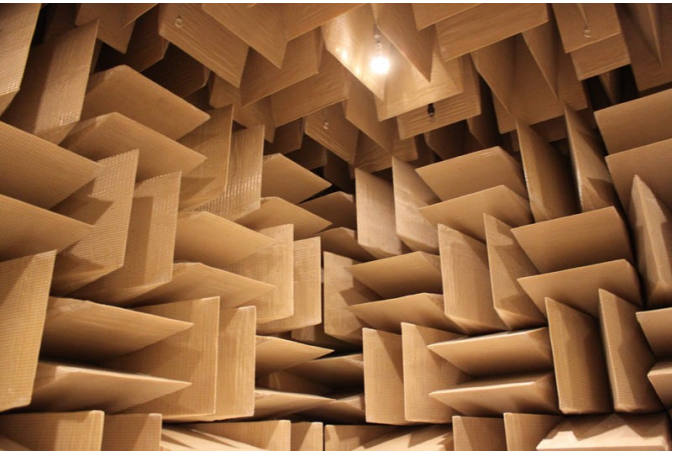
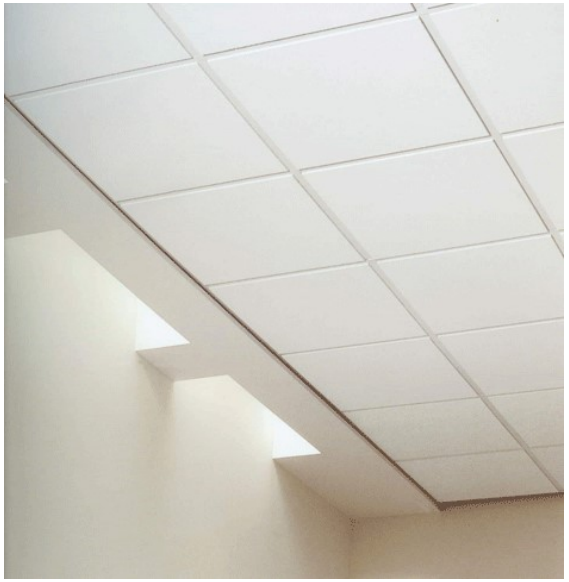


4 – Acoustic Comfort

Prof. Liam O'Brien

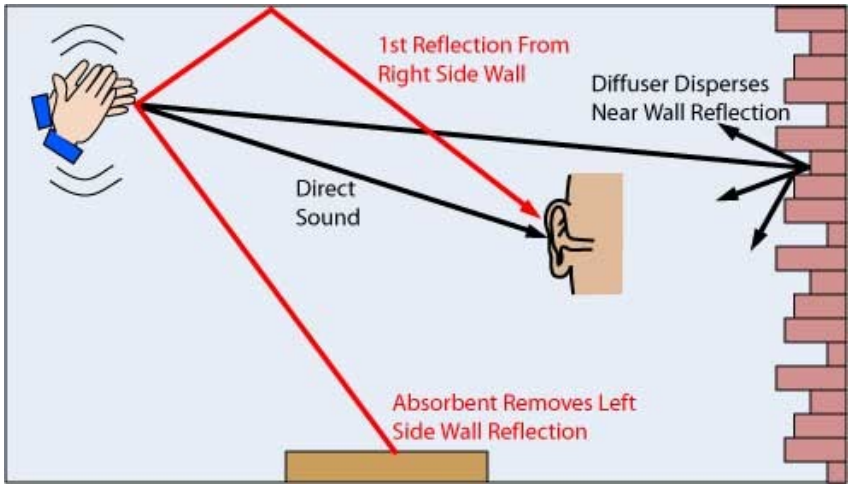


Topics today

- What is acoustic comfort? Why does it matter? How does it relate to other IEQ properties?
- What are the design considerations for acoustic comfort?
- How do we quantify noise and acoustic comfort?
- Acoustics and hearing damage

Acoustic Comfort

- Source -> Path -> Receiver
- Mitigation can occur anywhere in this system, but it's usually cheapest/easiest to target the source.
- Note parallel with IAQ/air pollutants:
  - Easiest to eliminate source in the first place
  - Substance/signal that is given off expands in area/volume, so mitigation beyond the source means a larger area to "treat"
  - Mitigation at the receiver would be inconvenient (e.g., involve protective equipment)

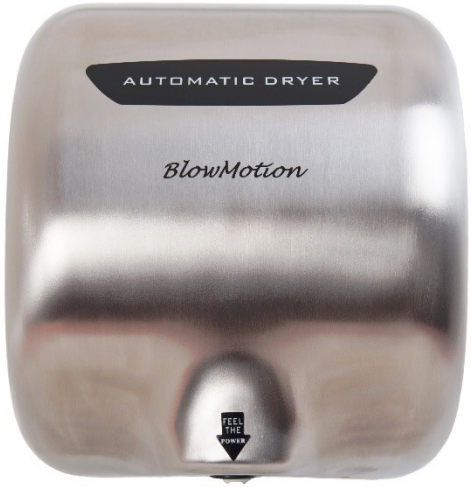


Sound Sources in Buildings

- HVAC (fans, ticking of hydronic systems, air movement)
- Lights
- Computer fans and office equipment
- Machinery
- People talking, typing
- Kitchen equipment

True or false

- The hand dryers in the Canal Building cause a sound pressure level (SPL) of 85 dB at 3 meters away, so if two of them are on simultaneously, the combined SPL is 170 dB.



