{\hat{p}_t}{\hat{p}_i} = \frac{2Z_2}{Z_2 + Z_1}$$

$$I_i = I_r + I_t$$

$$\tau = \frac{I_t}{I_i}; \tau = 1 - \frac{I_r}{I_i} = 1 - \frac{p_r^2}{p_i^2} = 1 - r^2 = 1 - \rho$$

$$\left. \begin{aligned} \rho &= \frac{|Z_2 - Z_1|^2}{(Z_2 + Z_1)^2} \\ \tau &= \frac{4Z_2 Z_1}{(Z_2 + Z_1)^2} \end{aligned} \right\} \tau + \rho = 1$$

- $\tau$  is also called absorption factor  $\alpha$  (different points of view...)



# (Acoustic) impedance – definition

---

- Ratio between two field quantities
  - Measures of the opposition that a system presents to the acoustic flow
  - Specific acoustic impedance ( $z$ =pressure/velocity) is an intensive property of a medium (e.g. air or water)
    - » Units:  $[N \cdot s/m^3 = Pa \cdot s/m = Rayl]$       $\underline{z} = \frac{\underline{p}}{\underline{u}} = \frac{|\underline{p}|}{|\underline{u}|} e^{i(\varphi_p - \varphi_u)} = \rho c$
  - Acoustic impedance ( $Z$ =pressure/flow) is the property of a particular geometry and medium
    - » E.g. we can discuss for example the  $Z$  of a particular duct
    - » Units:  $[Pa \cdot s \cdot m]$       $Z = \frac{z}{A}$
  - Scalar quantity

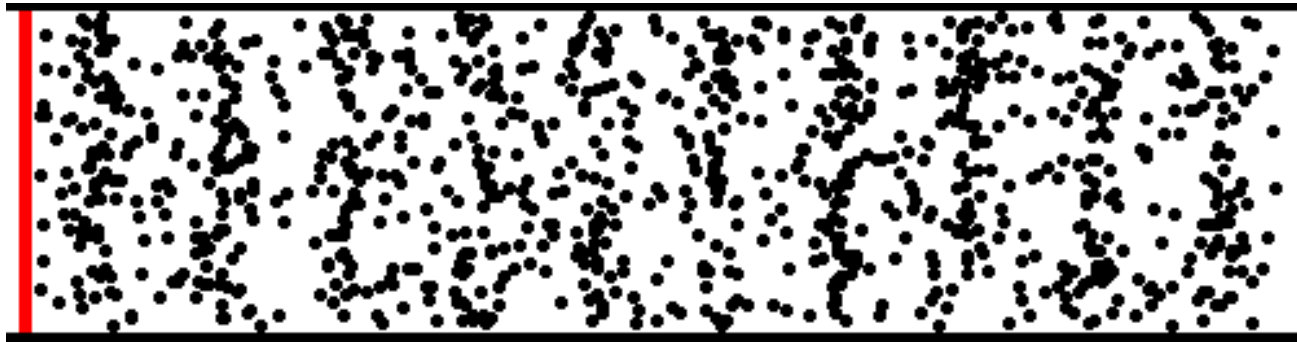


# Sound propagation – distance

---

- Pressure as function of time and position:  $p(x,t)$
- Plate sending out sound through a tube (no losses): *plane propagation*

$$p(x,t) = \hat{p}e^{i(\omega t - kx + \varphi)}$$

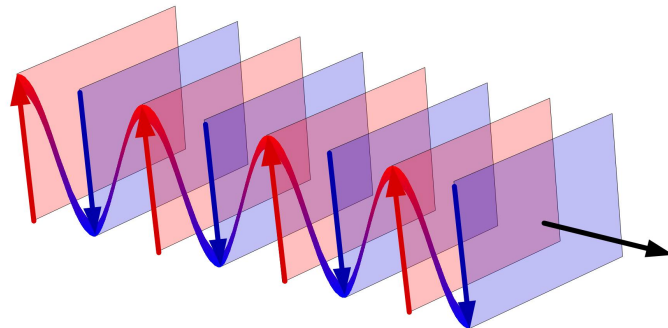


# Types of propagation – plane

---

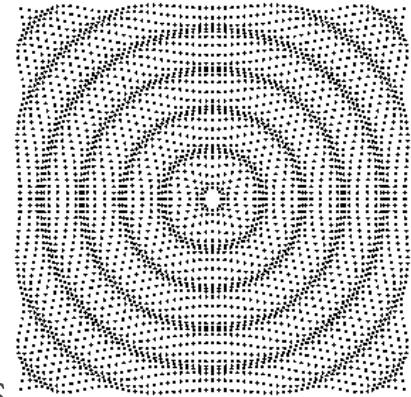
- Plane propagation:
  - Waves in a tube
  - Loudspeaker wall at concert
- The wavefront has same amplitude at various distances,
  - $p(t, x) = A \sin(\omega t - kx)$ .
- Then conservation of energy requires that the intensity at two different positions is the same.

$I \equiv \text{constant} ?$



# Spherical propagation

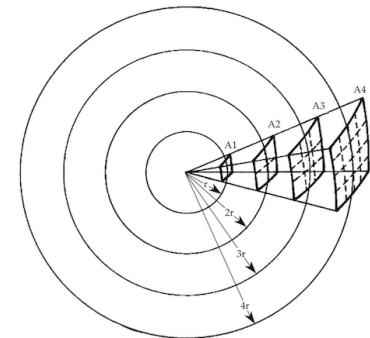
- Spherical propagation:
  - A pulsating sphere – point source
  - Exhaust of a car
- More complex wave equation in spherical coordinates
- Complex (as in complex numbers) relation between pressure and velocity that depends on the the relation between the source dimensions and wavelength or distance to receiver.



- If the source is small

$$I(r) \propto \frac{1}{r^2}; \quad \frac{I(r_1)}{4\pi r_1^2} = \frac{I(r_2)}{4\pi r_2^2} = \text{const} \Leftrightarrow I(r_2) = I(r_1) \frac{r_2^2}{r_1^2}$$

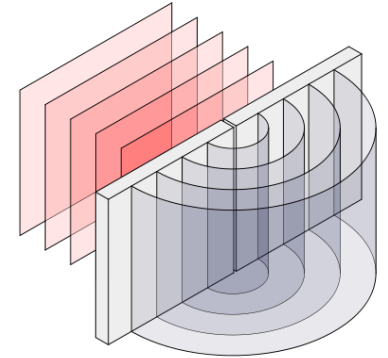
$$I(r) = \frac{\Pi}{4\pi r^2}$$



# Cylindrical propagation

---

- Cylindrical propagation:
  - A distribution of point sources – a line source
  - A road with constant traffic
- More complex wave equation
- $h$  is the height of the cylinder;  $r$  is the distance



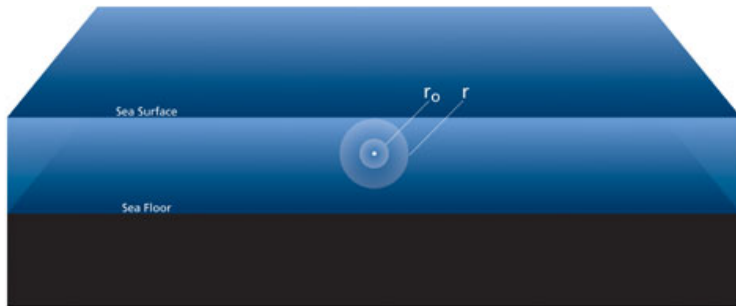
$$I(r) \propto \frac{1}{r}; \quad \frac{I(r_1)}{2\pi h r_1} = \frac{I(r_2)}{2\pi h r_2} = \text{const} \Leftrightarrow I(r_2) = I(r_1) \frac{r_2}{r_1}$$

$$I(r) = \frac{\Pi}{2\pi h r}$$



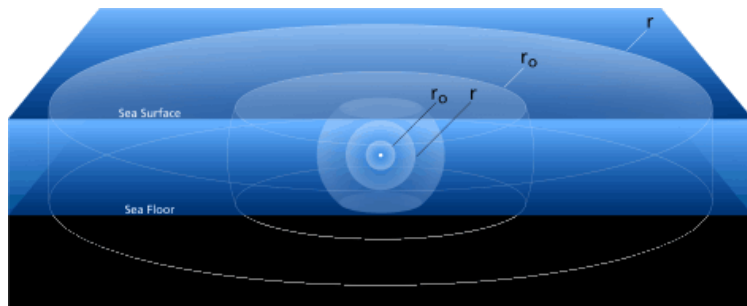
# Spherical VS Cylindrical propagation

---



Sound generated by a sound source (shown as a white dot) at mid-depth in the ocean is radiated equally in all directions. Sound levels are therefore constant on spherical surfaces surrounding the sound source. Sound levels decrease rapidly as sound spreads out from a sphere with a radius of  $r_0$  to a larger sphere with a radius  $r$ .

