RECORDING

Ljud i byggnad och samhälle (VTAF01) – Sound propagation outdoors

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Recap from previous lecture F5

- Recap...

Standing waves – Velocity profile

Standing waves – Pressure profile

Standing waves – Velocity profile

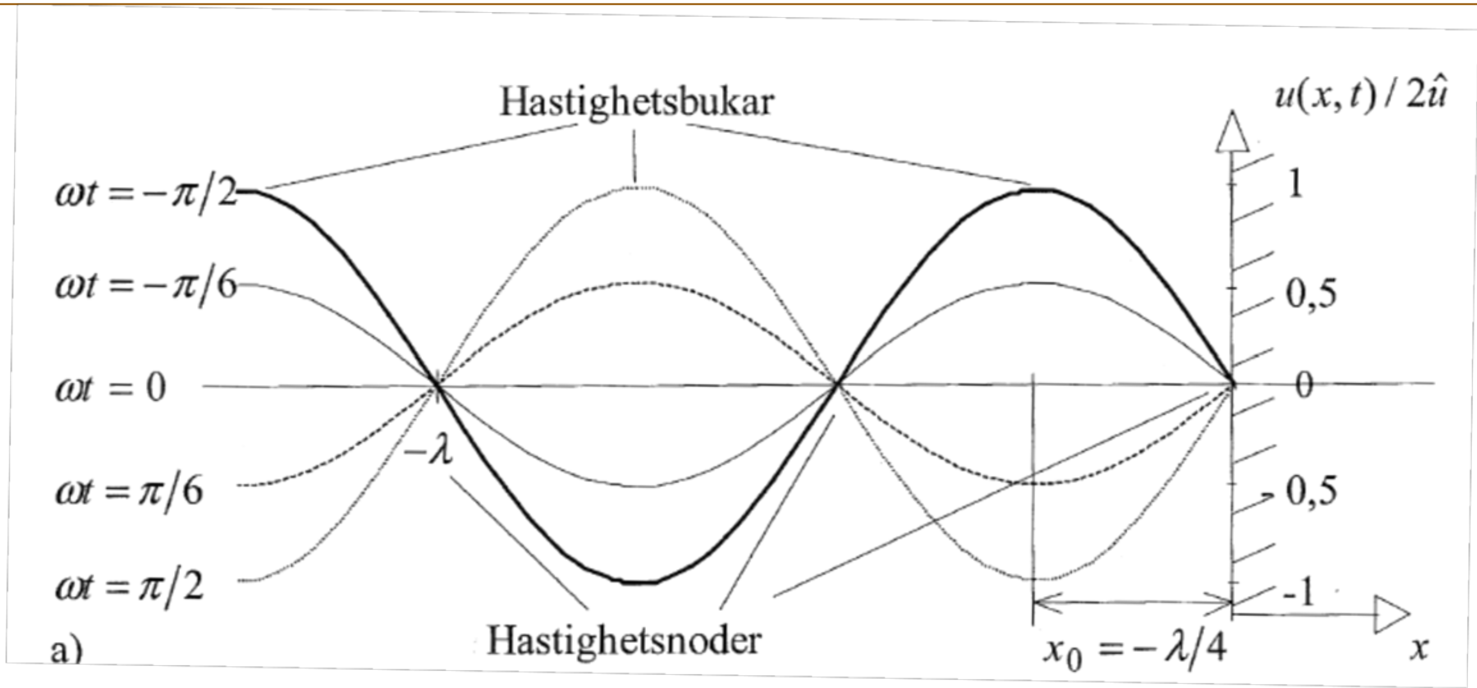


Figure: Ljud och vibrationer - Bodén

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

Standing waves – Pressure profile

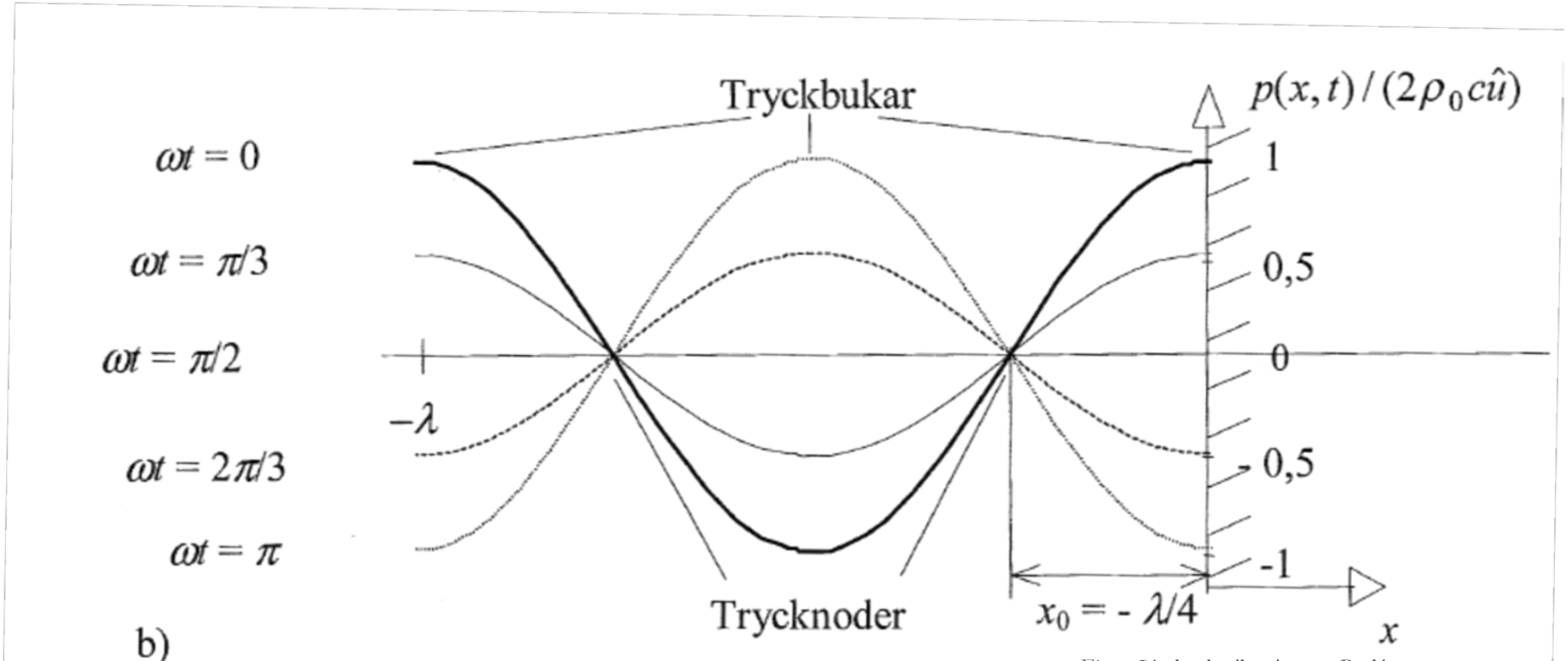
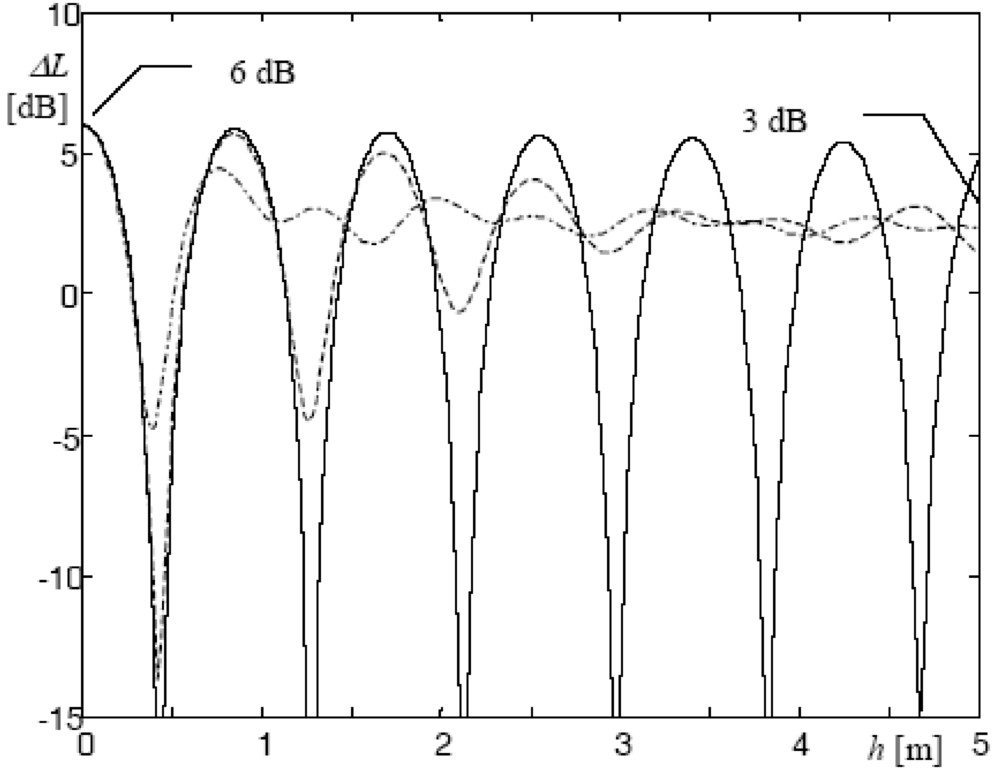


Figure: Ljud och vibrationer - Bodén

- 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. → Measurement by a hard wall

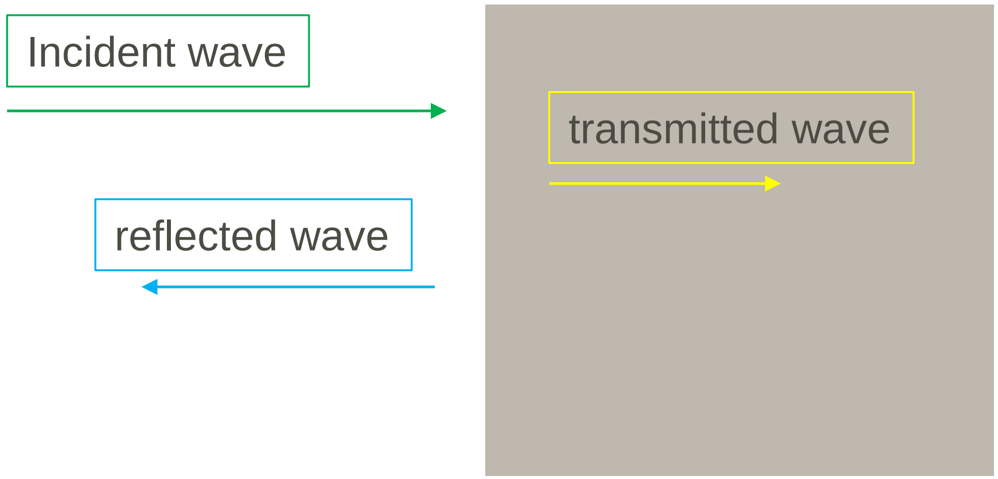
Measurement of SPL close to a hard surface



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



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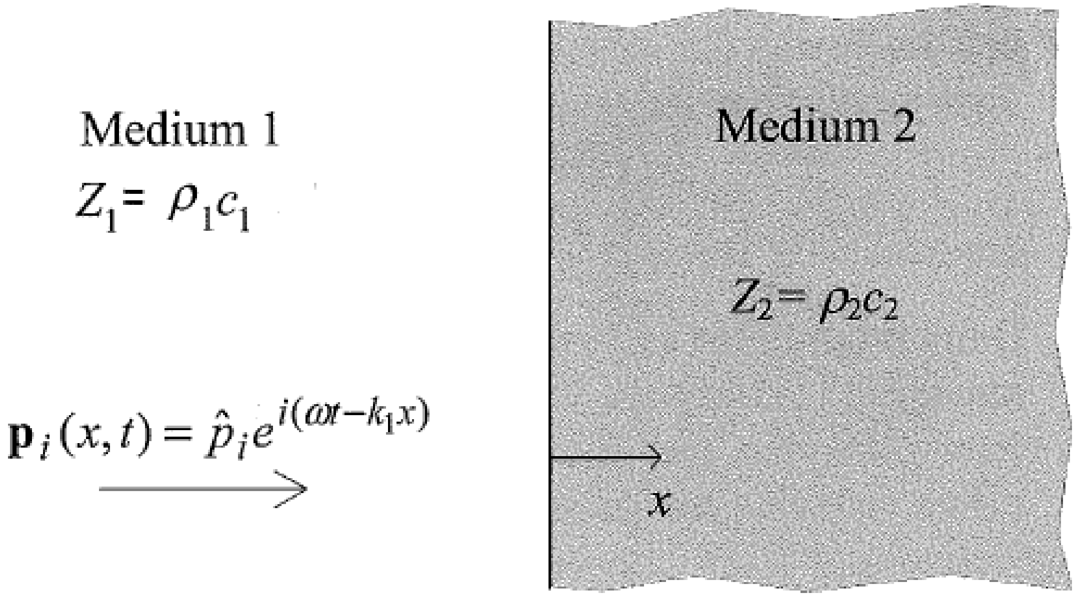
Transmission and reflection