Sound Sources outside Buildings

- Traffic
- Other street noises
- Wildlife
- Airplanes
- Construction

Noise, productivity, and health

- "Aircraft noise exposure at home was highly correlated with aircraft noise exposure at school and demonstrated a similar linear association with impaired reading comprehension."

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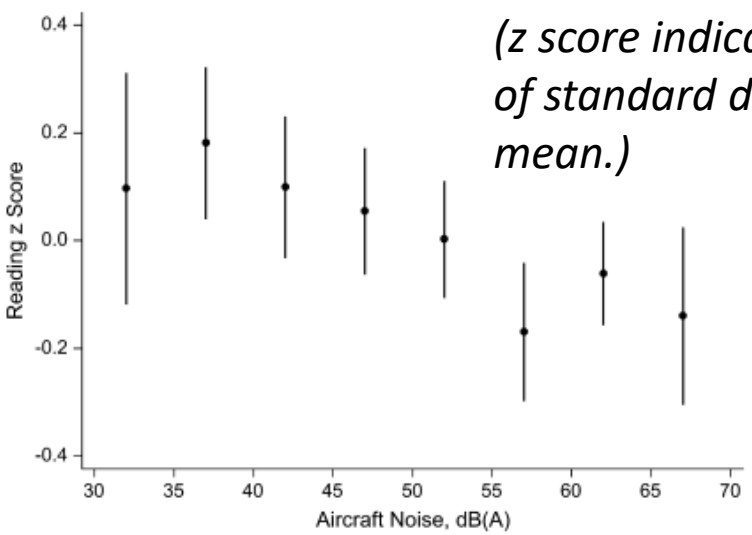
Original Contribution

Exposure-Effect Relations between Aircraft and Road Traffic Noise Exposure at School and Reading Comprehension

The RANCH Project

(z score indicates number of standard deviations from mean.)