<https://dosits.org/science/advanced-topics/cylindrical-vs-spherical-spreading/>



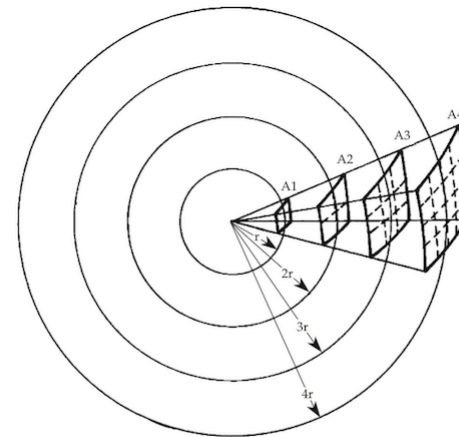
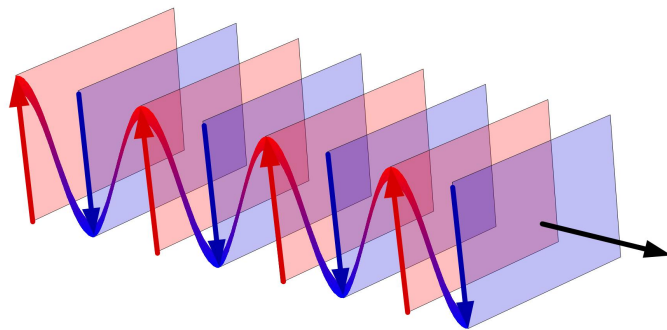
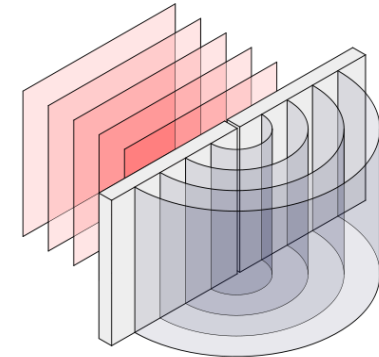
Sound generated by a source (shown as a white dot) in mid-ocean cannot continue to spread uniformly in all directions once it reaches the sea surface or sea floor. Once the sound is trapped between the top and bottom of the ocean it gradually begins to spread cylindrically, with sound radiating horizontally away from the source. Sound levels decrease more slowly as sound spreads from a cylinder with a radius of  $r_0$  to a larger cylinder with radius  $r$  compared with the rate of decrease for spherical spreading.



# Types of propagation

---

- Plane:  $I \equiv \text{constant}$  ;
- Cylindrical:  $I(r) \propto \frac{1}{r}$ ;  $I(r) = \frac{\Pi}{2\pi hr}$
- Spherical:  $I(r) \propto \frac{1}{r^2}$ ;  $I(r) = \frac{\Pi}{4\pi r^2}$



# Distance laws

---

- Spherical propagation  
(point source)

$$\Delta L = L(r_2) - L(r_1) = -20 \log\left(\frac{r_2}{r_1}\right)$$

Doubling the distance...

$$\Delta L = L(2r_1) - L(r_1) = -6\text{dB}$$

- Cylindrical propagation  
(line source)

$$\Delta L = L(r_2) - L(r_1) = -10 \log\left(\frac{r_2}{r_1}\right)$$

Doubling the distance...

$$\Delta L = L(2r_1) - L(r_1) = -3\text{dB}$$

- Plane wave

$$\Delta L = L(r_2) - L(r_1) = 0$$

Doubling the distance...

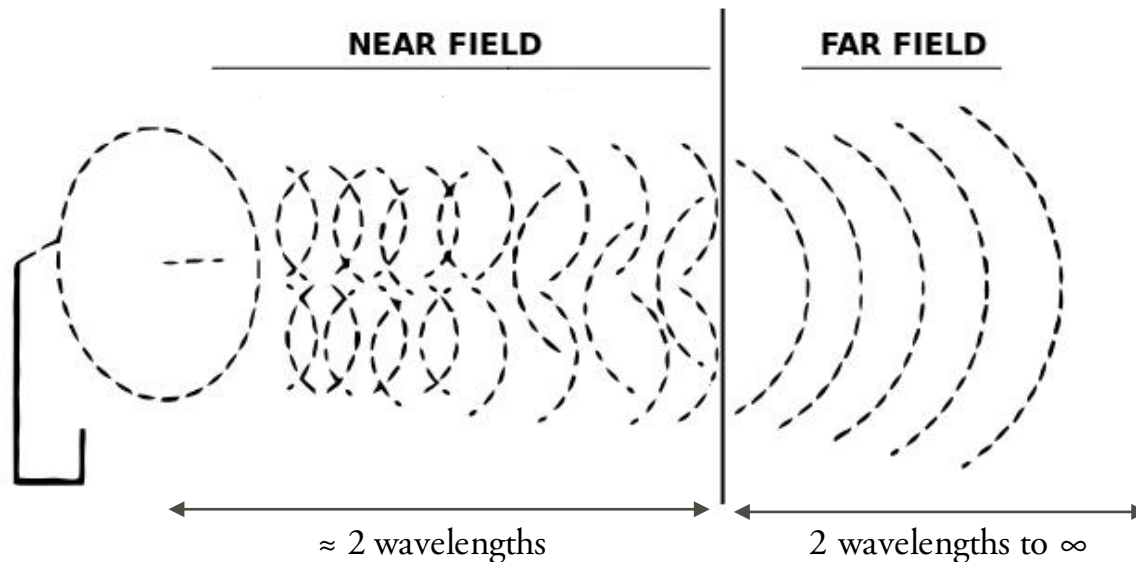
$$\Delta L = L(2r_1) - L(r_1) = 0$$



# Definitions (<http://www.acoustic-glossary.co.uk>)

---

- **Far field:** a region in free space, distant from a sound source, where the SPL obeys the Inverse Square Law (the SPL decreases 6 dB with each doubling of distance from the source for spherical waves).
- **Near field:** that part of a sound field, usually within about two wavelengths of a noise source, where there is no simple relationship between SPL and distance, where the sound pressure does not obey the Inverse Square Law.



# Do not mix up concepts...

---

## Frequently used false statements in the context of sound values and the distance of the sound source

Correct version	Wrong expression
Sound pressure (amplitude) falls inversely proportional to the distance $1/r$ from the sound source. <b>That is the <math>1/r</math> law or the inverse distance law.</b>	Sound pressure (amplitude) falls inversely proportional to the square of the distance $1/r^2$ from the sound source. Really wrong
Sound pressure level decreases by <b>(-)6 dB</b> for doubling of the distance from the source to $1/2$ (50 %) of the sound pressure initial value.	Sound pressure level decreases inversely as the the distance increases for doubling of distance from the source by <b>(-)3 dB</b> . wrong
Sound intensity (energy) falls inversely proportional to the square of the distance $1/r^2$ from the sound source. <b>That is the inverse square law <math>1/r^2</math>.</b>	Sound intensity (energy) falls inversely proportional to the distance $1/r$ from the sound source. wrong
Sound intensity level decreases by <b>(-)6 dB</b> for doubling of the distance from the source to $1/4$ (25 %) of the sound intensity initial value.	Sound intensity level decreases inversely as the square of the distance increases for doubling of distance from the source by <b>(-)3 dB</b> . wrong