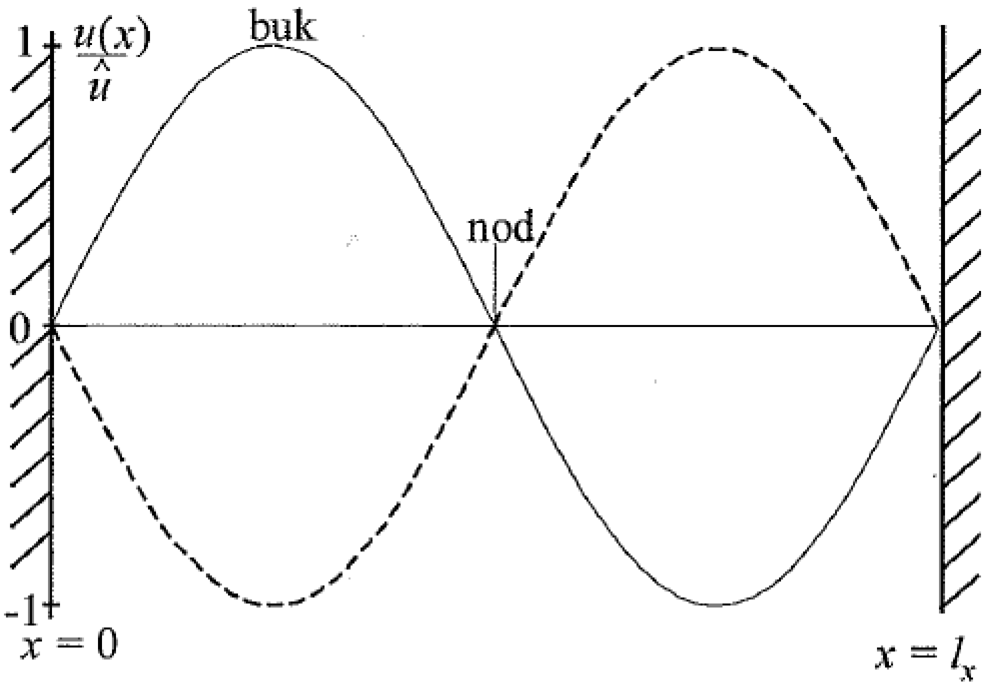


$$r = \frac{\hat{p}_r}{\hat{p}_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

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

Two hard walls– Velocity function

- Now we have different boundary conditions than before…



See Compendium pg 46.

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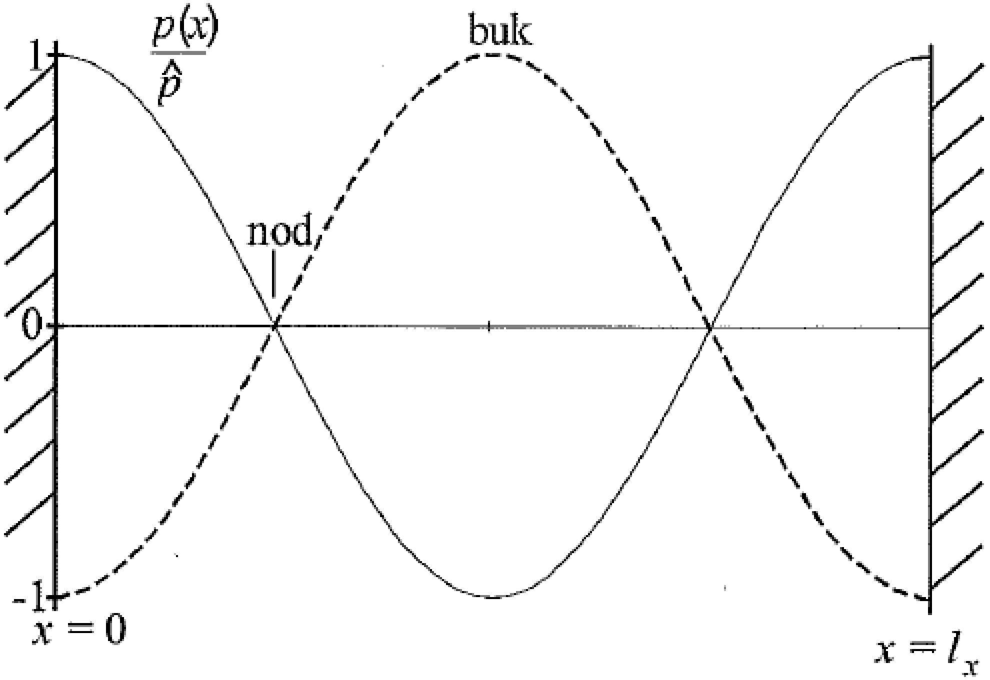
Two hard walls – Pressure function

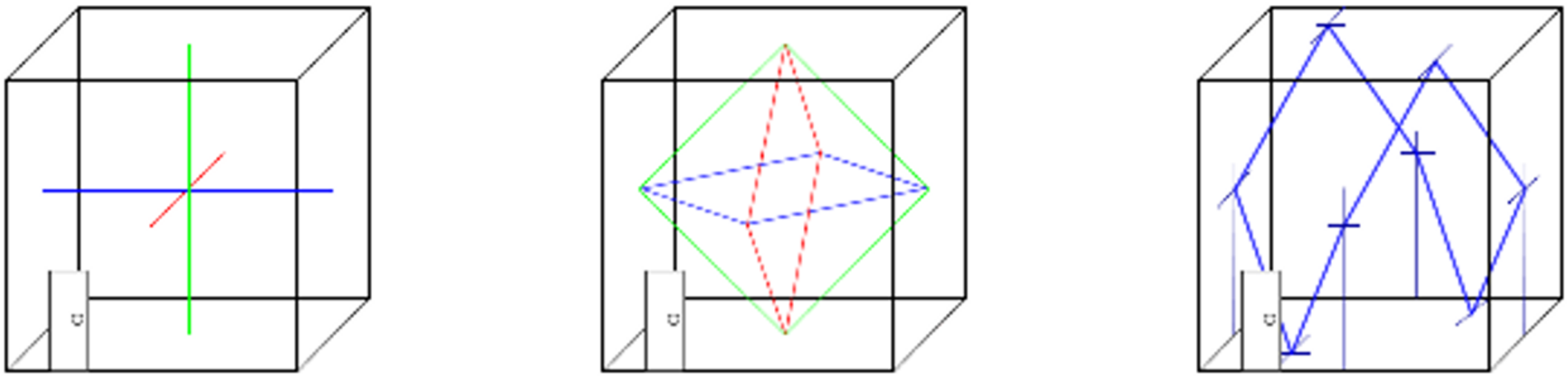
$$\frac{\partial^2 p}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \xrightarrow[\text{solution}]{\text{Homogeneous}} \lambda_n = \frac{2\pi}{k_n} = \frac{2\pi L}{n\pi} = \frac{2L}{n} \longrightarrow f_n = \frac{c}{\lambda_n} = \frac{c}{2}\frac{n}{L}$$



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

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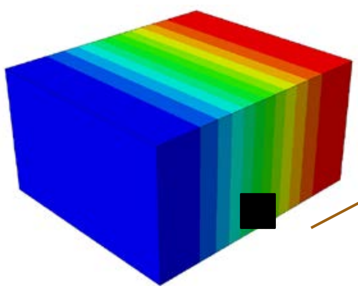
Forced response and modes

- 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).



(1,0,0)

Source: Carl Hopkins, *Sound Insulation*

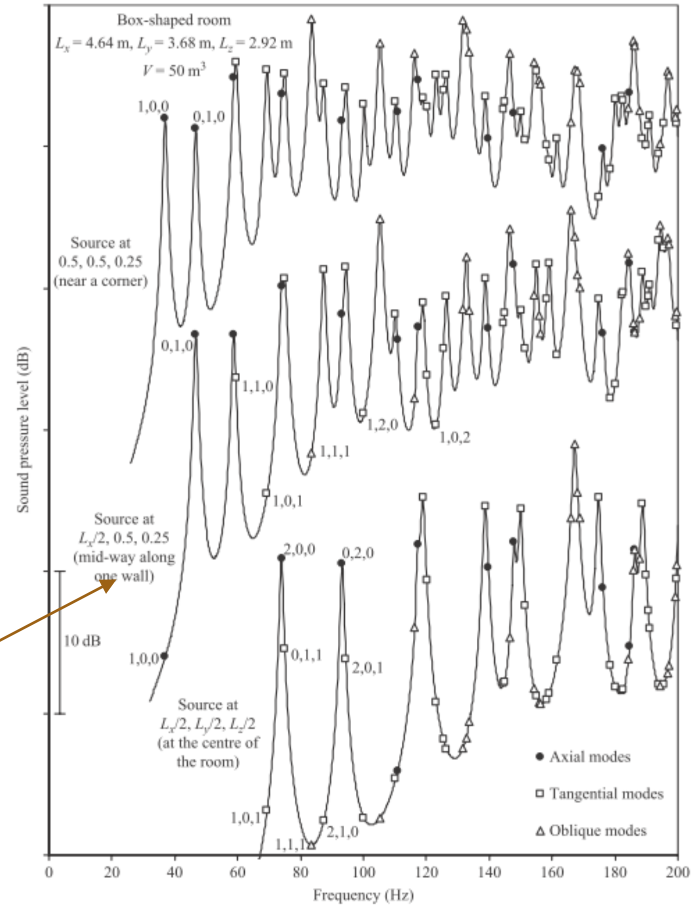


Figure 1.37

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.

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Mode count in a room

- How many modes we have in a room?

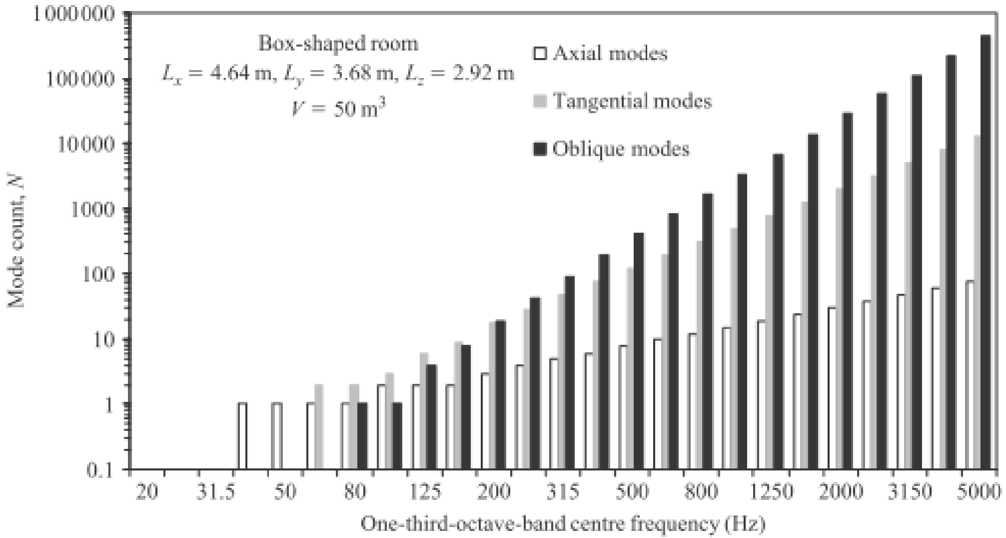

Figure 1.14

Mode count for axial, tangential, and oblique modes in a 50 m^3 box-shaped room.

Source: Carl Hopkins, *Sound Insulation*

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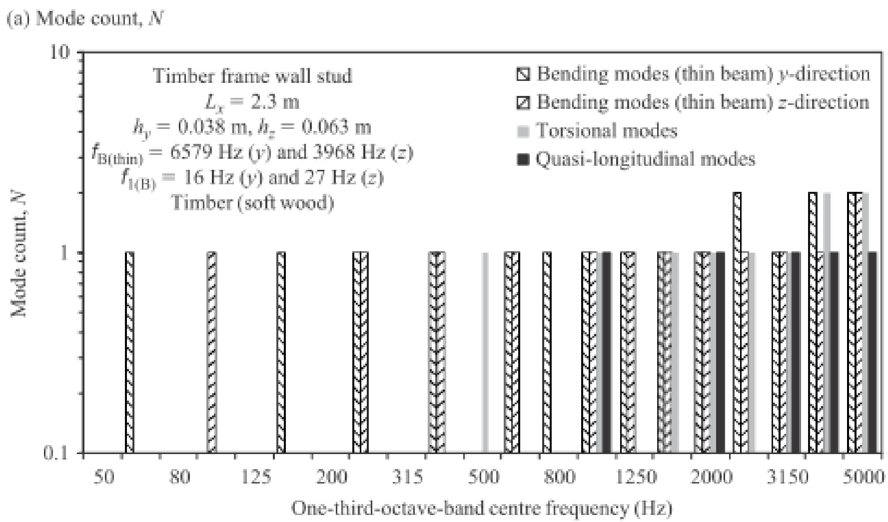
Modes in structures - beams

- 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



Source: Carl Hopkins, *Sound Insulation*

Modes in structures - plates

- Each structure has its own eigenfrequencies (modes) – like the string and the beam.
- In particular each kind of wave motion has its own eigenfrequencies.
- At lower frequencies only bending modes matter.