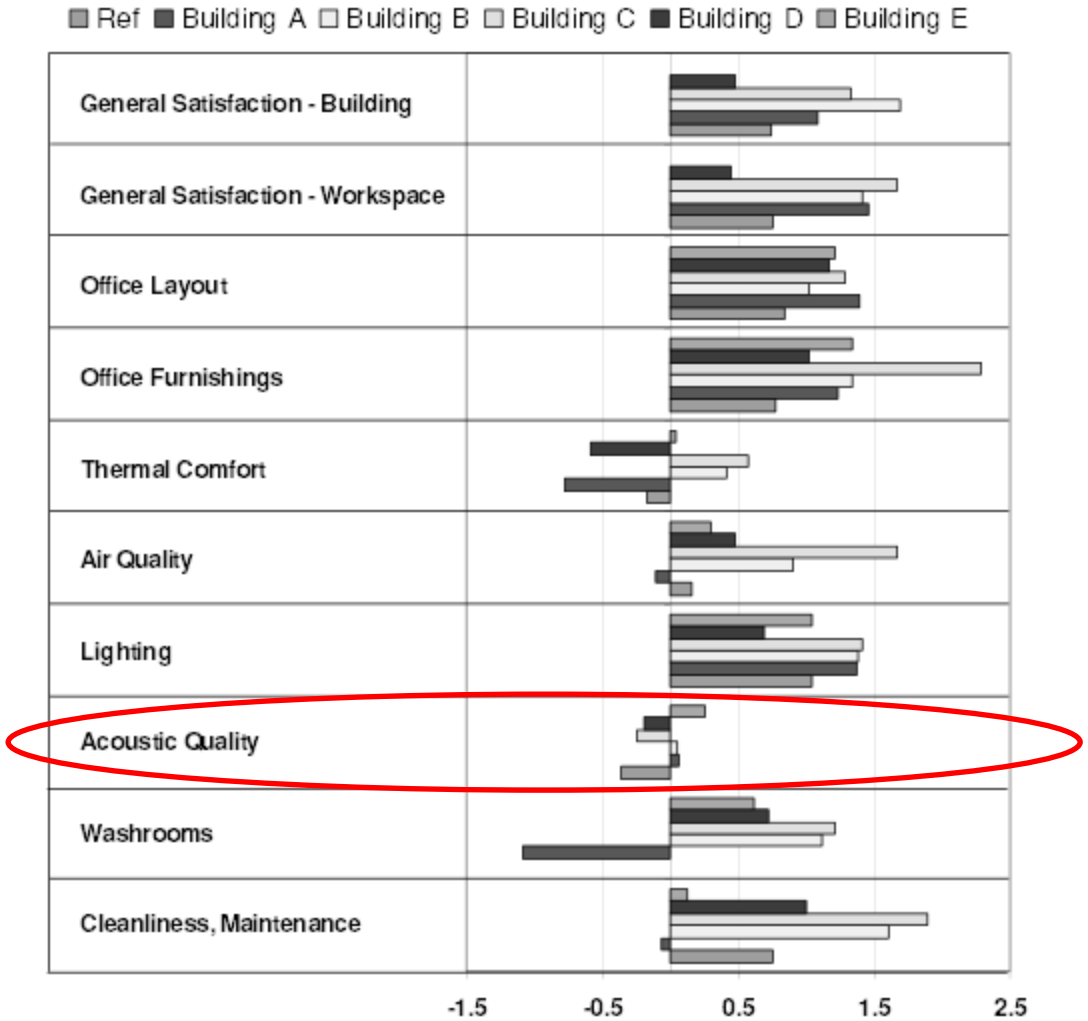


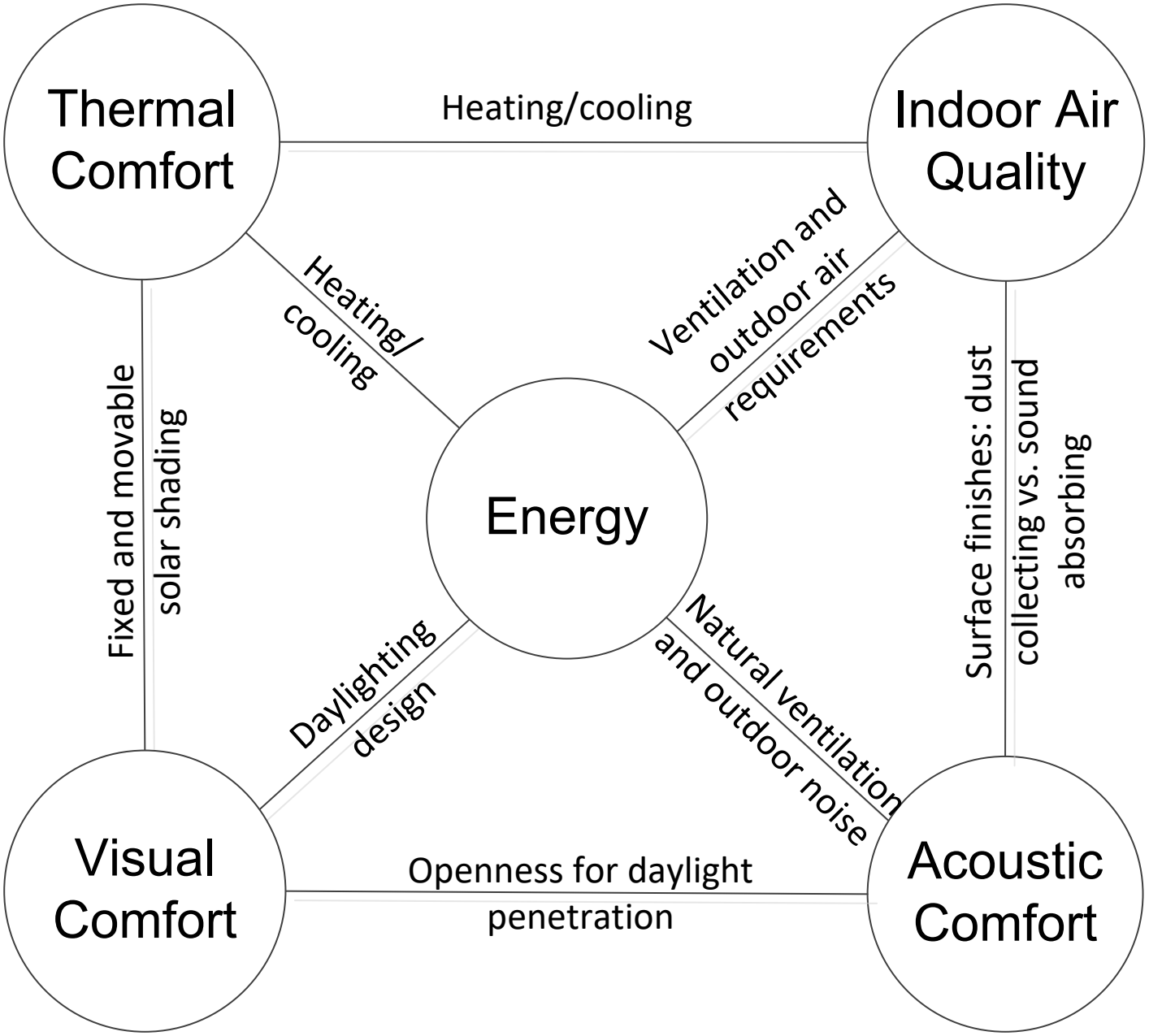
A 20 dB increase in aircraft noise can reduce students' reading level by up to 8 months.

Acoustics Metrics

- Sound power level (dB)
- Speech intelligibility index

- Acoustic quality is frequently rated poorly in “green” buildings




Thermal Comfort
Heating/cooling
Indoor Air Quality
Heating/ cooling
Ventilation and outdoor air requirements
Fixed and movable solar shading
Energy
Surface finishes: dust collecting vs. sound absorbing
Daylighting design
Natural ventilation and outdoor noise
Visual Comfort
Openness for daylight penetration
Acoustic Comfort

Privacy

https://www.cbc.ca/player/play/2431978084
@22:30

Two main acoustics considerations: inter-zone and intra-zone

- Interzone: noise from other zones (e.g., neighbour above walking around; loud music from neighbour)
- Intrazone: noise and sound quality from within a space (e.g., officemate is noisy, equipment, clarity of speaker/professor)

A-B-Cs of Building Acoustics

Given that a source exists and that personal ear protection is not an option, there are three options for mitigation:

1. **A**bsorb (use absorptive materials)
2. **B**lock (isolate sound)
3. **C**over/mask (e.g., white noise)

Sound and Noise according to ASHRAE

- Noise is unwanted sound. It is not just based on intensity, but also:
  - Unexpectedness
  - Uncontrollability
  - Timeliness (e.g., wakes you up at night)
  - Distracting information
  - Unpleasant (think dripping water in torture!)
  - Reminds you of unpleasant experiences (mosquito buzzing)
  - Any combination of these