Source: <http://www.sengpielaudio.com/calculator-distance.htm>



# Sound (acoustic) intensity – example

---

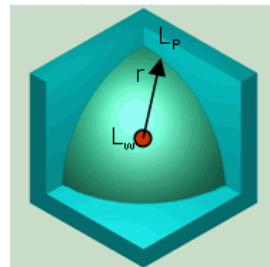
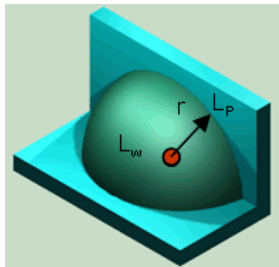
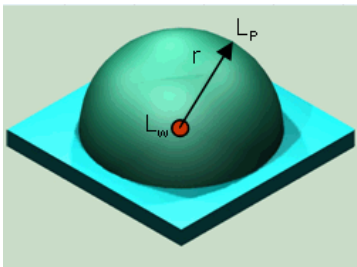
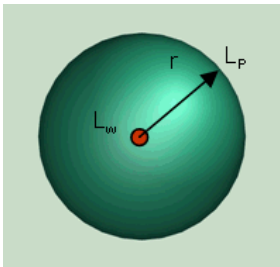
- **Ex:** In a rock concert, measurements are performed next to you yielding a value of 90 dB. Which level will a person who is 5 times further away from the speakers perceive, assuming...
  - ... plane wave propagation?
  - ... cylindrical wave propagation?
  - ... spherical wave propagation?



# Emission and directivity factor

---

- Sound emission
  - Sound power continuously emitted from a sound source
- Sound power level (SWL /  $L_W$  /  $L_{\square}$ ) or acoustic power
  - We have seen how it is related to sound intensity and sound power.
  - Each source radiates with a certain directivity
    - Described by directivity factor  $Q$



$$L_W = L_p + \left| 10 \log \left( \frac{Q}{4\pi r^2} \right) \right|$$

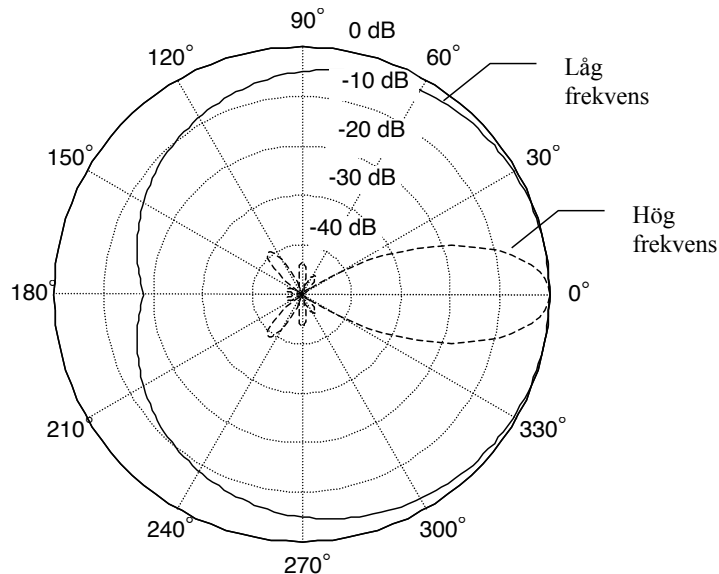
- $Q=1$ : Full sphere
- $Q=2$ : Half sphere
- $Q=3$ : Quarter sphere
- $Q=4$ : Eighth sphere

Source: [www.sengpielaudio.com](http://www.sengpielaudio.com)



# Emission and directivity factory

- Sound emission
  - Sound power continuously emitted from a sound source
- Sound power level (SWL /  $L_W$  /  $L_{\square}$ ) or acoustic power
  - We have seen how it is related to sound intensity and sound power.
  - Each source radiates with a certain directivity
    - Described by directivity factor  $Q$



$$L_W = L_p + \left| 10 \log \left( \frac{Q}{4\pi r^2} \right) \right|$$



# Notes (II)

---

- Sound pressure level (SPL /  $L_p$ )
  - Sound field quantity
  - Relation between sound pressure and distance from source:  $p \propto \frac{1}{r}$
  - Decreases by (-)6 dB for doubling of the distance from the source to 1/2 (50%) of the sound pressure initial value (spherical propagation)

$$L_{p,2} = L_{p,1} + \left| 20 \log \left( \frac{r_1}{r_2} \right) \right|$$

NOTE: A sound source produces sound power and this generates a sound pressure fluctuation in the air. Sound power is the distance independent cause of this, whereas sound pressure is the distance-dependent effect.

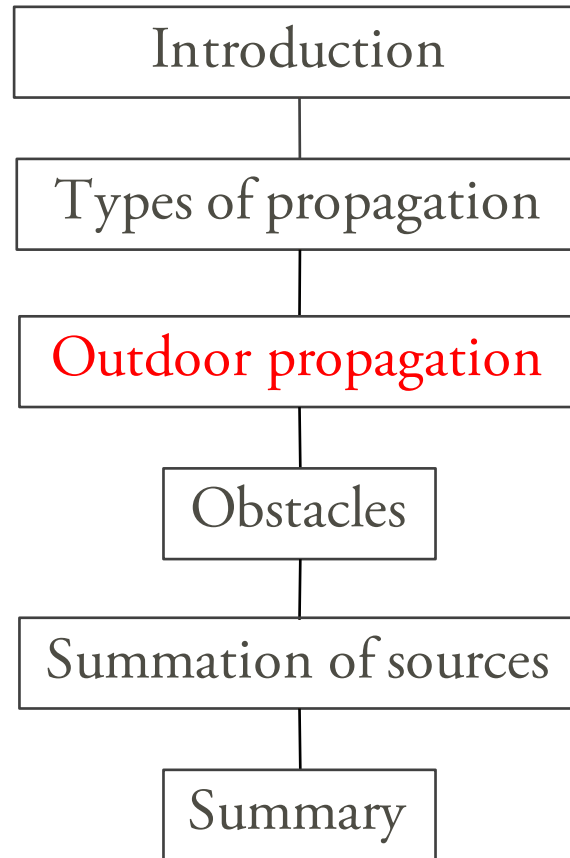
- Sound intensity level (SIL /  $L_I$ )
  - Sound energy quantity
  - Relation between sound intensity and sound pressure:  $I \propto p^2$
  - Decreases by (-)6 dB for doubling of the distance from the source to 1/4 (25%) of the sound intensity initial value (spherical propagation)

$$L_{I,2} = L_{I,1} + \left| 10 \log \left( \frac{r_1^2}{r_2^2} \right) \right|$$



# Outline

---



# Example: Regulations – Industry noise, new building

- Naturvårdsverket om buller från industrier

**Tabell 2.1. Utomhusriktvärden för externt industribuller angivna som ekvivalent ljudnivå i dBA. Tabellen gäller frifältsvärder. vid nyetablering av Industri.**

Områdesanvändning <sup>1)</sup>	Ekvivalent ljudnivå i dBA			Högsta ljudnivå i dBA-läge "FAST"
	Dag kl. 07-18	Kväll kl. 18-22 samt söndag och helgdag kl. 07-18	Natt kl. 22-07	Momentana ljud nattetid kl. 22-07
Arbetslokaler för ej bullrande verksamhet	60	55	50	-
Bostäder och rekreationsytor i bostäders grannskap samt utbildningslokaler och vårdbyggnader.	50	45	40 <sup>2)</sup>	55
Områden för fritidsbebyggelse och rörligt friluftsliv där naturupplevelsen är en viktig faktor. <sup>3)</sup>	40	35	35	50

1) Vid de fall där kringliggande områden ej utgörs av angivna områdestyper bör bullervillkoren anges på annat sätt, t ex ljudnivå vid stadsplanegräns eller på ett visst avstånd från anläggningen.

2) Värdet för natt behöver ej tillämpas för utbildningslokaler.

3) Avser områden som planlagts för fritidsbebyggelse och rörligt friluftsliv.