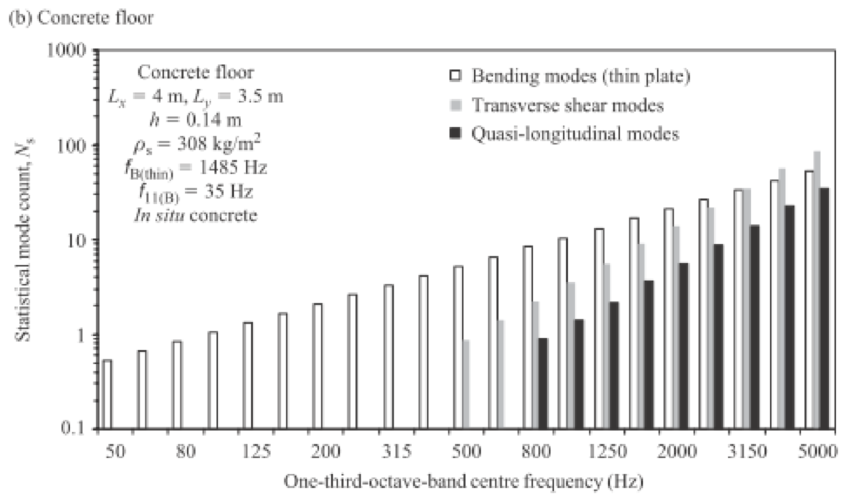


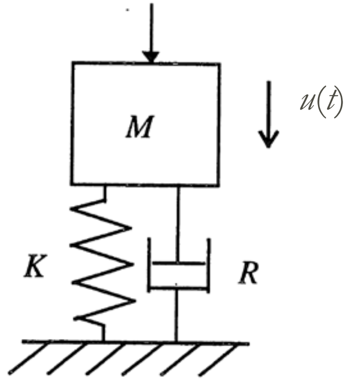
Figure 2.28

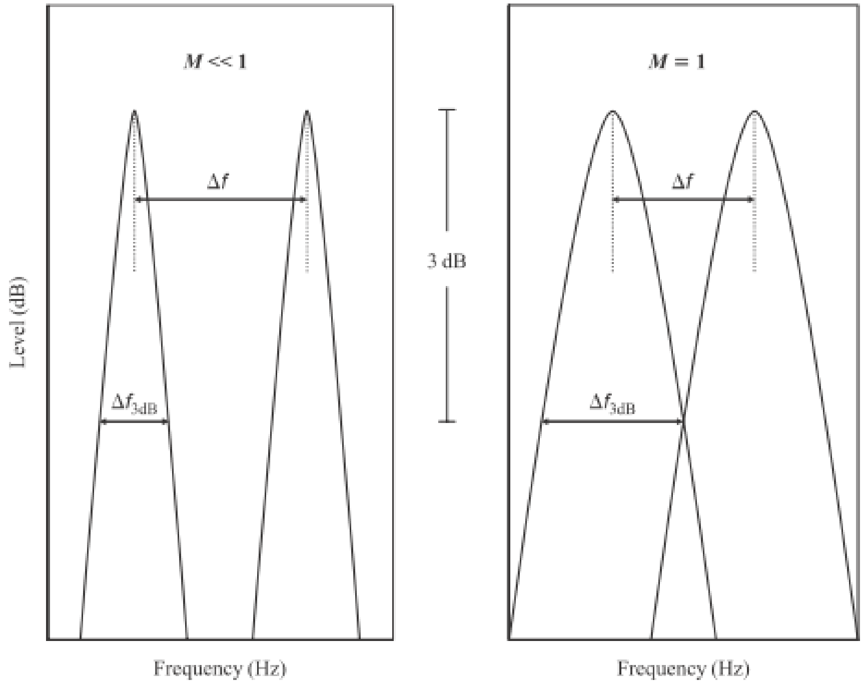
Plates: statistical mode counts for a sheet of plasterboard, a concrete floor, and two different masonry walls. Note that values are only shown at and above the frequency band that contains the estimated fundamental mode for each wave type.

Source: Carl Hopkins, *Sound Insulation*

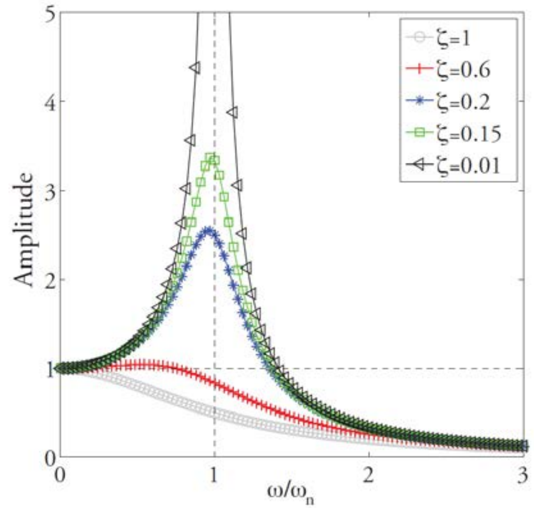
Overlap of modes

- Damping will make modes overlap.

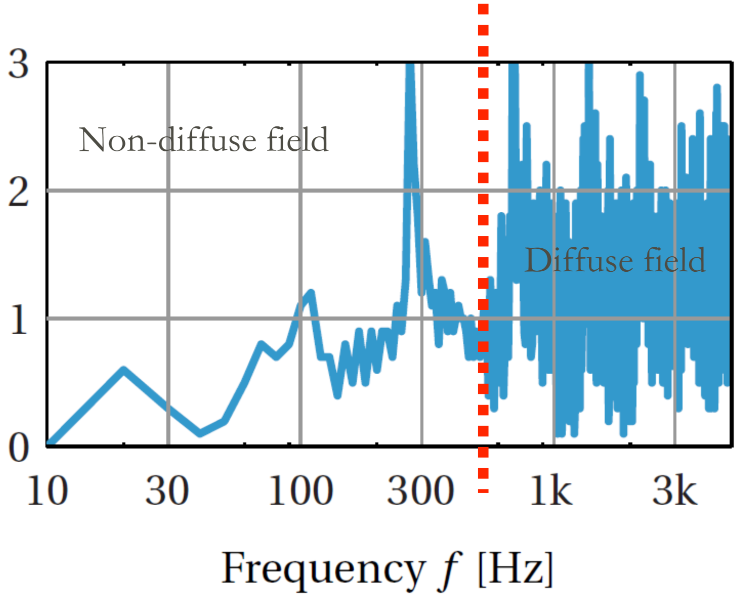




Source: Carl Hopkins, *Sound Insulation*



Diffuse field & Non-diffuse field



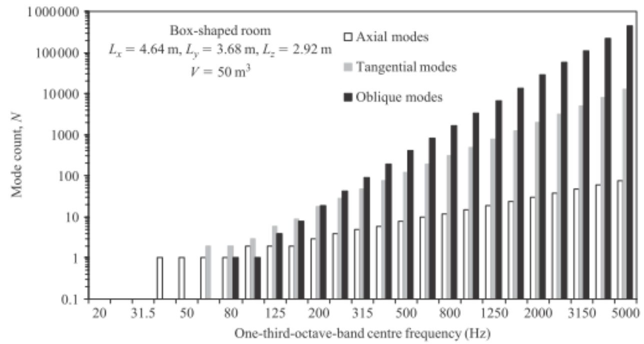


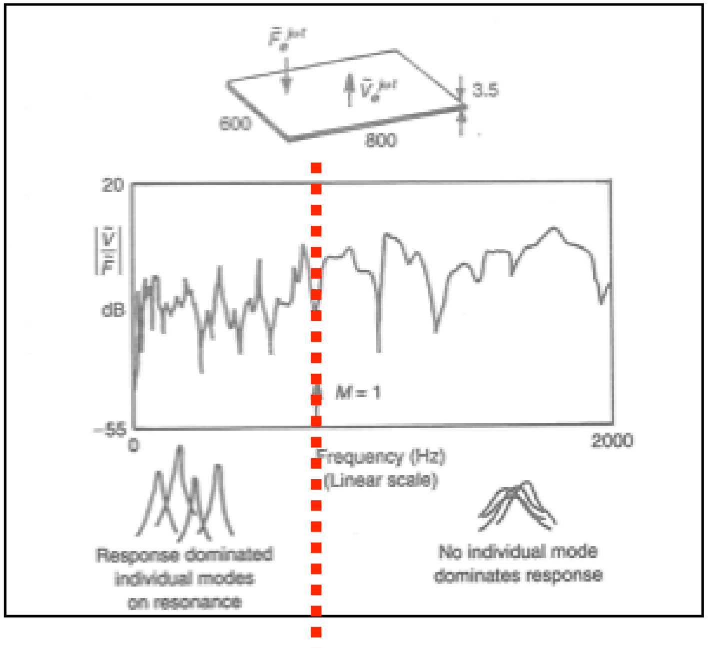
Figure 1.14

Mode count for axial, tangential, and oblique modes in a 50 m^3 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
  - More about this in room acoustics lectures

Diffuse field & Non-diffuse field

- Go back to transfer functions…



Fahy, Gardonio

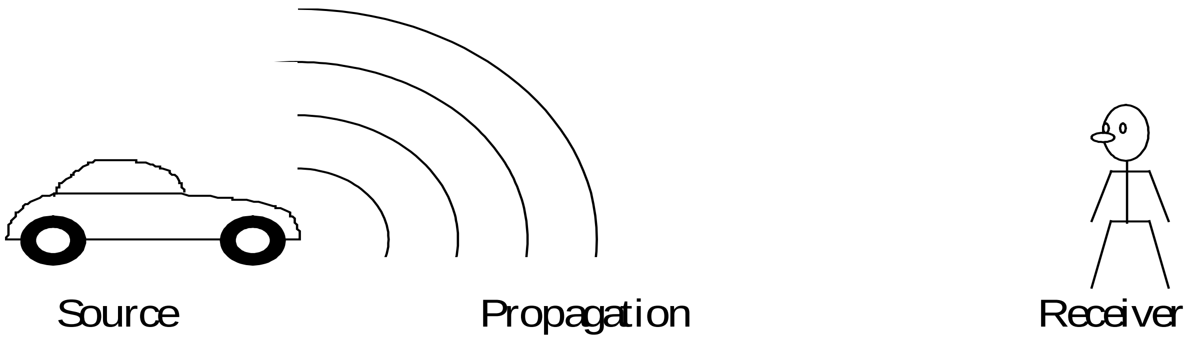
- Clear peaks i.e. clear modes
- Characteristic of the structure
- Detailed precise description attempted

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

Recap from previous lecture F5

- End of recap...

How does sound propagate?



Sound power and sound intensity

- Today we introduce key concepts to describe sound sources and the propagation of sound from them – sound power and sound intensity.
    - Already introduced during exercises. Today official introduction! Besides their definition we can also see why these concepts are useful tools for an acoustician.
- In the end we will look at some phenomena occurring outdoor and with propagating waves in general.
- But before looking at how sound propagates, let's define *where* sound may propagate.

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

- **Direct field:** the region in which the sound measured 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 is uniform i.e. the reflected sound dominates, as opposed to the region close to a noise source where the direct sound dominates. The 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

Diffuse field

Sound power and sound intensity

- A loudspeaker consumes electrical power [W] just like a lamp.
- The loudspeaker change 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 fictious 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^2].
  - For a free propagating wave with planar form, $\bar{\mathrm{I}} = \frac{\widetilde{\mathrm{p}^2}}{\rho\mathrm{c}}$
  - For a free propagating wave with spherical form (r radial distance), $\bar{\mathrm{I}} = \frac{\widetilde{\mathrm{p}^2}}{r^2\rho\mathrm{c}}$

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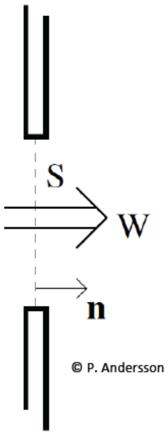
Sound (acoustic) power – definition

- 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: $\overline{W} = \frac{1}{T}\int_0^T W(t)dt$



- In decibels…

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

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 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 [W/m²]
  - Instantaneous value: $\vec{I}(t) = p(t)\vec{v}(t)$
  - Vector quantity: energy flow and direction: $\bar{\vec{I}} = \langle pv \rangle = \frac{1}{T}\int_0^T p(t)\vec{v}(t)dt$
  - In a free field (plane waves): $\bar{I} = \frac{\widetilde{p^2}}{\rho c}$; $\bar{I} \propto p^2$
- In decibels… $L_I = 10\log\left(\frac{\bar{I}}{I_{ref}}\right)$; $I_{ref} = 10^{-12}\ {W}/{m^2}$

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

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

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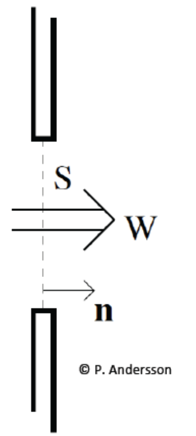
Sound (acoustic) power – definition

- Rate of energy transported through a surface [W=J/s]
- Instantaneous value: $W(t) = \int_S \vec{I}(\vec{x},t) \cdot \vec{n} dS = \int_S I_n(\vec{x},t) dS$



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Sound (acoustic) power / intensity

- Real parts of quantities are of interest when talking about power or intensity.
- $I = \mathrm{Re}(Z)u_{rms}^2$.
- $I = \mathrm{Re}(p)\mathrm{Re}(u)$

Relation between SPL, SWL, SIL

- For plane waves with harmonic motion (See course material for detailed derivations),
  - $\bar{\mathrm{I}} = \frac{1}{T}\int_0^T p(t)v(t)\mathrm{d}t = \frac{1}{\rho c}\frac{1}{T}\int_0^T p^2(t)\mathrm{d}t = \frac{\widetilde{\mathrm{p}^2}}{\rho \mathrm{c}}$ (squared rms value of pressure).
- $L_I = 10\log_{10}\left(\frac{I}{I_{ref}}\right) = 10\log_{10}\left(\frac{\widetilde{\mathrm{p}^2}}{\rho \mathrm{c} I_{ref}}\right) = 10\log_{10}\left(\frac{\widetilde{\mathrm{p}^2}\cdot p_{ref}^2}{p_{ref}^2 \rho \mathrm{c} I_{ref}}\right) =$
  $10\log_{10}\left(\frac{\widetilde{\mathrm{p}^2}}{p_{ref}^2}\right) + 10\log_{10}\left(\frac{p_{ref}^2}{\rho \mathrm{c} I_{ref}}\right) = L_p - 0{,}008\mathrm{dB} \approx L_p.$
- Numbers in decibel may be similar but they are two very different quantities!