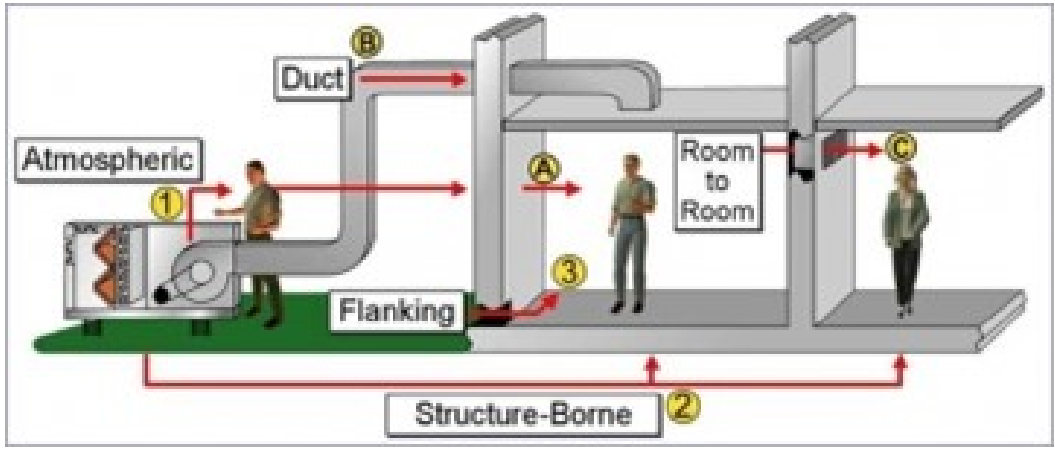
Acoustic quality in green buildings

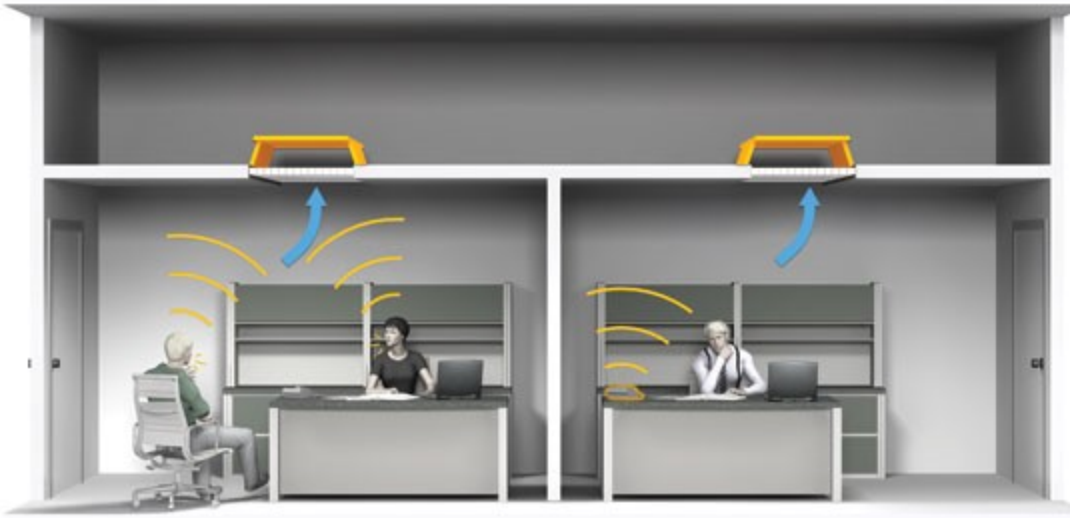
Acoustics and natural ventilation

Newsham, Birt, Arsenault, Thompson, Veitch, Mancini, Galasiu, Gover, Macdonald, Burns (2012)

HVAC and acoustics

- HVAC affects acoustics in two ways:
  1. It provides a pathway between spaces
  2. Fans and other equipment can be noisy (in some cases white noise from ventilation is welcome)





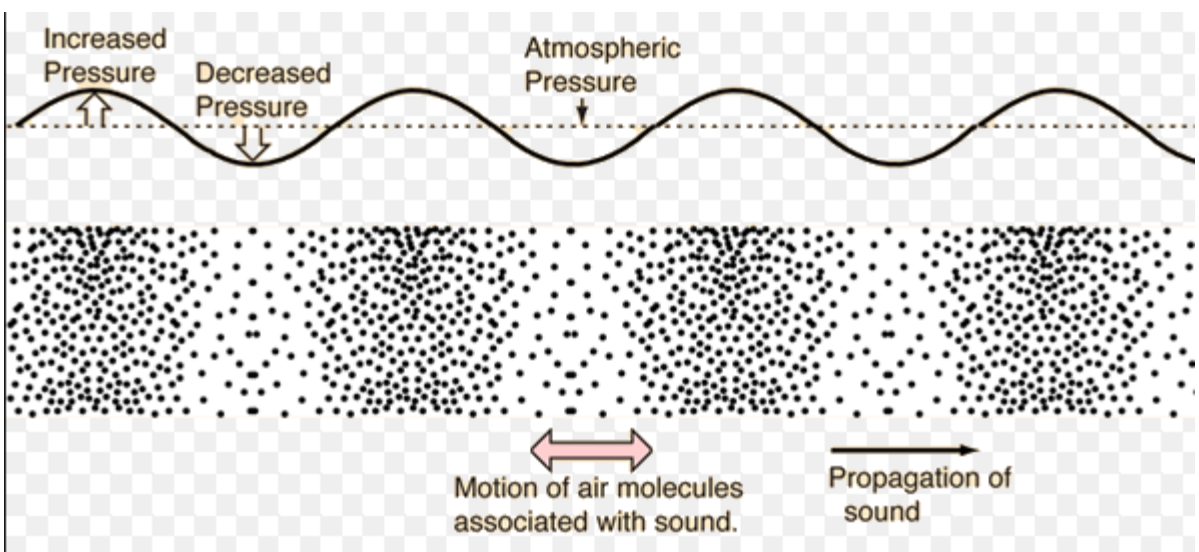
Sound Sources

- Sound occurs when a vibration is exerted on some solid or fluid medium.
- It travels by pressure waves; thus it can't occur in a vacuum.
- Sound that travels in air is called "airborne sound" or "sound".
- Sound that is transmitted in solid structures (e.g., ducts) is called structure-borne sound.
- The speed of sound in air at 20°C is 344 m/s