# Example: Regulations – Industry noise, existing building

- Naturvårdsverket om buller från industrier

**Tabell 2.2 Utomhusriktvärden för externt industribuller angivna som ekvivalent ljudnivå i dBA. Tabellen gäller frifältsvärden för befintlig industri.**

Områdesanvändning <sup>1)</sup>	Ekvivalent ljudnivå i dBA			Högsta ljudnivå i dBA-läge "FAST"
	Dag kl. 07-18	Kväll kl. 18-22 samt söndag och helgdag kl. 07-18	Natt kl. 22-07	Momentana ljud nattetid kl. 22-07
Arbetslokaler för ej bullrande verksamhet	65	60	55	-
Bostäder och rekreationsytor i bostäders grannskap samt utbildningslokaler och vårdbyggnader.	55	50	45 <sup>2)</sup>	55
Områden för fritidsbebyggelse och rörligt friluftsliv där naturupplevelsen är en viktig faktor. <sup>3)</sup>	45	40	40	50

1) Vid de fall där kringliggande områden ej utgörs av angivna områdestyper bör bullervillkoren anges på annat sätt, t ex ljudnivå vid stadsplanegräns eller på ett visst avstånd från anläggningen.

2) Värdet för natt behöver ej tillämpas för utbildningslokaler.

3) Avser områden som planlagts för fritidsbebyggelse och rörligt friluftsliv.

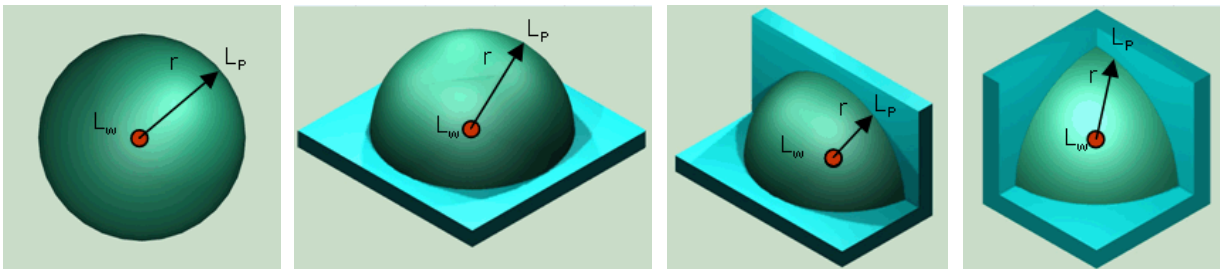


# How it goes in practice

---

- There is an industry with many noise sources.
- New apartment buildings are planned in a adjacent field. Or the industry wants to increase its production capacity increasing its buildings/machineries.
- Acousticians go to the plant and estimate sound power of various sources at short distance – in this way each source is measured in an objective way.
- Go back to the office, and from the estimated sound power compute sound pressure at new distances; perhaps add new sources, or modify existing ones with lower SWL.
- Evaluate calculated SPL with regulations.

$$L_W = L_p + \left| 10 \log \left( \frac{Q}{4\pi r^2} \right) \right|$$



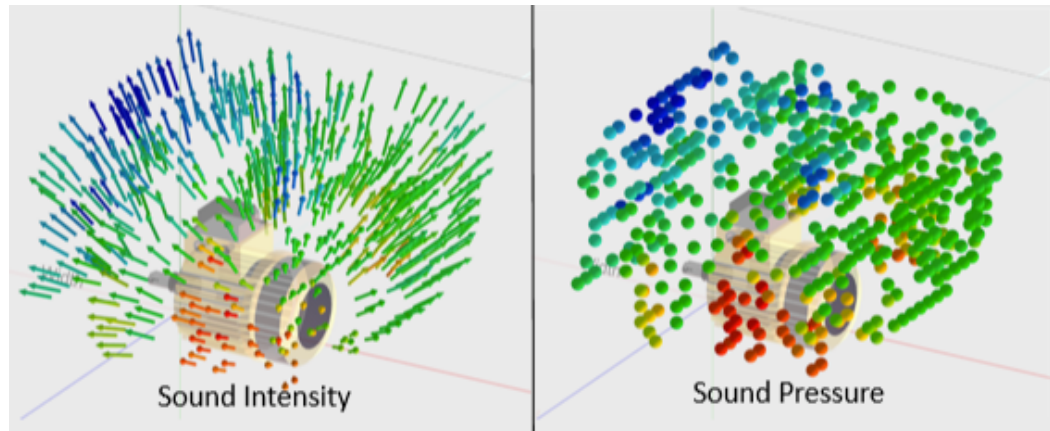
Source: [www.sengpielaudio.com](http://www.sengpielaudio.com)



# And sound intensity?

---

- Often sound power is estimated using sound pressure.
- However sound power can also be estimated from sound intensity
- Sound intensity is a more robust quantity.
  - Energetic quantity;
  - Vector.
- Measuring sound intensity is slower, more difficult and more expensive.



# Sound intensity measurement with probe

---

- It is an instrument composed of two (phase matched) microphones
  - Intensity:  $\vec{I} = \langle pv \rangle = \frac{1}{T} \int_0^T p(t)\vec{v}(t)dt$
  - Pressure: average between the two microphones
  - Velocity (from F4):  $\frac{\partial p}{\partial x} = -\rho \frac{\partial v}{\partial t}$
  - Spatial derivatives may be approximated as finite differences...
  - Derivative on velocity turned into an integral (integration over time performed in the instrument).



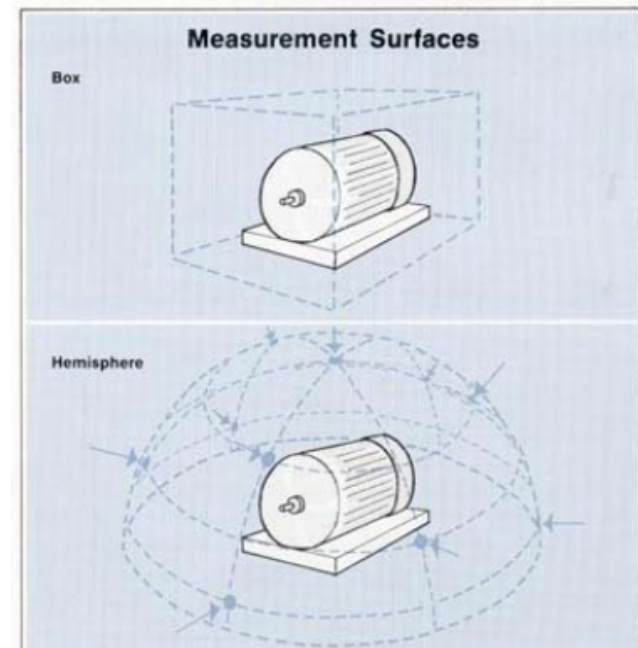
# How it goes in practice

---

- Sound pressure or sound intensity is measured on an fictious surface around the source.
- Then by knowing the distance from the source and the surface of the fictious surface, sound power can be estimated.

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

$$L_W = L_p + \left| 10 \log \left( \frac{Q}{4\pi r^2} \right) \right|$$



<https://www.bksv.com/media/doc/br0476.pdf>



# Sound reference source

---

- Sound power of an indoor source can also be estimated using a reference source (a fan).
- SPL caused by the reference source of which the SWL is known in a certain room is measured.
- The SPL of the source under study is also measured.
- The two measured SPLs are compared.
- Remember: SPL is a field property.
  - Thanks to the standardized reference source the influence of the environment to the source's SPL is eliminated.



# Regulations – wind turbine noise

---

- By the façade

Case	Measure	Value
Normal	$L_{Aeq,24h}$	40 dBA
Low background noise	$L_{Aeq,24h}$	35 dBA
If the sound contains audible tones		-5 dB more

NOTE: regulations regarding traffic noise in the next lecture

- Same procedure: sound power of the wind turbine is estimated using standardized measurement procedure.