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Relation between SPL, SWL, SIL

- The amount of power passing through that surface is a measure for the strenght 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. ($4\pi 0.2821^2 = 1$).

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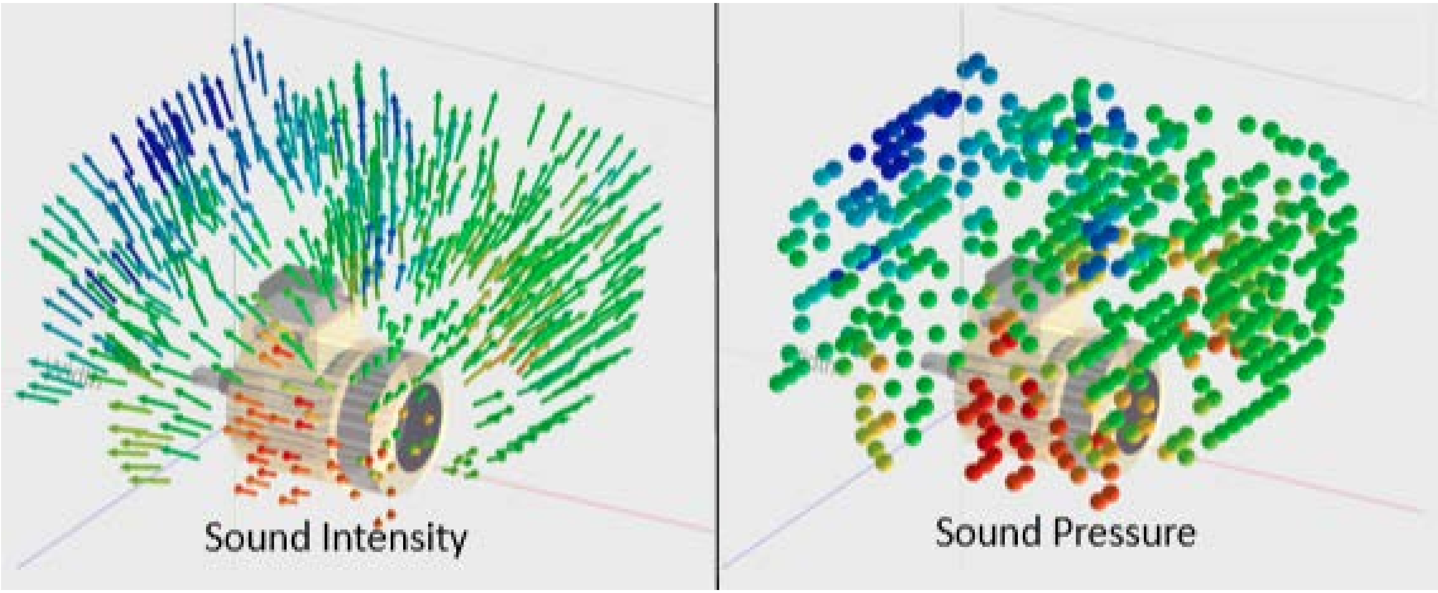
Relation between SPL, SWL, SIL

- Easy to mix-up concepts but they are different!

Relation between SPL, SWL, SIL

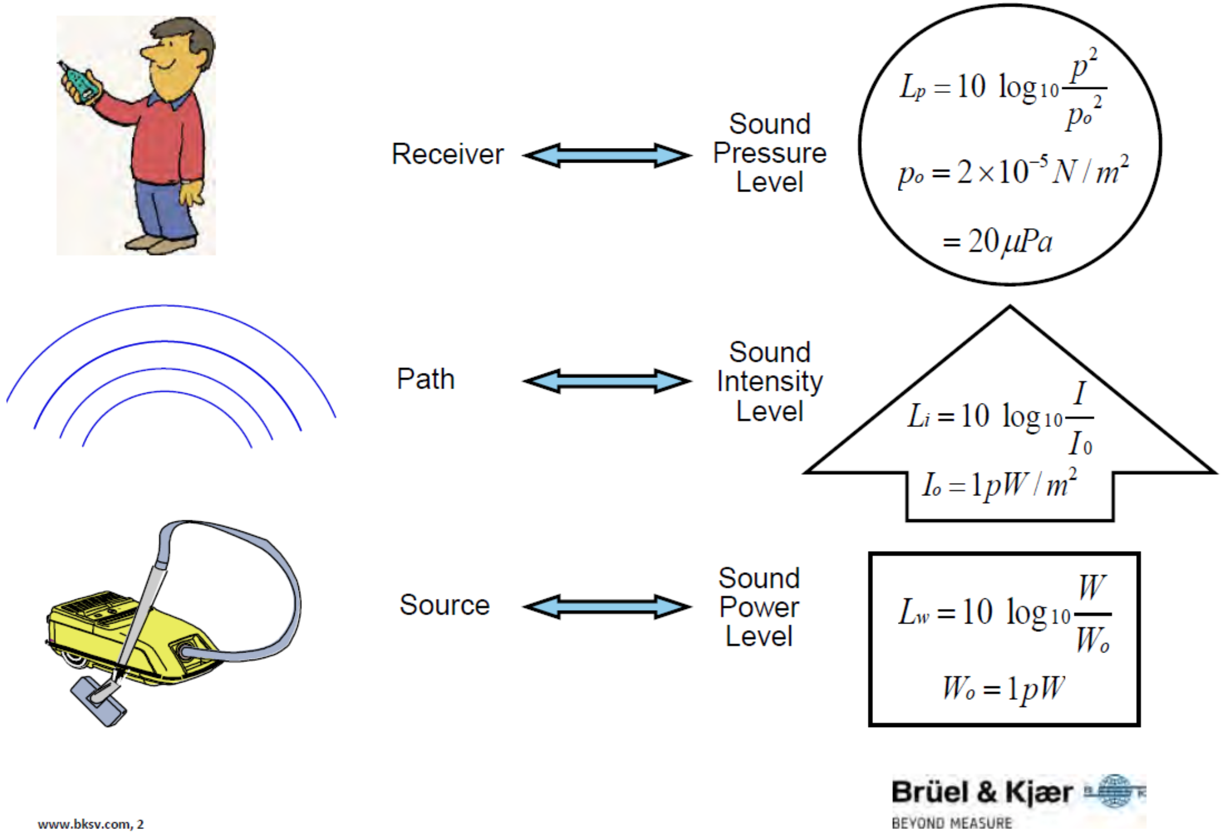
- Sound Pressure (SPL), Sound Power (SWL), and Sound Intensity (SIL) acoustic quantities that can be expressed in dB. They describe different aspects of sound, and the decibels for each represent different measurement quantities.
  - SPL, [Pa]
    - Amplitude level of sound at a specific location in space (scalar quantity)
    - Dependent on the location and distance to the source
    - Property of the sound field
  - SWL, [W]
    - Rate at which sound is emitted from an object
    - Independent of location or distance
    - Scalar quantity, property of the source
  - SIL, [W/m^2]
    - Sound power flow per unit of area
    - Vector quantity
    - Sound energy quantity

Relation between SPL, SWL, SIL

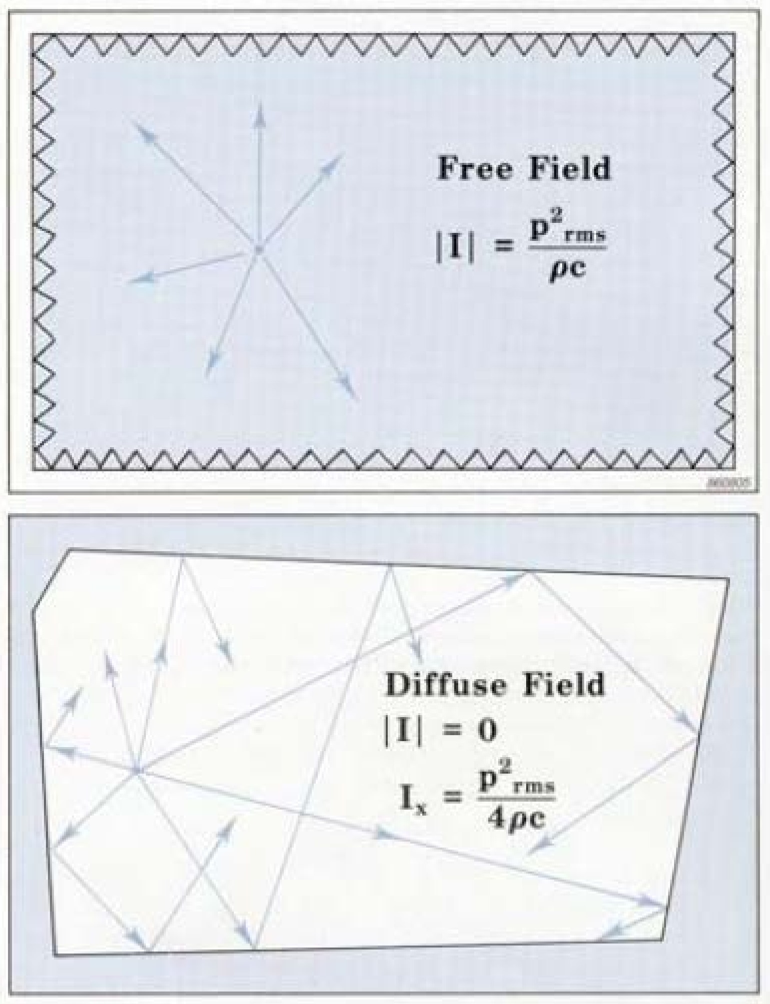


Amplitudes are the same / Directions are the difference (easier to troubleshot with SI)

Relation between SPL, SWL, SIL

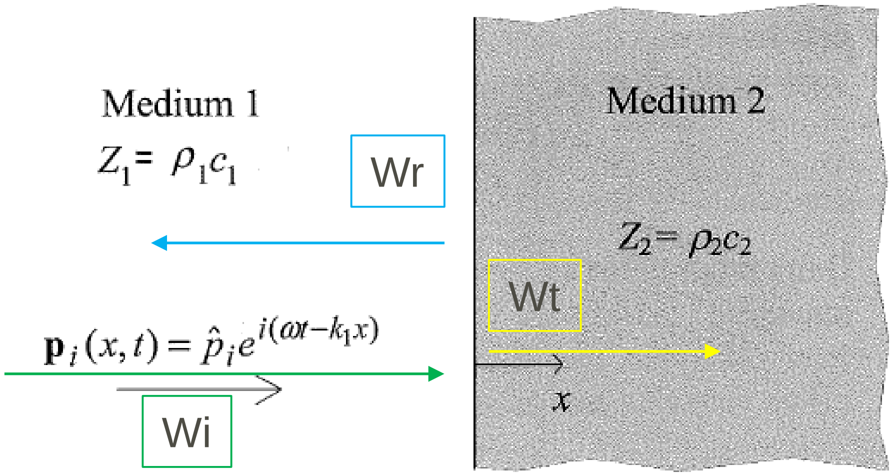


Intensity in diffuse and free fields.



Transmission and reflection – power-related quantities

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



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

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

$$I_i = I_r + I_t$$

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

$$\rho = \frac{|Z_2 - Z_1|^2}{(Z_2 + Z_1)^2}$$

$$\tau = \frac{4Z_2 Z_1}{(Z_2 + Z_1)^2}$$

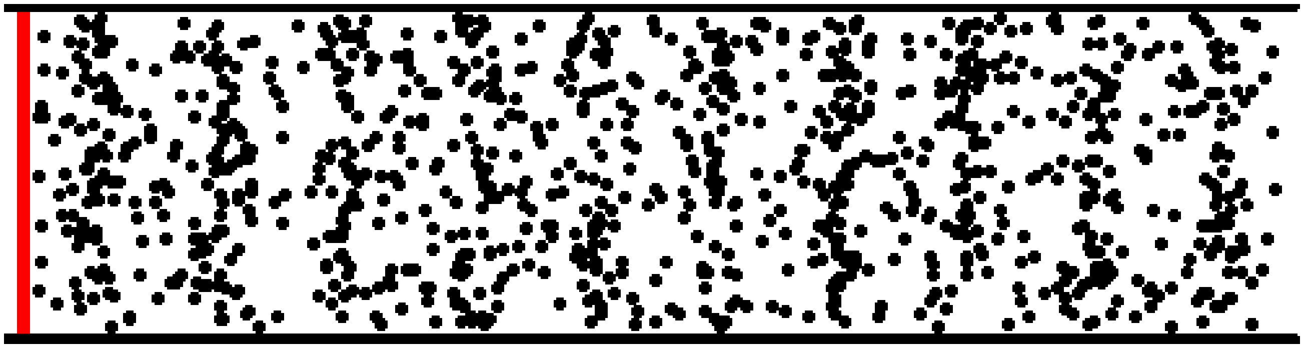
$$\tau + \rho = 1$$

- τ is also called absorption factor α (different points of view…)

Sound propagation – distance

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

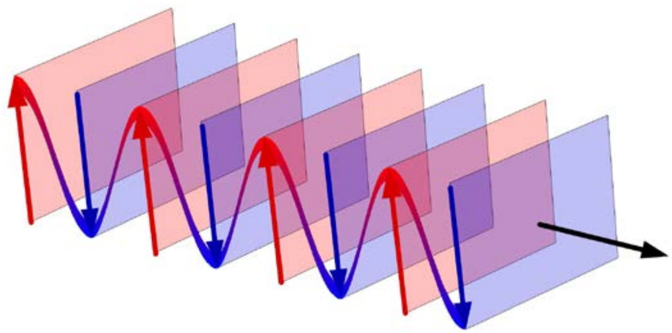
$$p(x,t) = \hat{p}e^{i(\omega t - kx + \varphi)}$$



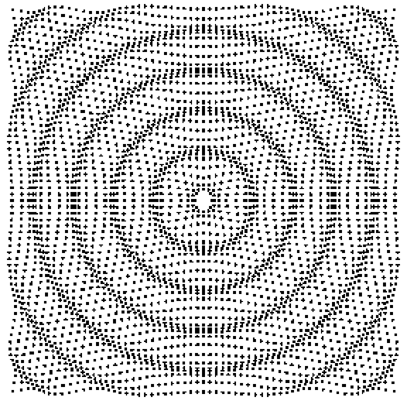
Types of propagation – plane

- 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.