Wave nature of sound

- Sound travels as a pressure wave through a medium (air, other fluids, solids).
- Through air, sound travels at about 340 m/s (it's slightly dependent on air temperature)

$$v_{sound\ in\ air} \approx 331.4 + 0.6T_C \ \ m/s$$

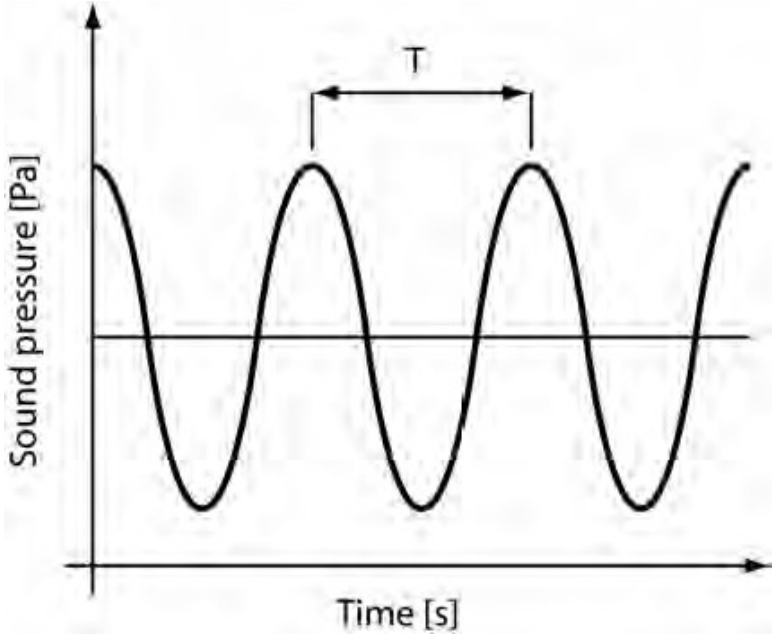


Wave nature of sound

- Like for light (or any waves):

  Wavelength (λ) × frequency (f) = speed (c)

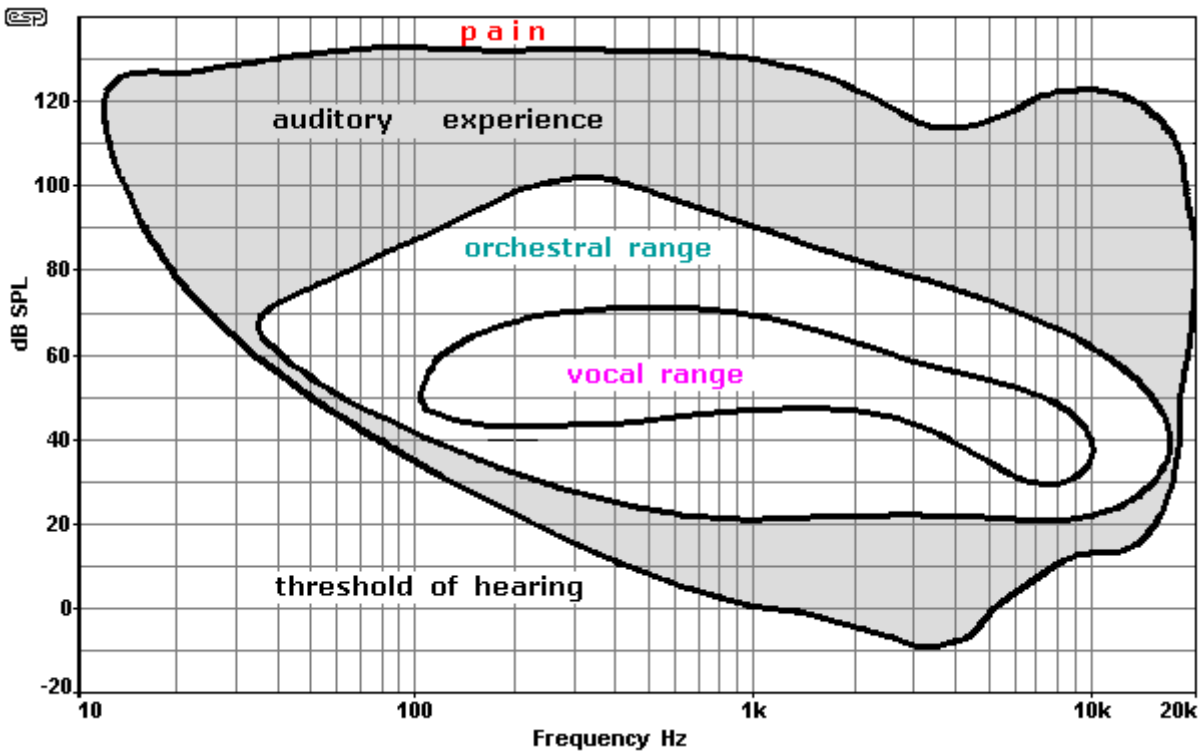
- Wavelength is measured from peak to peak, valley to valley, etc.