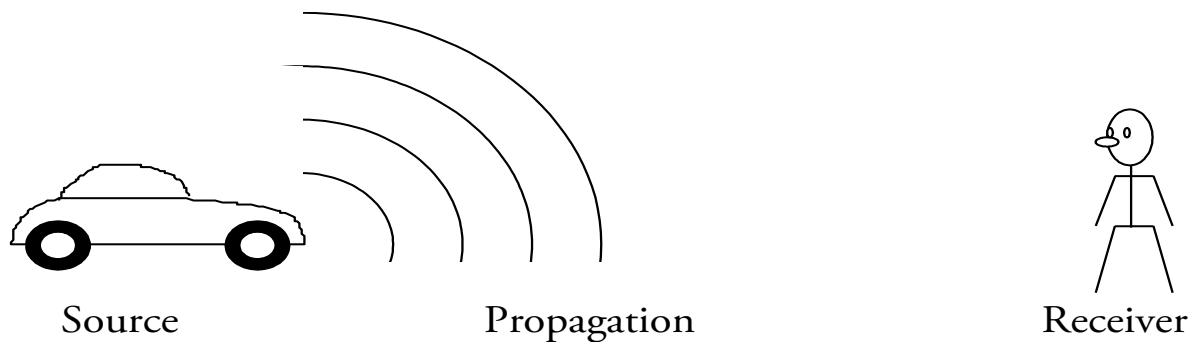


# Outdoor sound propagation – influencing factors

---

Factors influencing the sound propagation outdoors

1. Weather and wind
2. Obstruction (hindering) objects
3. Reflection



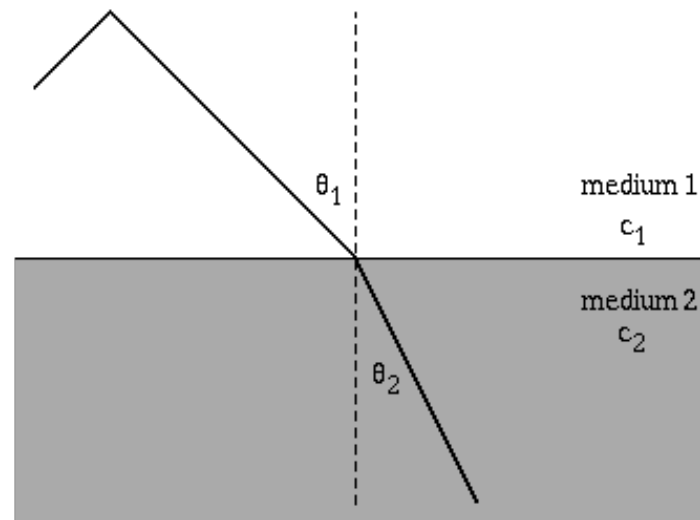
# Refraction of sound waves

---

- Snell's law

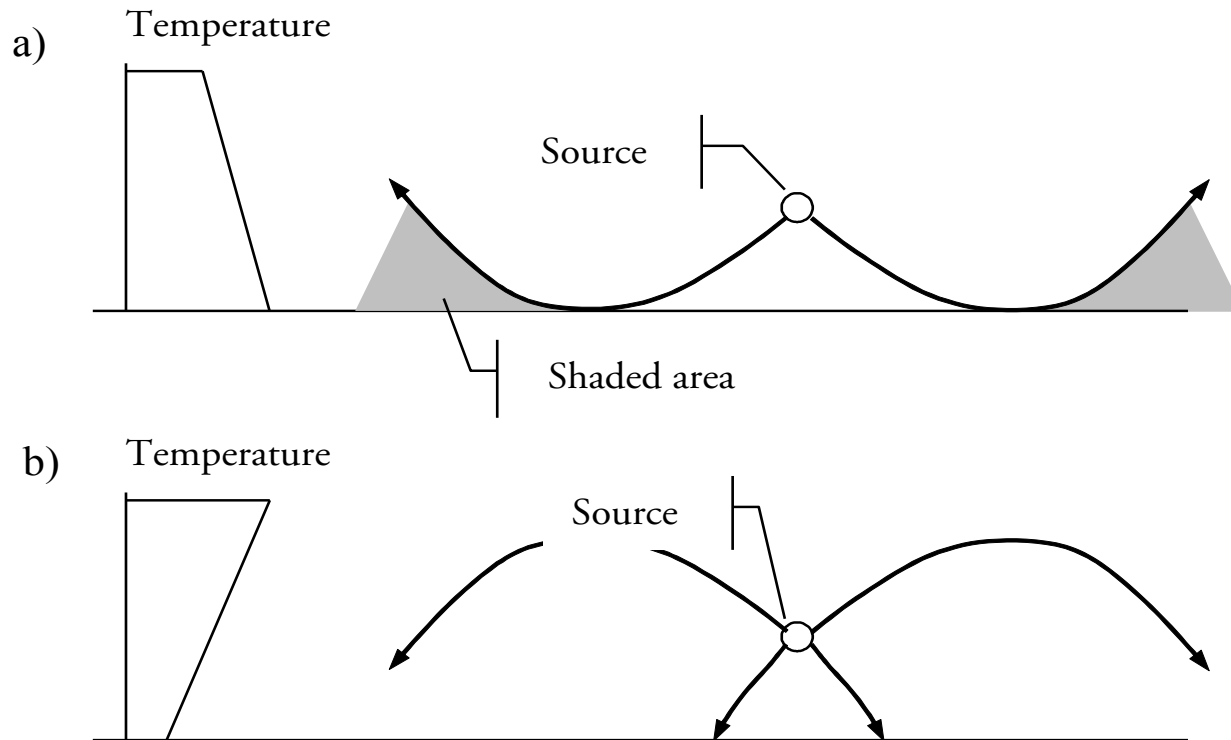
- Speed of propagation varies
- Frequency remains constant

$$\frac{c_1}{\cos(\theta_1)} = \frac{c_2}{\cos(\theta_2)}$$

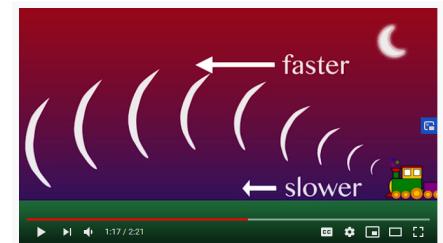
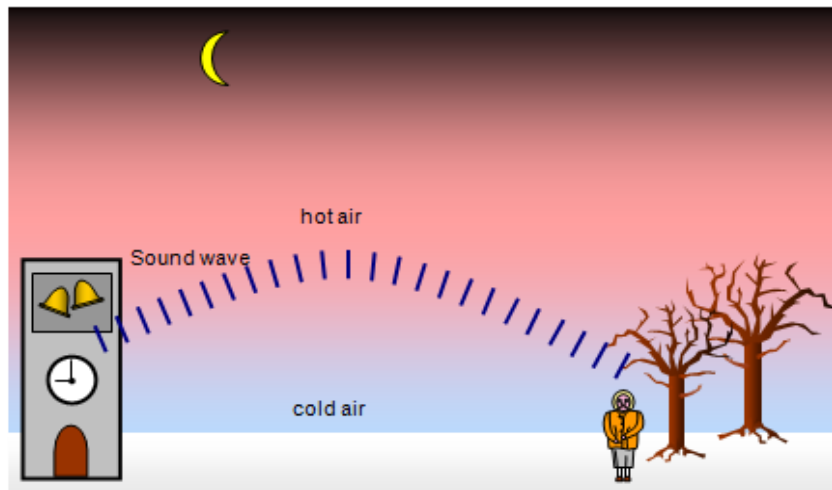
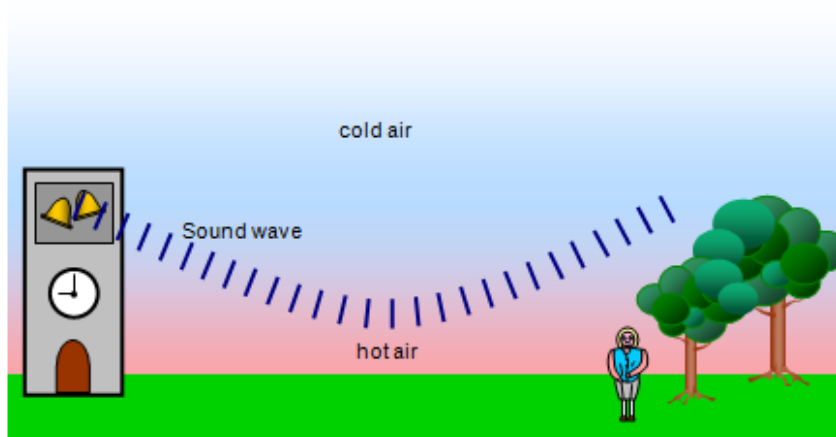