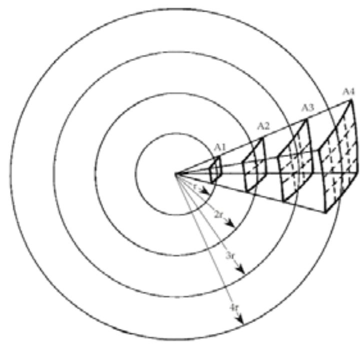
$\mathrm{I} \equiv \text{constant}$;



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 wavelenght or distance to receiver.
- <u>If the source is small</u>



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

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

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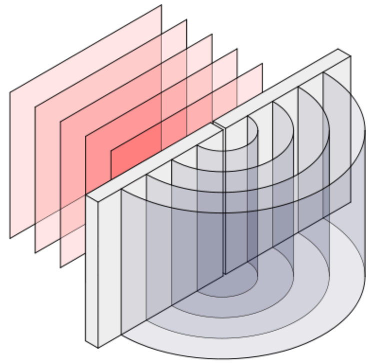
Cylindrical propagation



- 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

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

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

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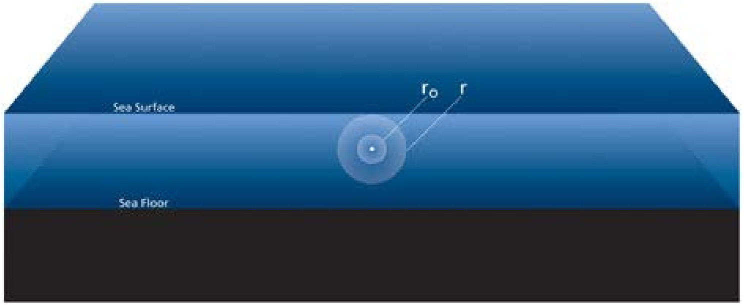
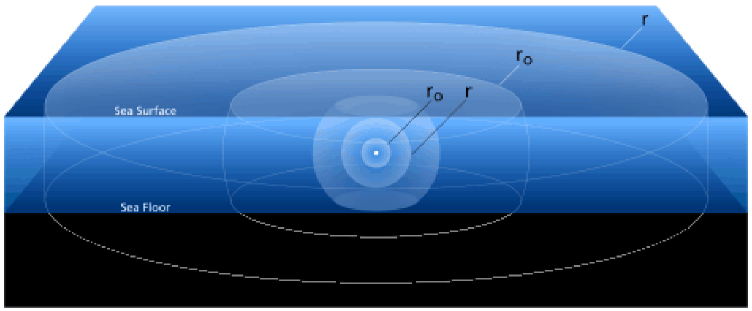
Spherical VS Cylindrical propagation



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 r0 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 r0 to a larger cylinder with radius r compared with the rate of decrease for spherical spreading.

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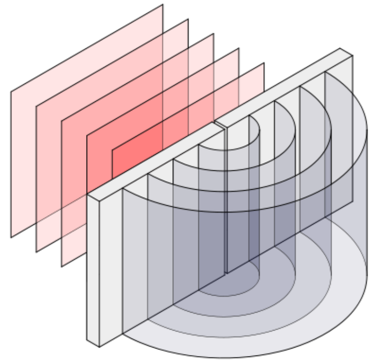
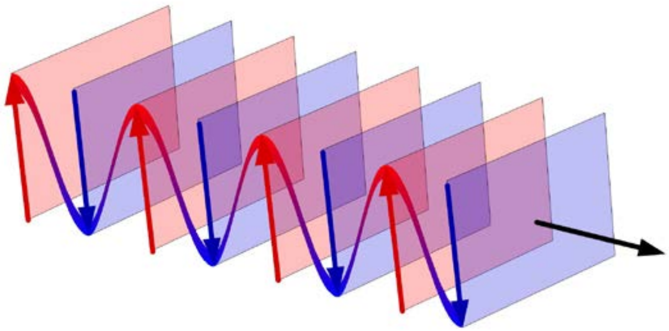
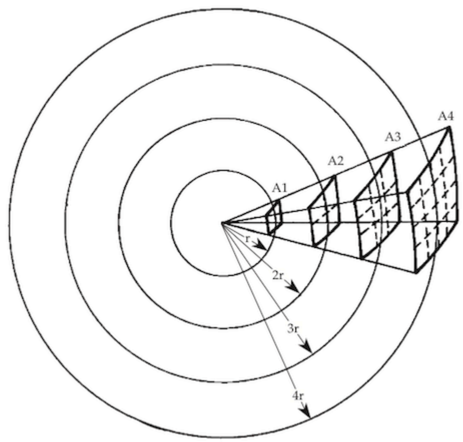
Types of propagation

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

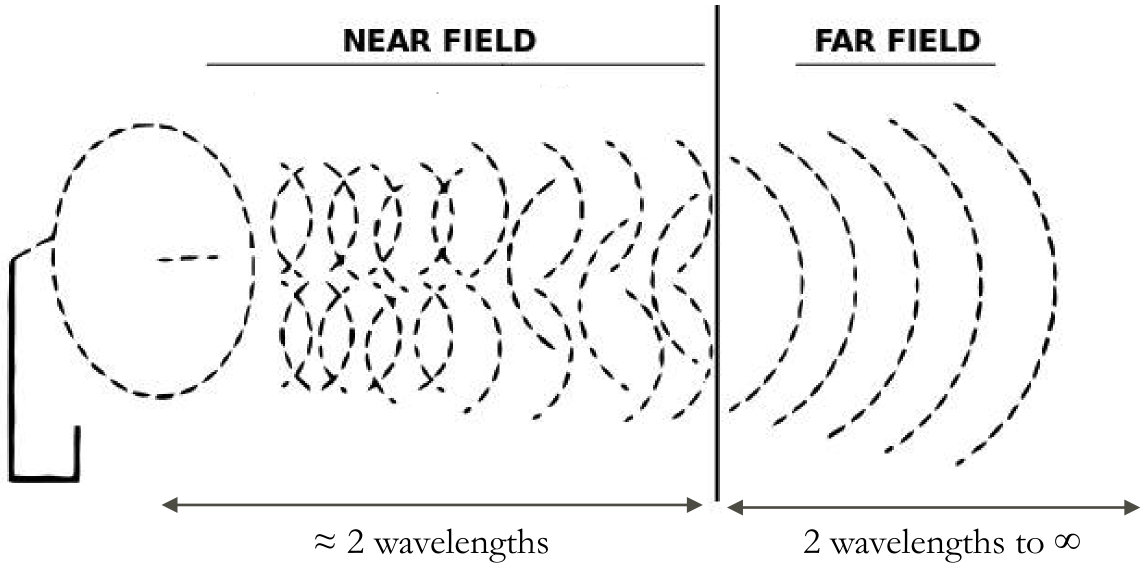
$$\Delta L = L(r_2) - L(r_1) = 0$$

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.



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Do not mix up concepts…

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

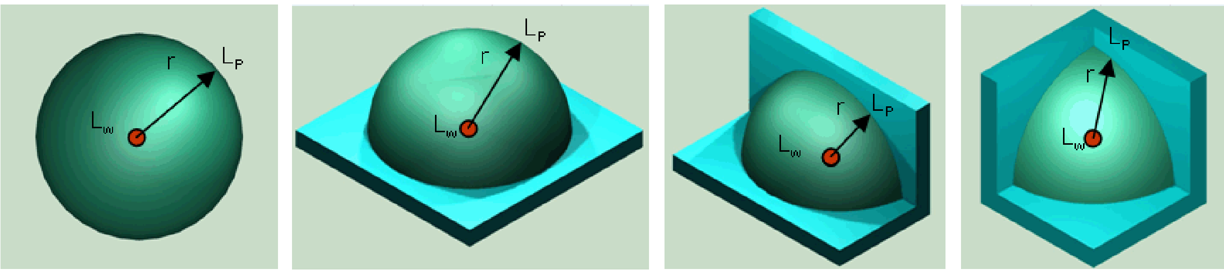
Correct version	Wrong expression
Sound pressure (amplitude) falls inversely proportional to the distance **1/*r*** from the sound source. **That is the 1/r law or the inverse distance law.**	**Sound pressure** (amplitude) falls inversely proportional to the square of the distance $1/r^2$ from the sound source. Really wrong
Sound pressure level decreases by **(−)6 dB** 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 **(−)3 dB**. wrong
Sound intensity (energy) falls inversely proportional to the square of the distance $1/r^2$ from the sound source. **That is the inverse square law $1/r^2$.**	**Sound intensity** (energy) falls inversely proportional to the distance **1/*r*** from the sound source. wrong
Sound intensity level decreases by **(−)6 dB** 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 **(−)3 dB**. wrong

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

Emission and directivity factor

- Sound emission
  - Sound power continuously emitted from a sound source

- Sound power level (SWL / L_W / L_Π) 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



Source: www.sengpielaudio.com

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

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

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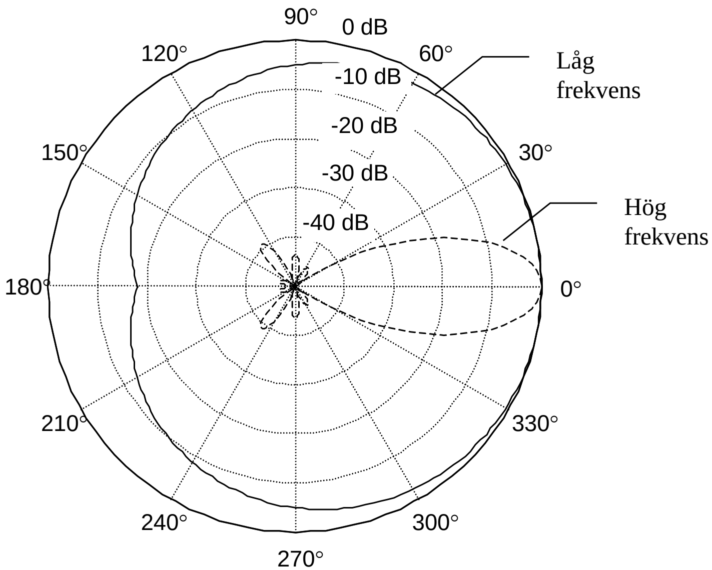
Emission and directivity factory

- Sound emission
  - Sound power continuously emitted from a sound source

- Sound power level (SWL / L_W / L_Π) 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



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

Outdoor sound propagation (cylindrical)

Geometrical divergence (distance –r- reduction)

$$L_p = L_w + 10\log Q - 20\log(r) - 10\log\left(\frac{4\pi p_0^2}{\rho_0 c W_0}\right) \approx L_w + DI - 20\log(r) - 11$$

Directivity index (DI)

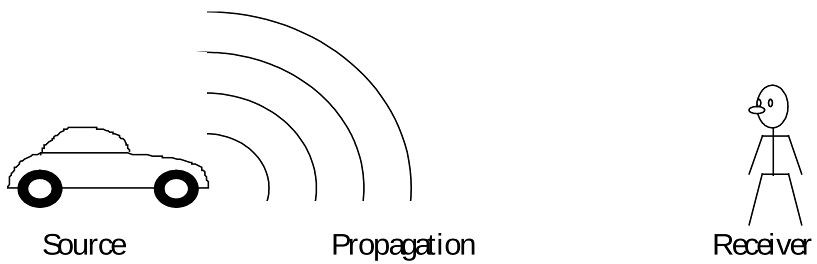
Under typical weather conditions

In real atmosphere, conditions deviate from spherical due to e.g. absorption of sound in air, metheorological conditions, interaction with ground and obstacles...

$$L_p \approx L_w + DI - 20\log(r) - 11 - A_{abs} - A_E \longrightarrow A_E = A_{weather} + A_{ground} + A_{turbulence} + A_{vegetation} + A_{barrier} + A_{misc}$$

Atmospheric or air absorption [dB]
$A_{abs} = \gamma[\text{dB/km}] \cdot r$

Wind, temperature



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[1]	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[2]	55
Områden för fritidsbebyggelse och rörligt friluftsliv där naturupplevelsen är en viktig faktor. [3]	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.