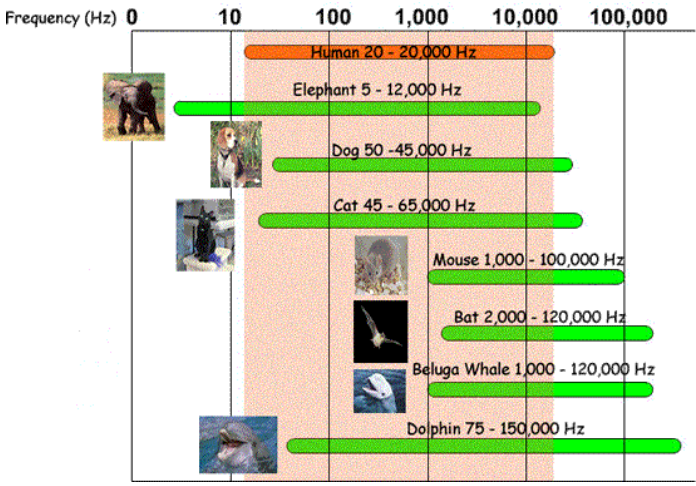


Frequency sweep

https://www.youtube.com/watch?v=hvkipAlRKq0

How low and high can you hear?





Frequency sweep

How low and high can you hear?

Octaves

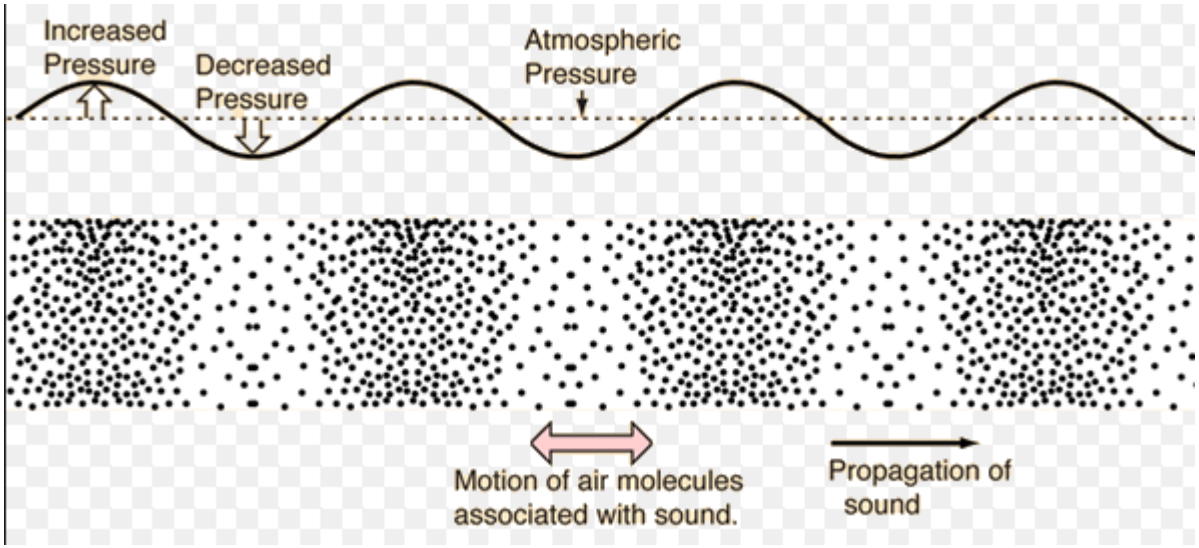
- Sound loudness and material properties (e.g., absorption) are normally given for each part of the audible spectrum.
- Octaves are used to specify properties at specific ranges.

Isofone	1	2	3	4	5	6	7	8	9	10
Middle frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	16000
Correction A-weighing (dB)	–39.4	–26.2	–16.1	–8.6	–3.2	0	+1.2	+1.0	–1.1	

Low Medium High

Sound Pressure

- The magnitude (amplitude) of sound waves, in terms of pressure change, is on the order of one-millionth (about 0.1 Pa) as much as absolute atmospheric pressure (~100,000 Pa).



Review of Log Scale

- Log scales are useful when we are dealing with a wide range of magnitudes (e.g., 0.0001 to trillions).
- In acoustics, our ears are sensitive enough to detect sound levels that are 10^{-6} as strong as deafening levels.
- So it would be impractical to deal with integer levels to define loudness and other acoustic units.

The Bel and Decibel

If sound is increased in intensity by a factor of 10,000, what is the change in decibels?

Decibels are based on the power of 10

$I_A \Rightarrow 10{,}000\ I_A \qquad 10^4$

40 dB

Why the factor of 10?

That makes it decibels.The change would be 4 Bels (named after Alexander Graham Bell).But 40 to 41 decibels is about the just noticeable difference in sound intensity.This makes the decibel a conveniently sized unit.