# Outdoor sound propagation – Temperature (I)

- Sound propagation speed:  $c_{air} = \sqrt{\frac{\gamma P_0}{\rho_{air}(T=0^\circ)}} \left(1 + \frac{T_{air}[^\circ C]}{2 \cdot 273}\right) = 331.4 \cdot \left(1 + \frac{T_{air}[^\circ C]}{2 \cdot 273}\right)$ 
  - In a cold winter night, the sound is heard "slower" than in a summerday



# Outdoor sound propagation – Temperature (II)



<https://youtu.be/ZgwEAUHpNrs>

Source: <http://www.schoolphysics.co.uk>

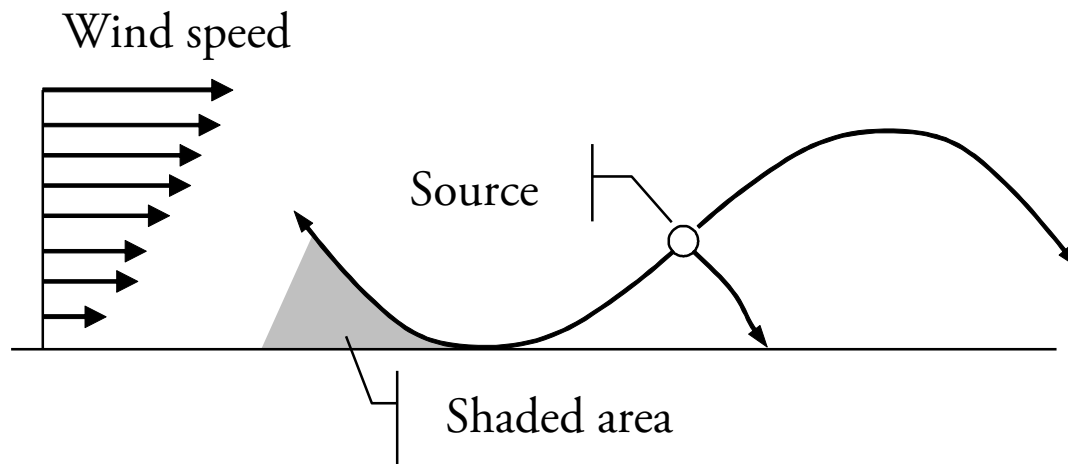


LUND  
UNIVERSITY

# Outdoor sound propagation – Wind

---

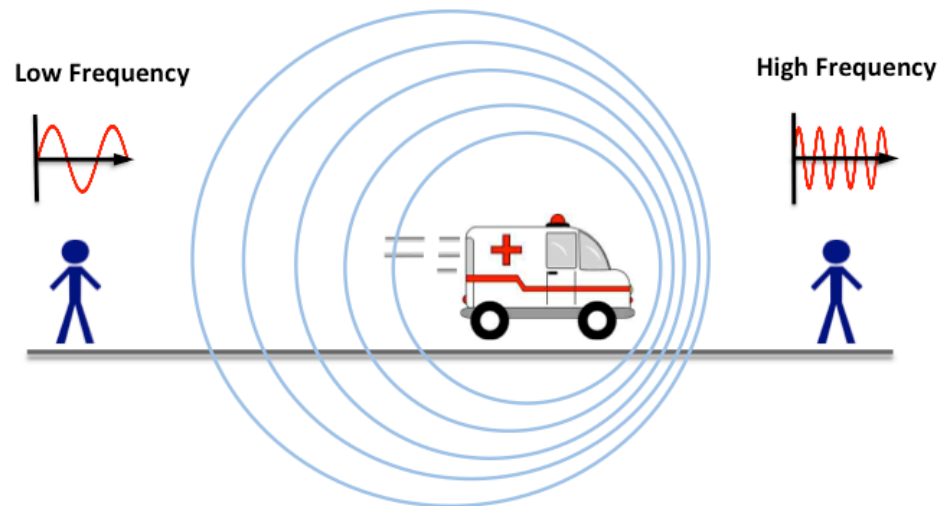
- Generally greater than the temperature dependence
- Upwind / Downwind
- SPL reduction due to turbulence: 4-6 dB/100m
  - » Independent of wind direction
  - » More obvious the greater the wind speed is



# Doppler effect

---

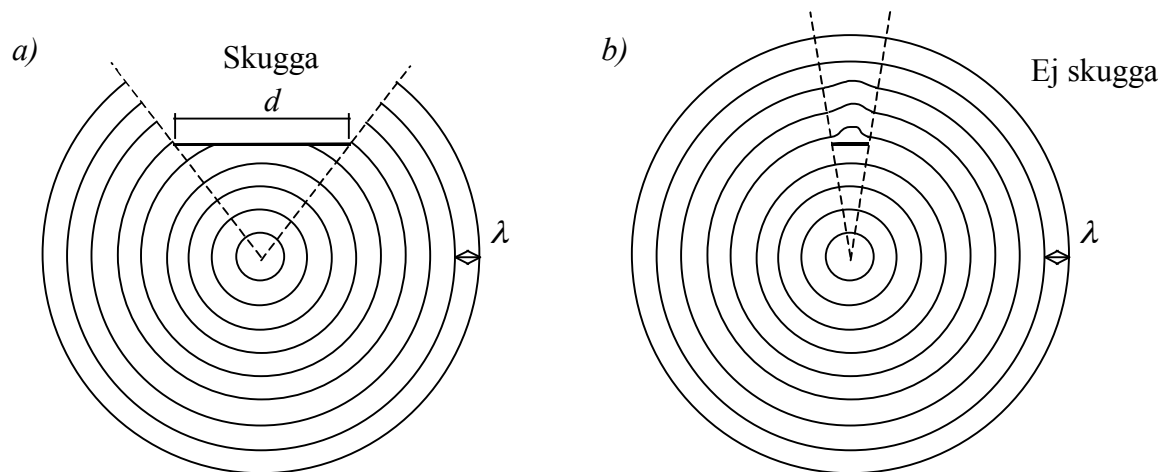
- Change in frequency or wavelength of a wave (or other periodic event) for an observer moving relative to its source



# Diffraction – Sound ”bending”

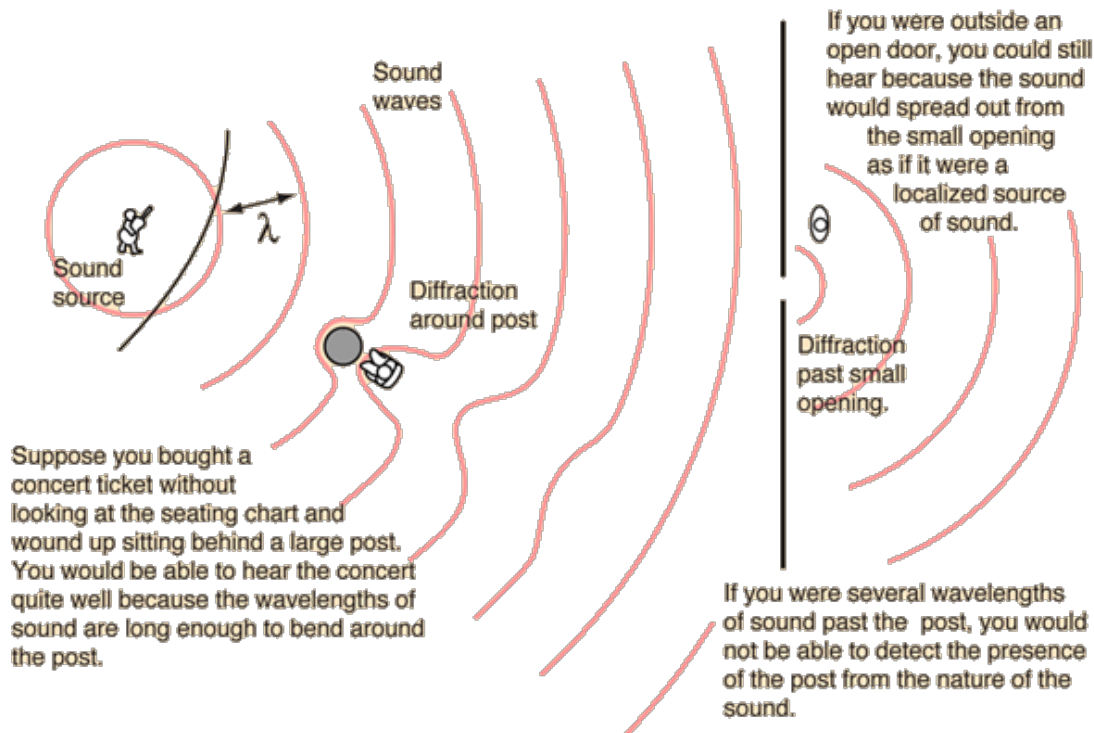
---

- Diffraction: the bending of waves around small\* obstacles and the spreading out of waves beyond small\* openings.
  - If  $d > \lambda \rightarrow$  the obstacle ”exists”
  - If  $d < \lambda \rightarrow$  the sound bends around the obstacle