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[1]	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[2]	55
Områden för fritidsbebyggelse och rörligt friluftsliv där naturupplevelsen är en viktig faktor. [3]	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.

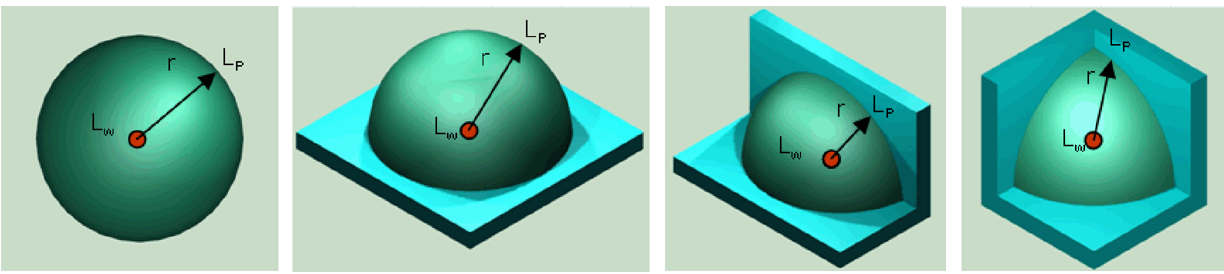
2) Värdet för natt behöver ej tillämpas för utbildningslokaler.

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.

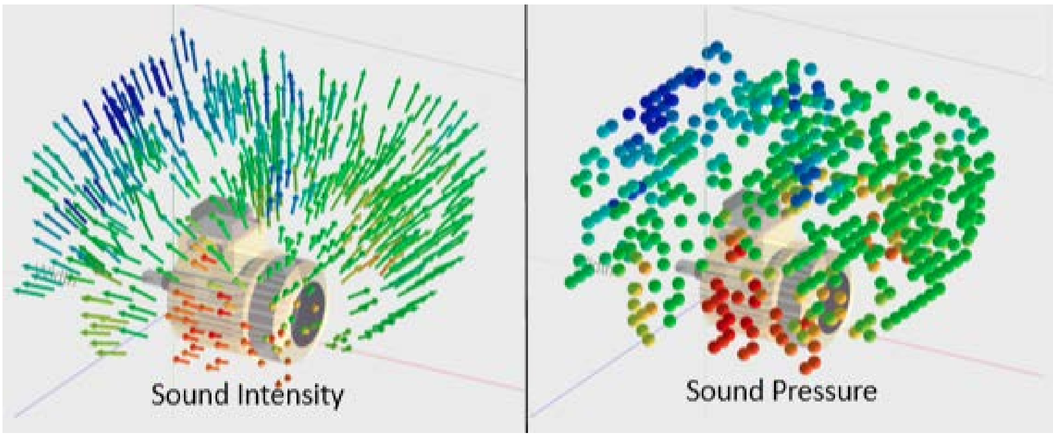
$$L_W = L_p + \left|10\log\left(\frac{Q}{4\pi r^2}\right)\right|$$



Source: www.sengpielaudio.com

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.



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Sound intensity probe

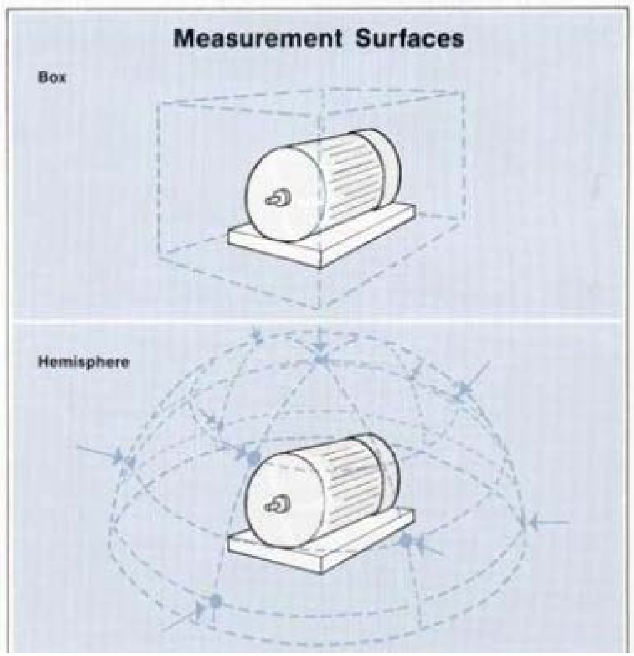
- It is an instrument composed of two (phase matched) microphones
  - Intensity: $\vec{I} = \langle pv \rangle = \frac{1}{T}\int_0^T p(t)\vec{v}(t)dt$
  - Pressure: average between the two microphones
  - Velocity (from F4): $\frac{\partial p}{\partial x} = -\rho \frac{\partial v}{\partial t}$
  - Spatial 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.

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Regulations – wind turbine noise

- By the façade

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

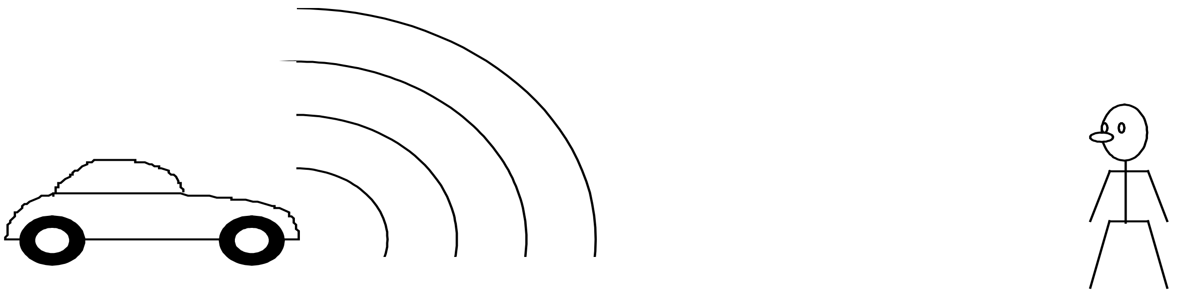
NOTE: regulations regarding traffic noise in the next lecture

- 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

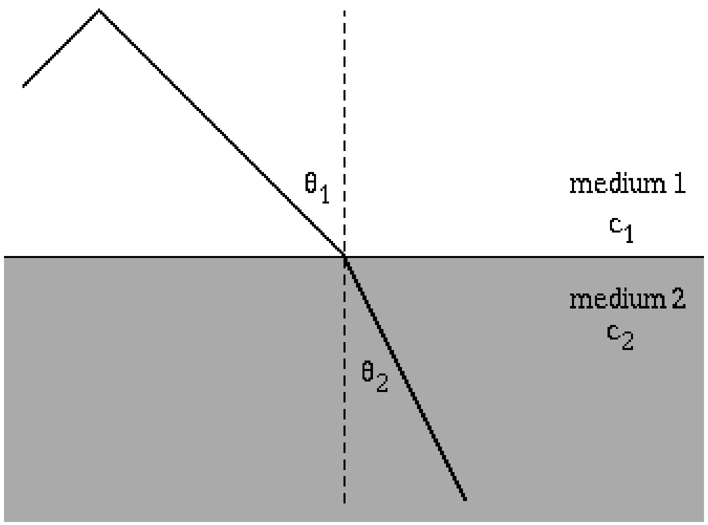
1. Weather and wind
2. Obstruction (hindering) objects
3. Reflection



Refraction of sound waves

- Snell's law
  - Speed of propagation varies
  - Frequency remains constant

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



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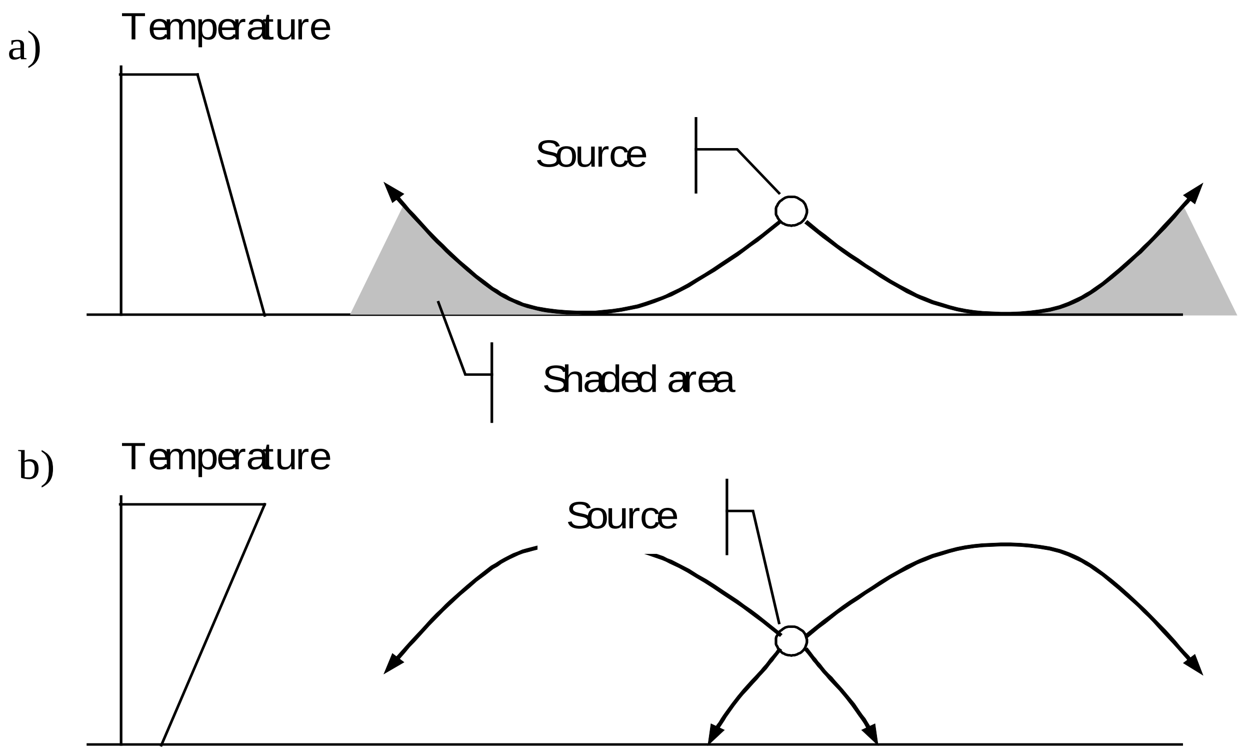
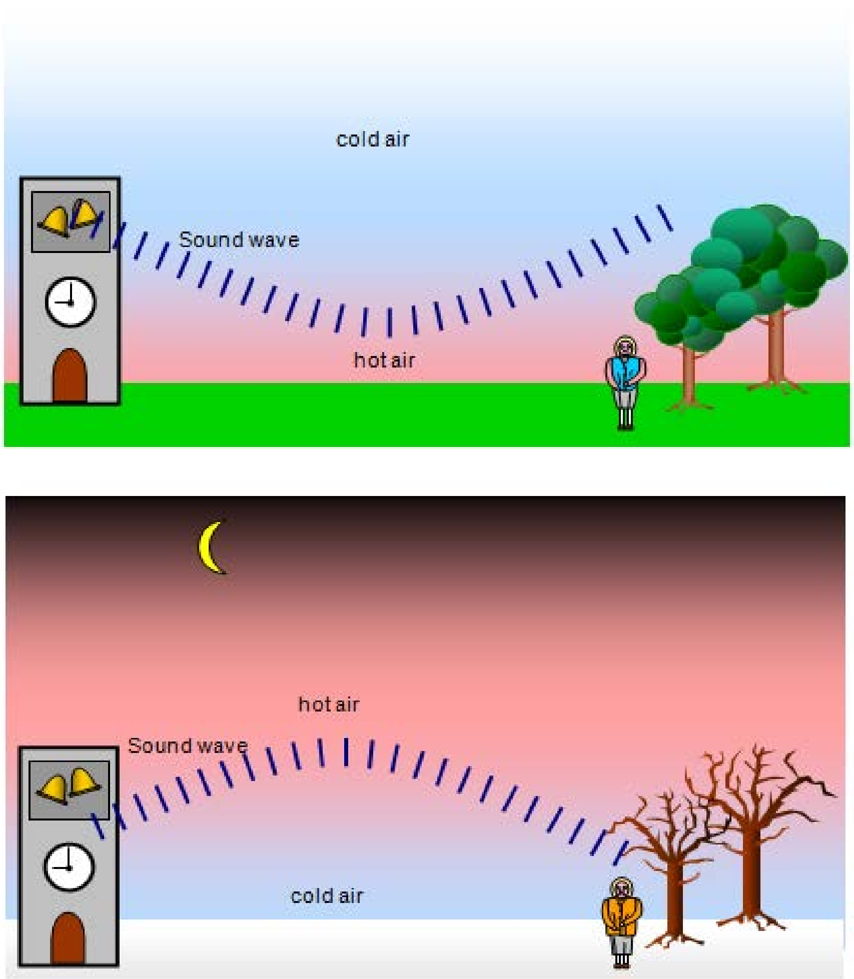
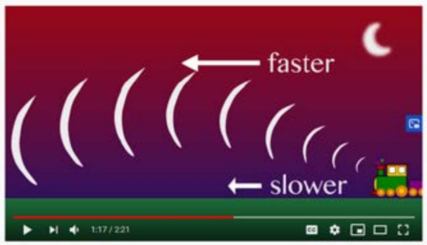
Outdoor sound propagation – Temperature (I)