Sound Pressure Level

- Sound pressure level is the most common metric for sound loudness.
- Sound level is quantified in units of decibels (dB) or bels. 1 bel = 10 dB.
- It is a logarithmic scale. Sound pressure level is:

$$L_p = 10 \log\left(\frac{p}{p_{ref}}\right)^2 = 20 \log\left(\frac{p}{p_{ref}}\right)$$

- p is the root mean square (RMS) pressure.
- Sound levels CANNOT be added linearly, but rather using:

$$L_{power\text{-}sum} = 10 \log\left\{\sum_i 10^{L_i/10}\right\}$$

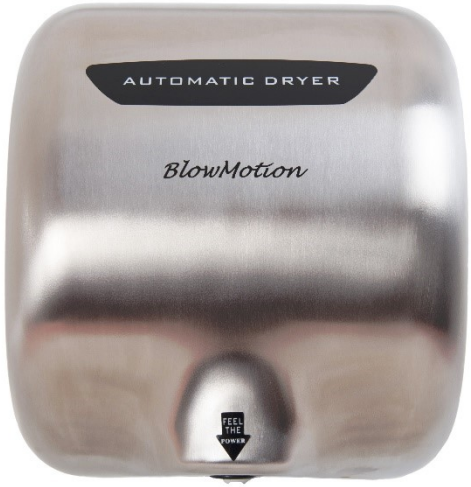
- $P_{ref} = 2\times10^{-5}$ Pa (minimum audible level by the human ear)

Rules of thumb for adding SPLs

When two decibel values differ by	Add the following amount to the higher value
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 to 9 dB	1 dB
10 dB or more	0 dB

True or false

- The hand dryers in the Canal Building cause a sound pressure level (SPL) of 85 dB, so if two of them are on simultaneously, the combined SPL is 170 dB.



Example

- Two sounds sources – one at 60 dB and the other at 70 dB – are present. Calculate the combined sound pressure level using the simplified and exact approaches.

Typical SPLs

Source	Sound Pressure, Pa	Sound Pressure Level, dB re 20 μPa	Subjective Reaction
Military jet takeoff at 30 m	200	140	Extreme danger
Artillery fire at 3 m	63.2	130	
Passenger jet takeoff at 15 m	20	120	Threshold of pain
Loud rock band	6.3	110	Threshold of discomfort
Automobile horn at 3 m	2	100	
Unmuffled large diesel engine at 40 m	0.6	90	Very loud
Accelerating diesel truck at 15 m	0.2	80	
Freight train at 30 m	0.06	70	Loud
Conversational speech at 1 m	0.02	60	
Window air conditioner at 3 m	0.006	50	Moderate
Quiet residential area	0.002	40	Quiet
Whispered conversation at 2 m	0.0006	30	
Buzzing insect at 1 m	0.0002	20	Perceptible
Threshold of good hearing	0.00006	10	Faint
Threshold of excellent youthful hearing	0.00002	0	Threshold of hearing

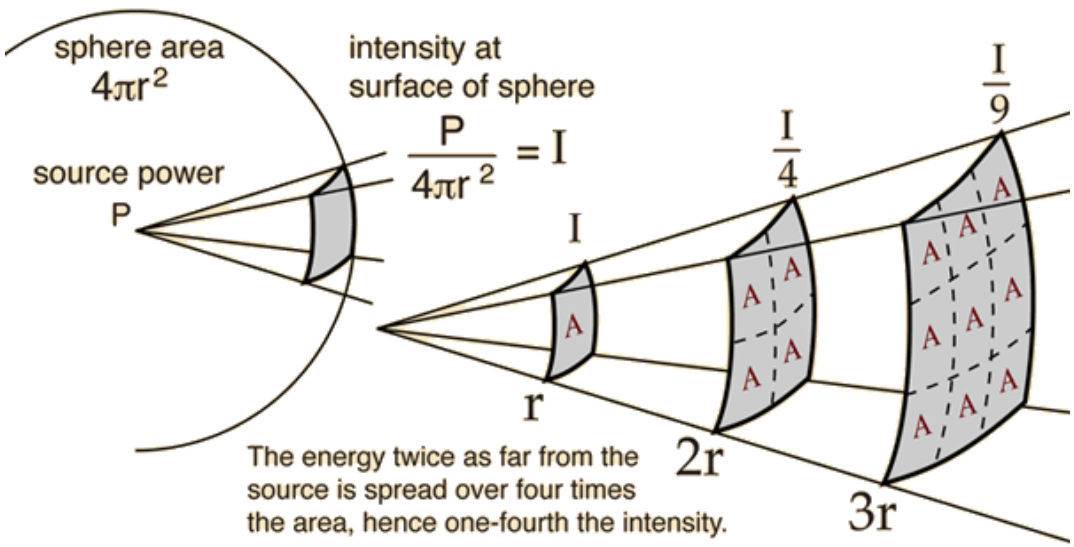
Perceived change in sound pressure level

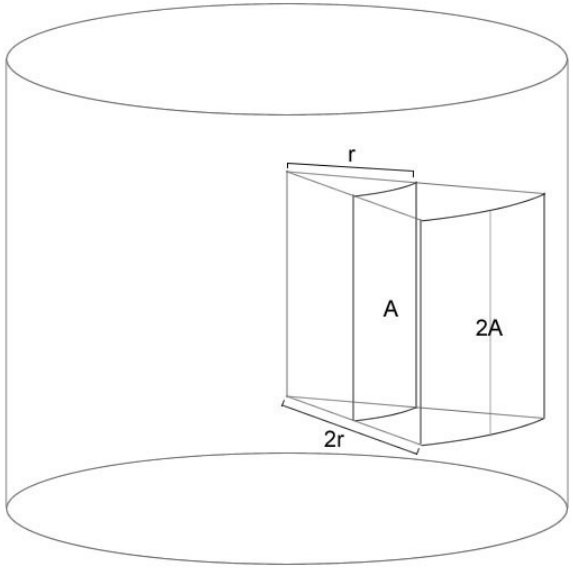
- Human's approximate doubling/halving of sound loudness by an increase/decrease of a bel (10 dB)

Subjective Change	Objective Change in Sound Level (Approximate)
Much louder	More than +10 dB
Twice as loud	+10 dB
Louder	+5 dB
Just perceptibly louder	+3 dB
Just perceptibly quieter	–3 dB
Quieter	–5 dB
Half as loud	–10 dB
Much quieter	Less than –10 dB

Sound sources: Point, Line, Surface

- Similarly to light, sound sources can be represented by point, light, and surface sources.