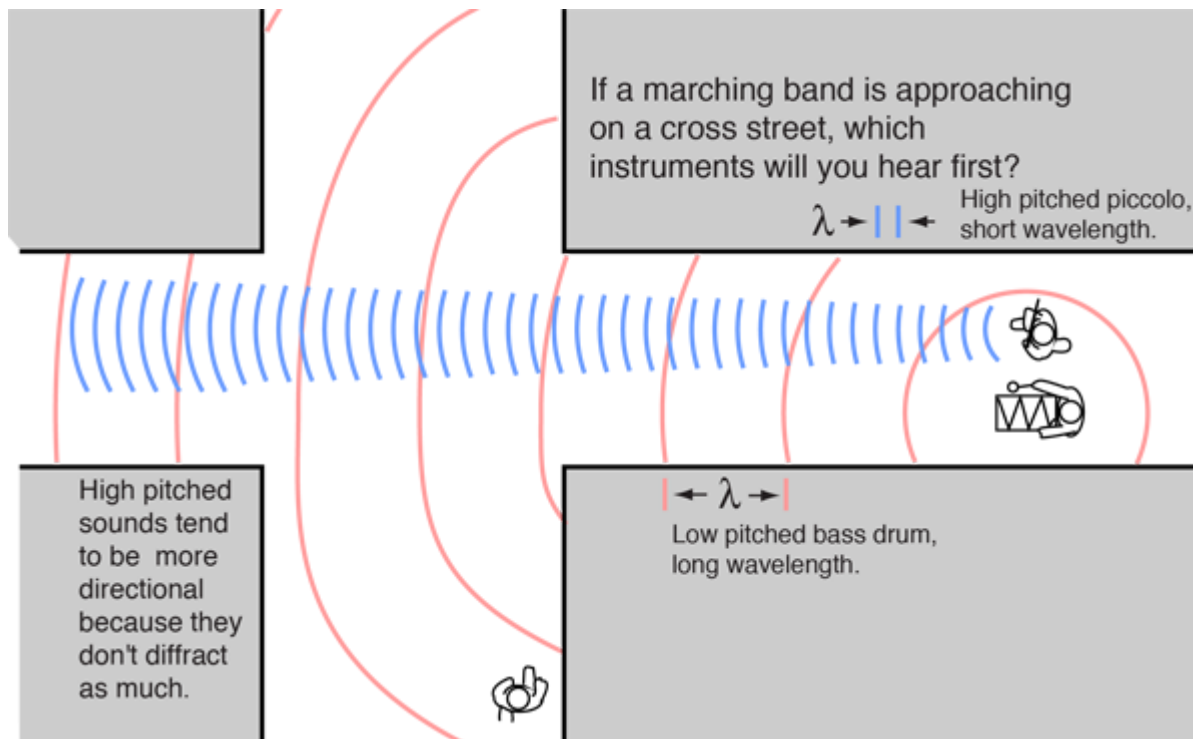
# Diffraction – Sound "bending"

- Diffraction: the bending of waves around small\* obstacles and the spreading out of waves beyond small\* openings.



# Diffraction – Sound "bending"

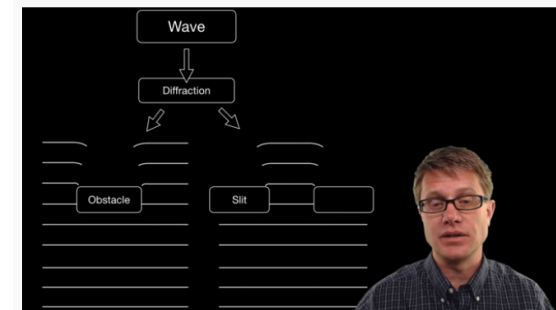
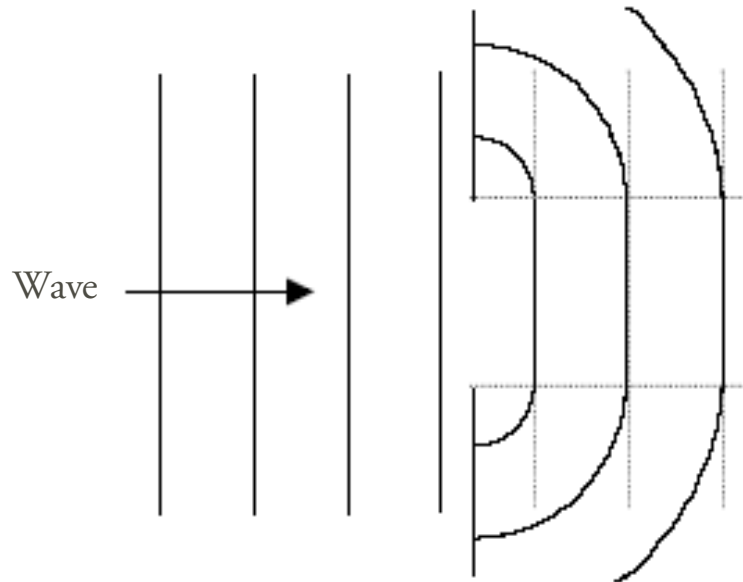
- Diffraction: the bending of waves around small\* obstacles and the spreading out of waves beyond small\* openings.



# Diffraction – Slit

---

- Opening  $\ll \lambda$ : spherical wave after the obstacle (slit)
- Opening  $\gg \lambda$ : plane wave after the obstacle (slit)