- Sound propagation speed: $c_{air} = \sqrt{\dfrac{\gamma P_0}{\rho_{air}(T=0^\circ)}}\left(1+\dfrac{T_{air}[^\circ C]}{2\cdot 273}\right) = 331.4\cdot\left(1+\dfrac{T_{air}[^\circ C]}{2\cdot 273}\right)$
  - 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

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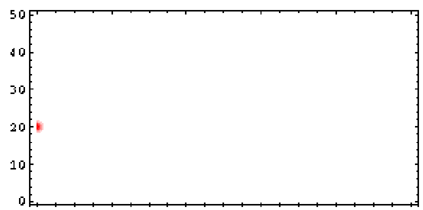
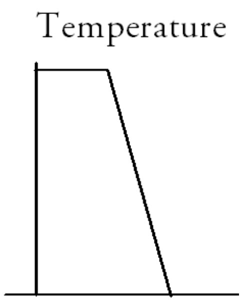
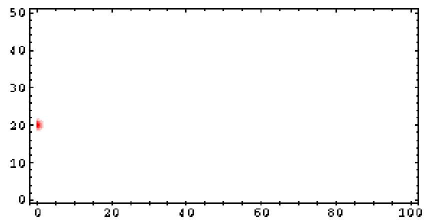
Outdoor sound propagation – Temperature (III)



Wave pulse propagates in a medium where the wave speed is constant in all directions

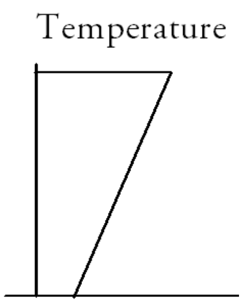
a)

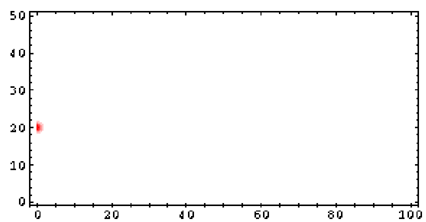




Propagation of a spherical wave: wave speed in the x-direction is constant, whereas in the vertical y-direction decreases with height ($c = 1 - 0.05y$)

b)

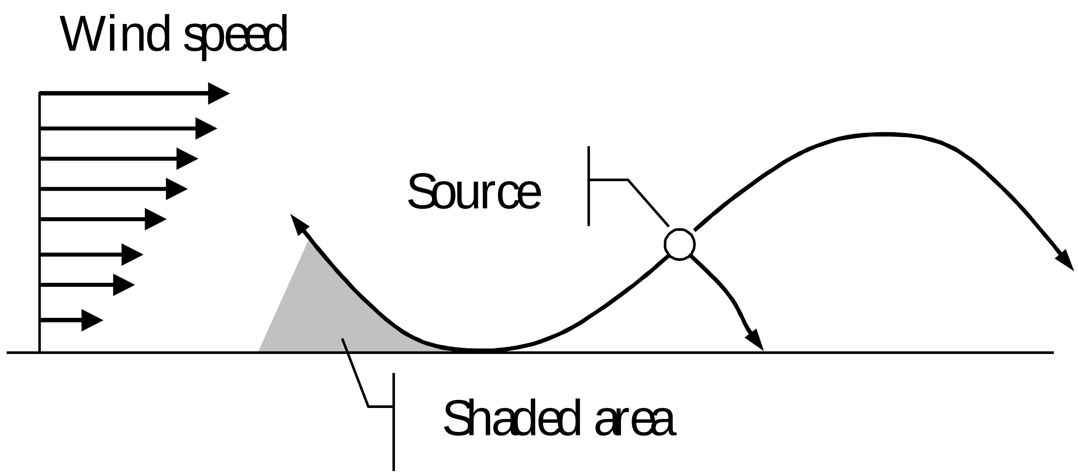




Propagation of a spherical wave: wave speed in the x-direction is constant, whereas in the vertical y-direction increases with height ($c = 1 + 0.05y$)

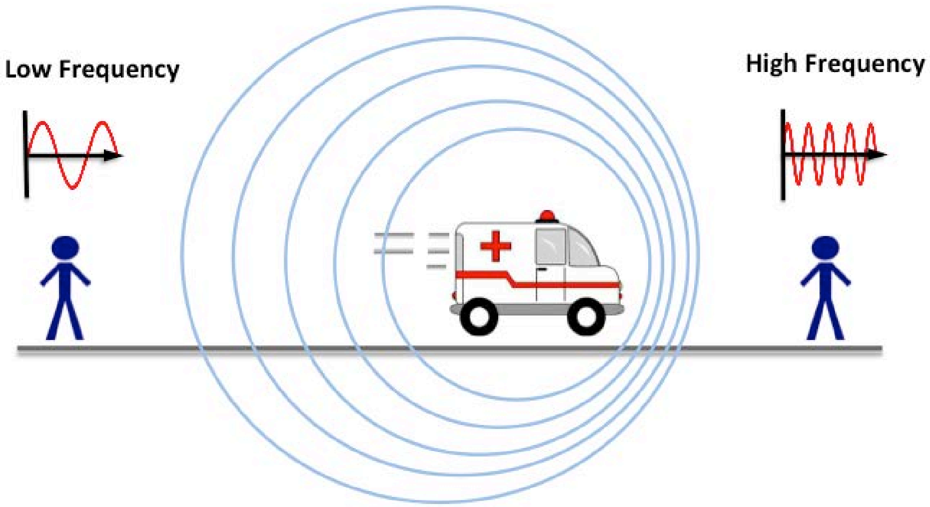
Outdoor sound propagation – Wind

- 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



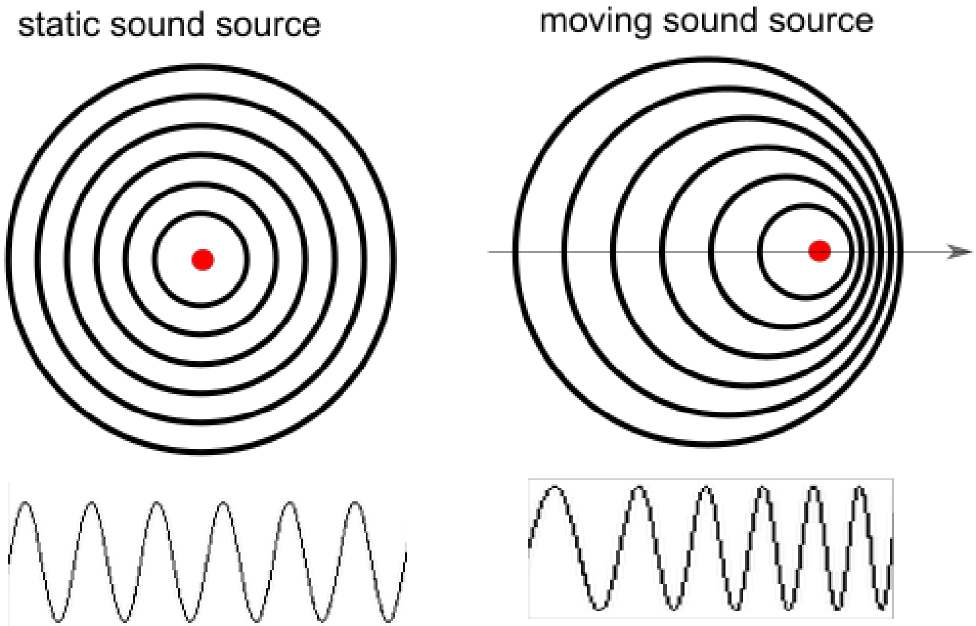
Doppler effect

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



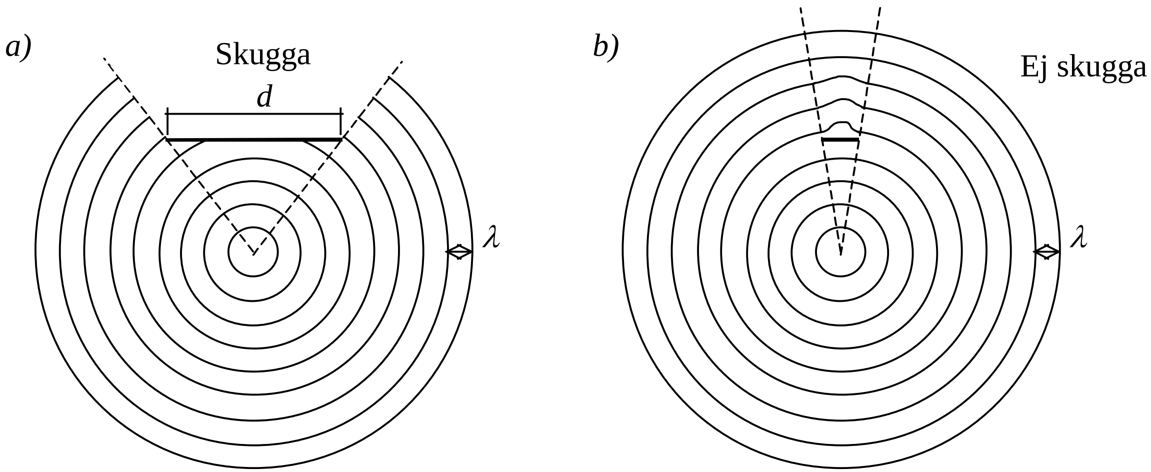
Doppler effect

- Example: video



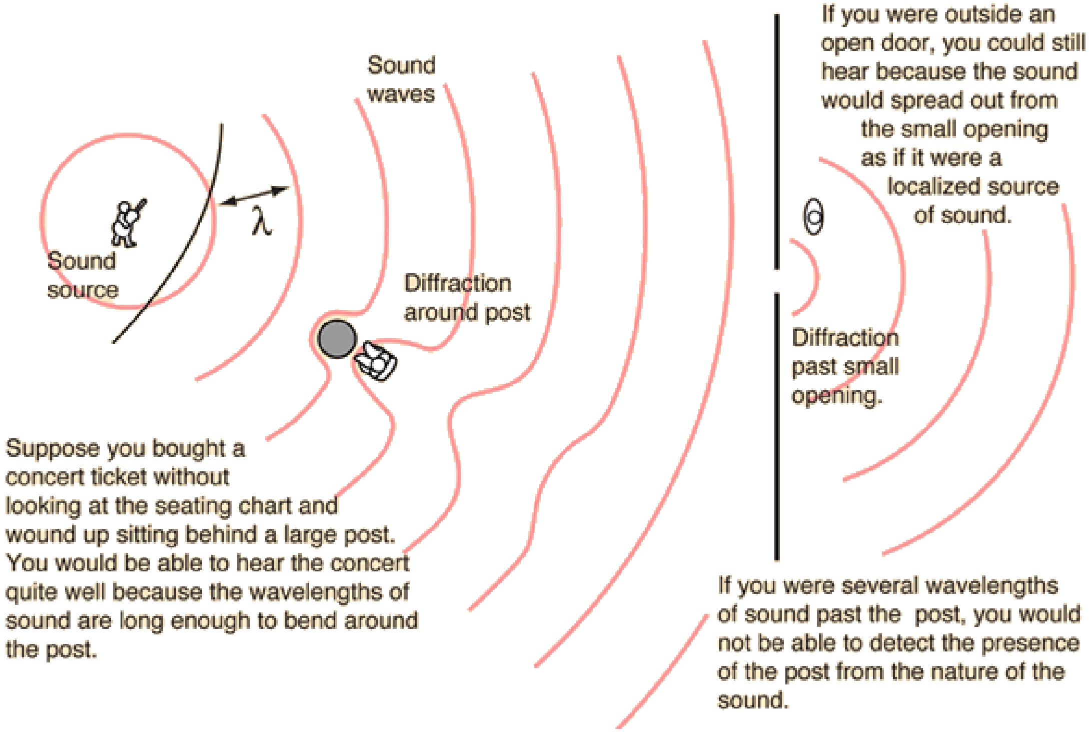
Diffraction – Sound ”bending”

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



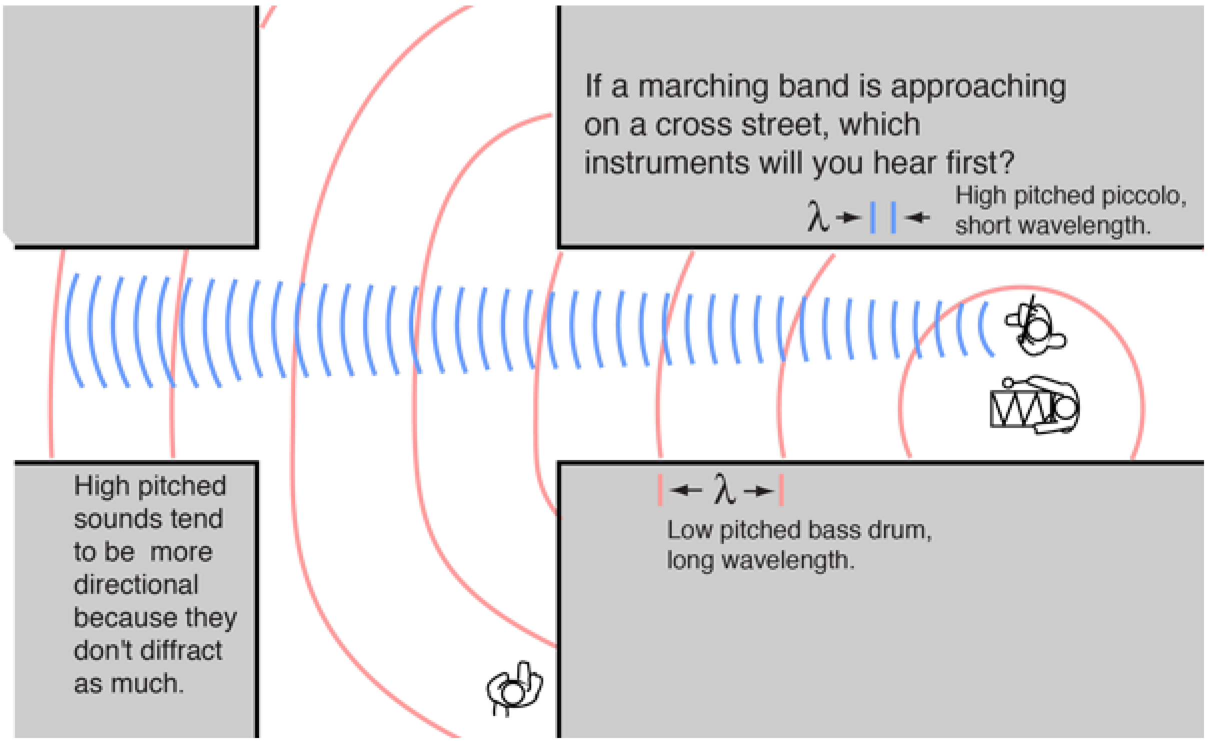
Diffraction – Sound ”bending”

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



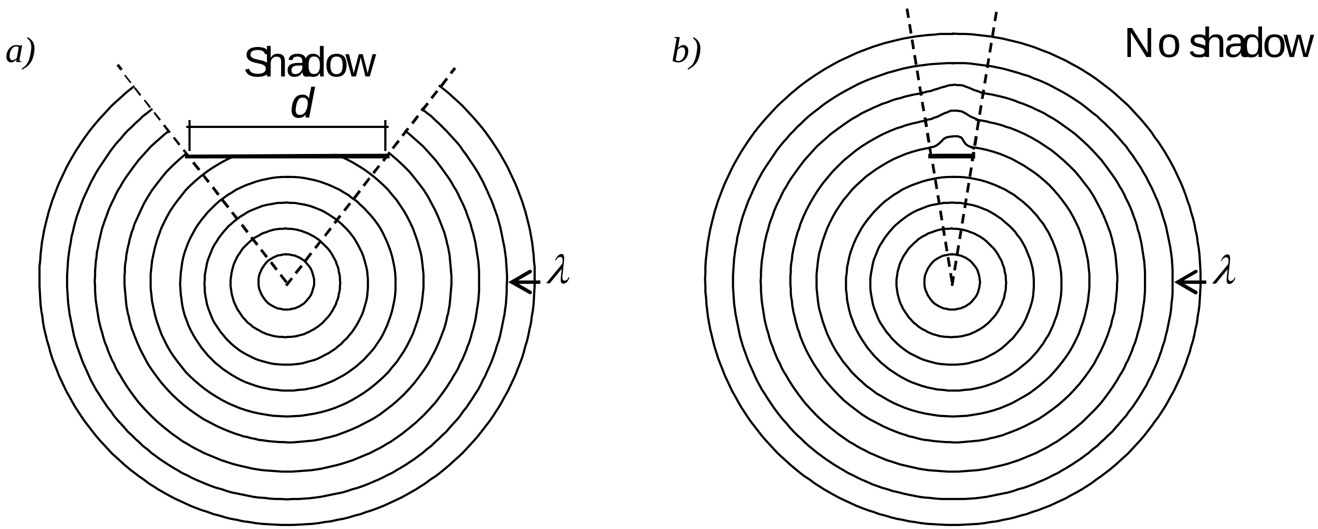
Diffraction – Sound ”bending”

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



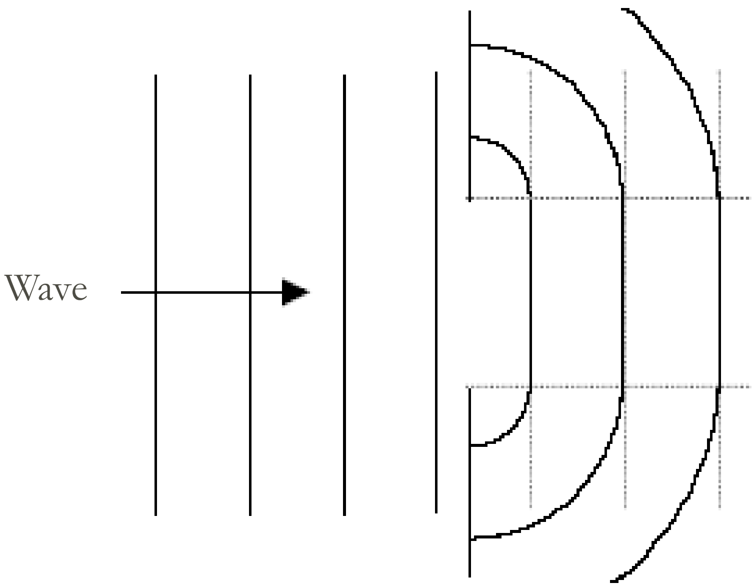
Diffraction – Sound ”bending”

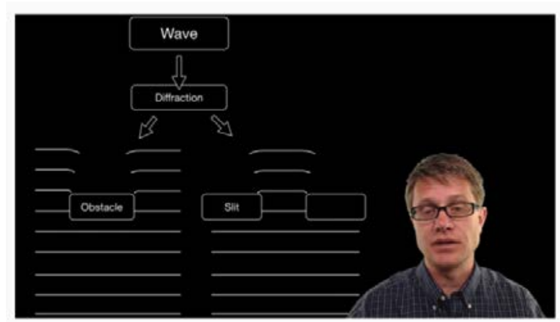
- Om $d > \lambda$ → the obstacle ”exists”
- Om $d < \lambda$ → the sound bends around the obstacle



Diffraction – Slit

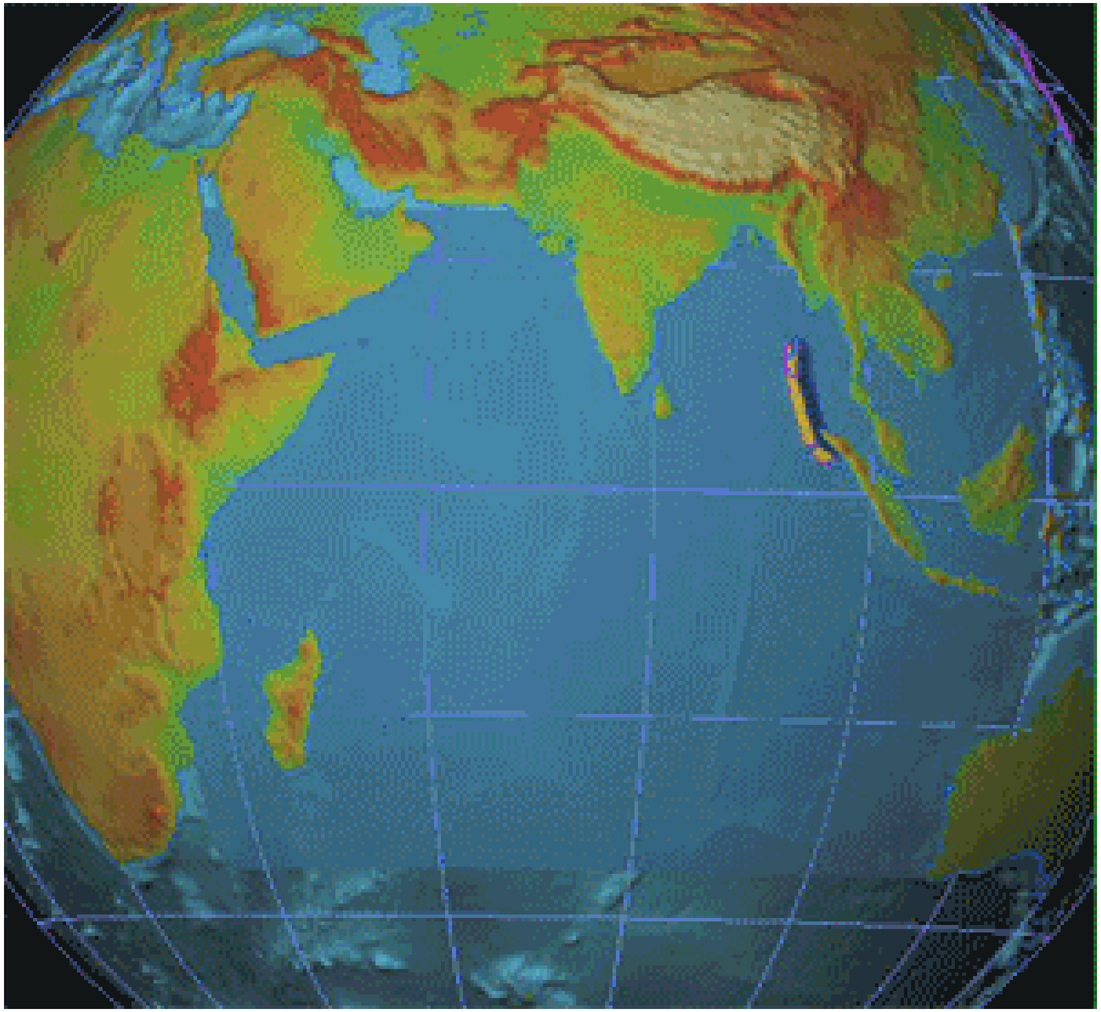
- Opening << λ: spherical wave after the obstacle (slit)
- Opening >> λ: plane wave after the obstacle (slit)





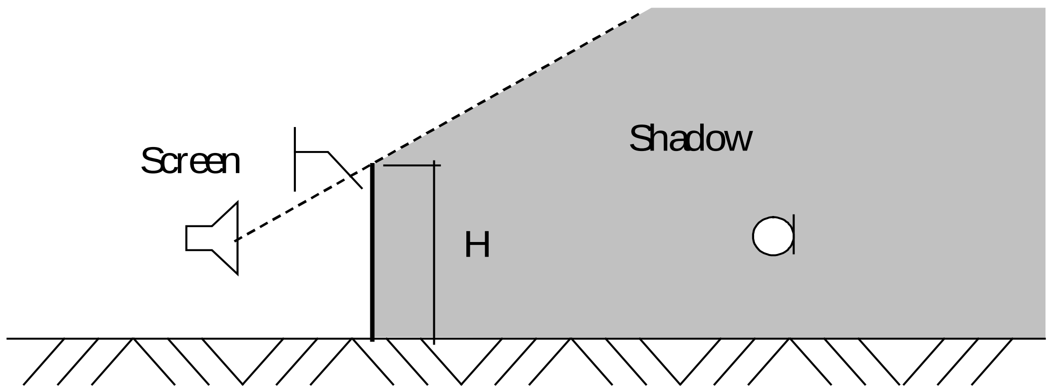
https://youtu.be/1bHipDSHVG4

Example – Tsunami

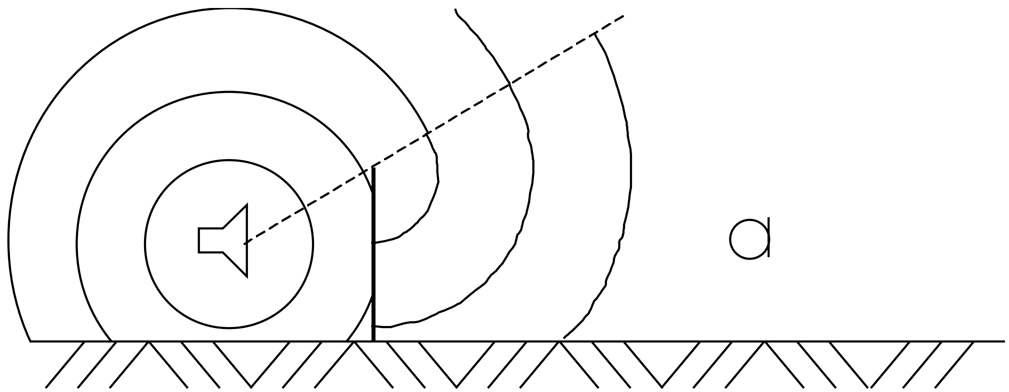


Noise barriers

- $\lambda << H$



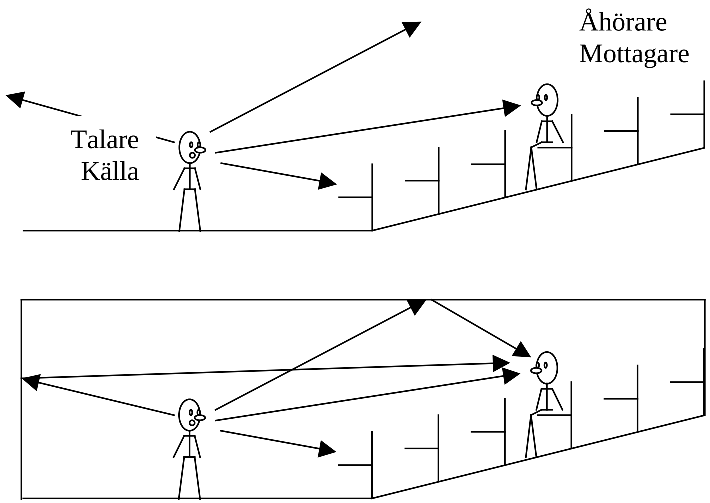
- $\lambda >> H$



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

Thank you for your attention!

mathias.barbagallo@construction.lth.se

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