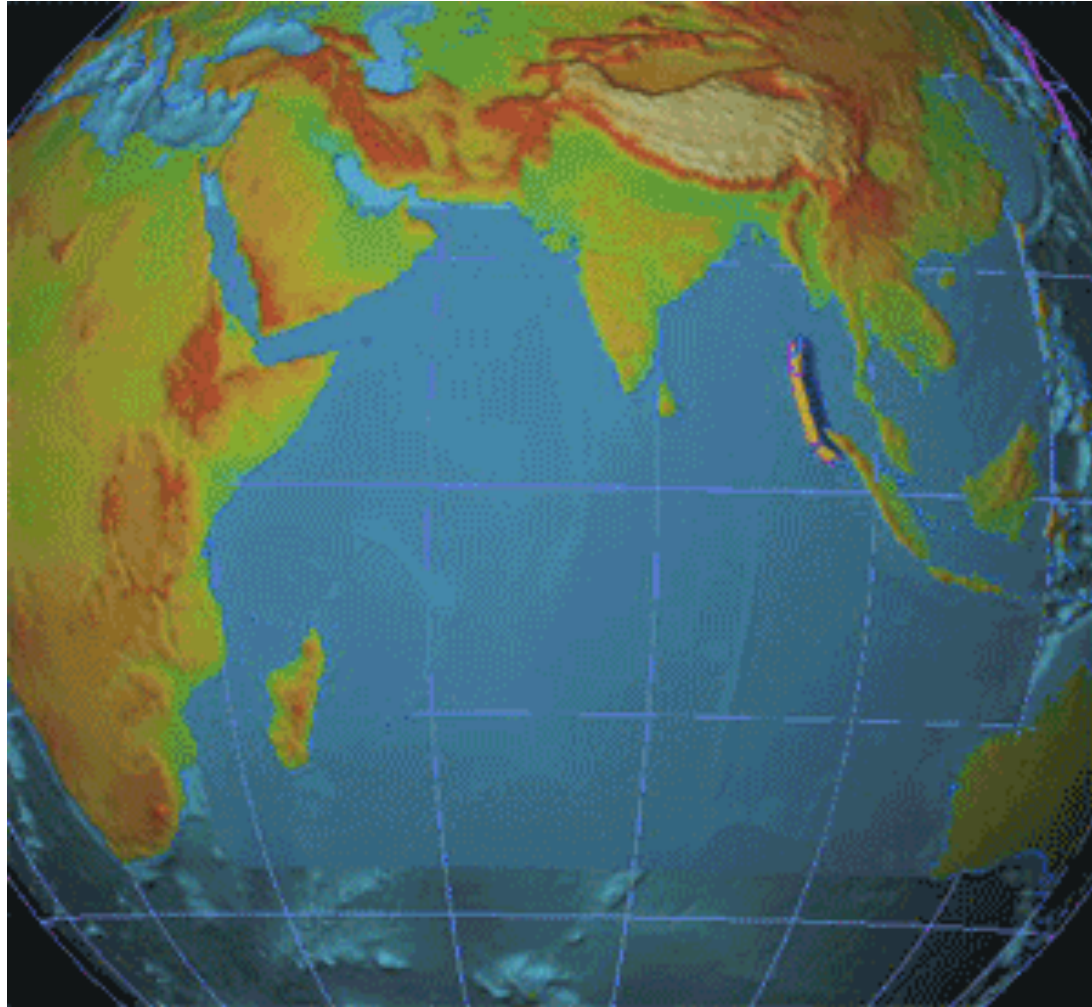


<https://youtu.be/1bHipDSHVG4>



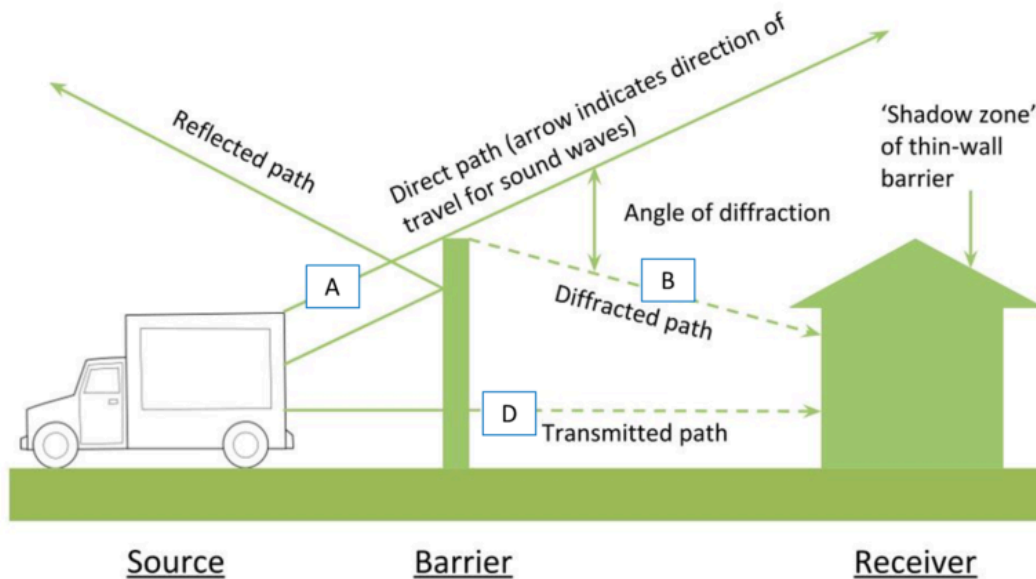
# Example – Tsunami

---



# Noise barriers

- Many propagation principles can be applied for open spaces

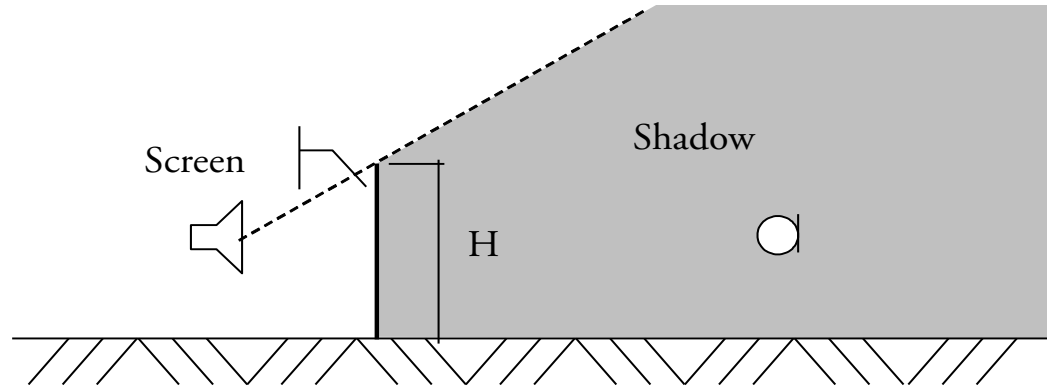


[Chuo Expressway Tokyo]

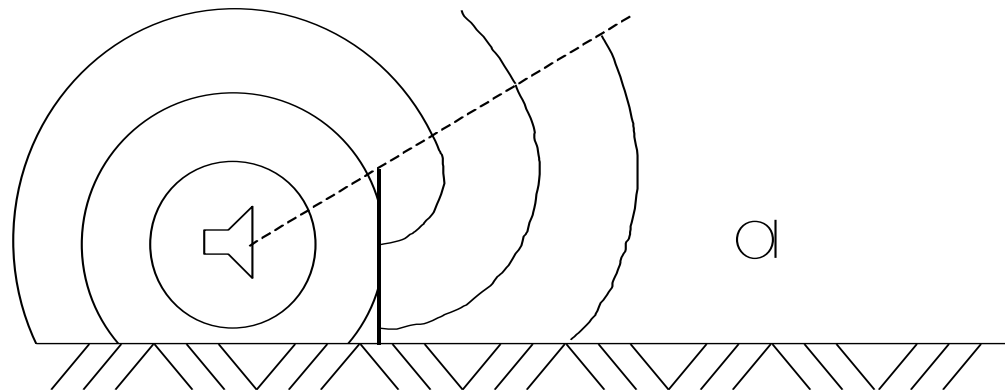


# Noise barriers

- $\lambda \ll H$



- $\lambda \gg H$



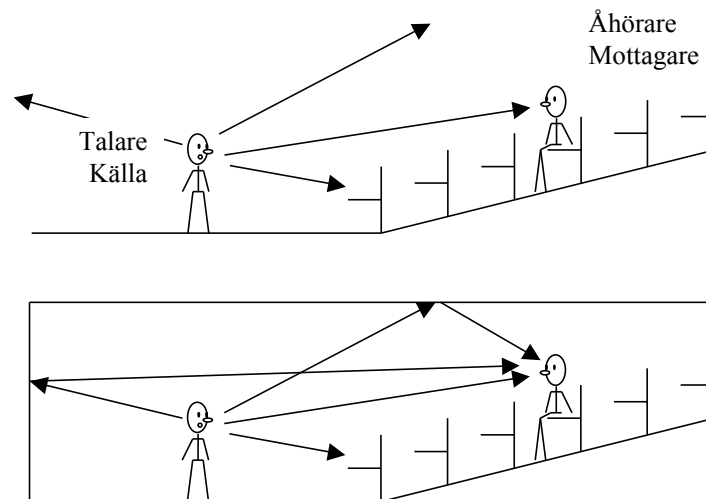
MORE ABOUT THIS IN THE TRAFFIC NOISE LECTURE



# Indoor sound propagation?

---

- Indoor sound propagation comprises effects of absorption and reflection.
- Basic concepts on the three types of propagations hold in principle.
  - Office landscape example of cylindrical propagation?
- More on that after the break (room acoustics).



# Summary

---

- Sound power, sound intensity
- Types of propagation
  - Plane
  - Cylindrical
  - Spherical
- Outdoor propagation
- Wave obstacles (barriers)



Thank you for your attention!

*nikolas.vardaxis@construction.lth.se*



**LUND**  
**UNIVERSITY**