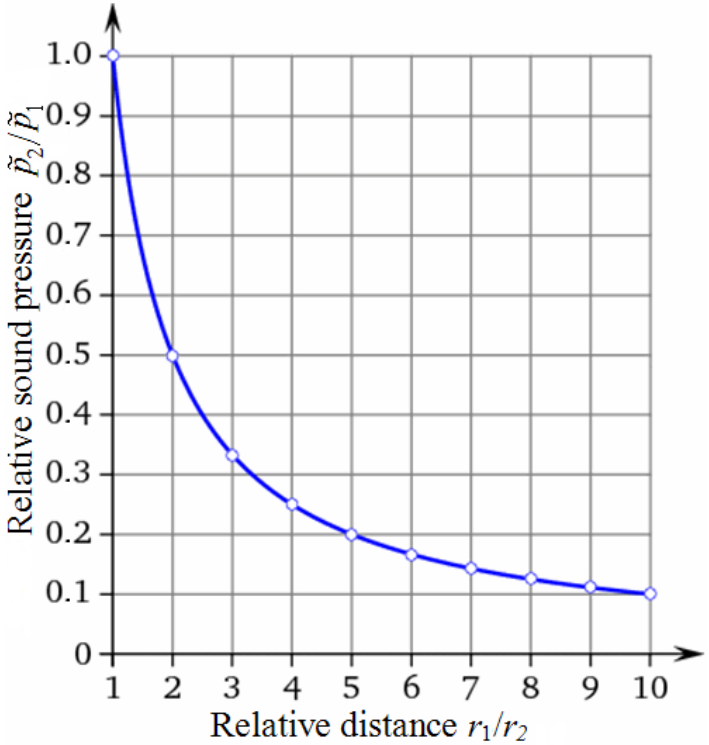


Sound pressure level and distance

- Sound pressure level decreases with distance according to the following formula.

$$SPL_2 = SPL_1 + 20\log(r_1/r_2)$$

r_1 and r_2 are the distance from a source, while SPL_1 and SPL_2 are the corresponding sound pressure levels at those distances.



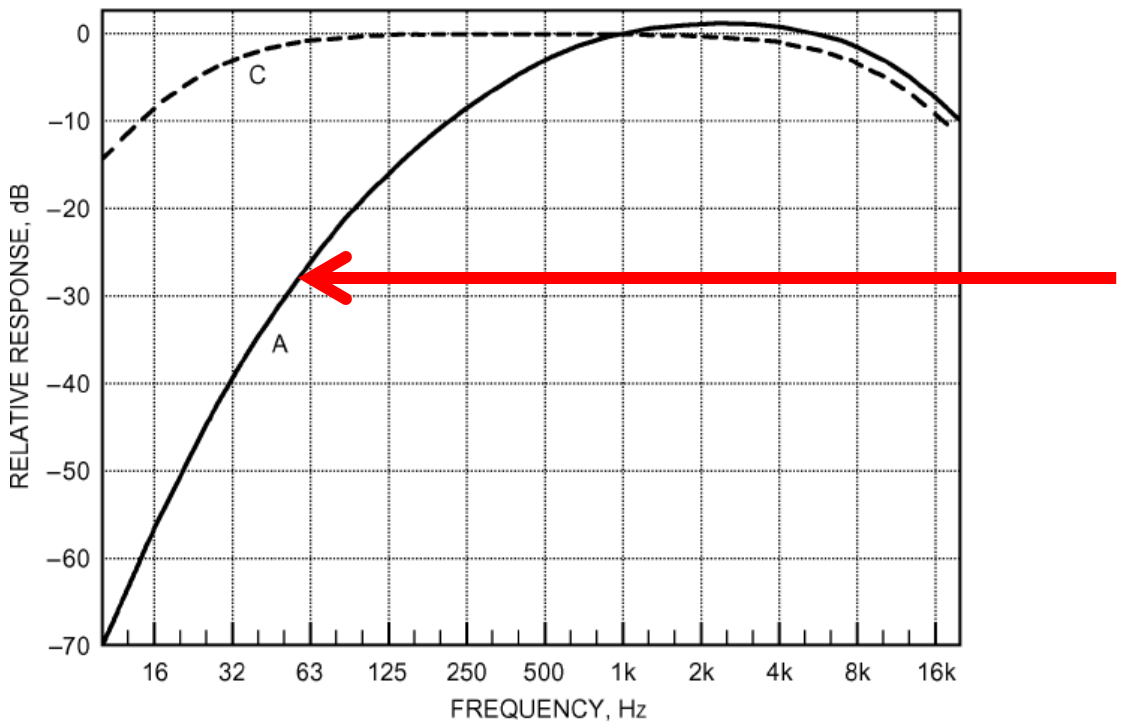
Example

You are at a concert and want to move away from the stage such that the music sounds only half as loud. Originally, the music had a sound pressure level of 90 dB and you were just 20 meters from the stage (assumed to be a point source). How far do you need to move away?

(hint: a source sounds half as loud if the SPL drops by 10 dB)

Human Hearing

- Our ears' sensitivity depends on the frequency of sound (just like eyes and light).
- Sound pressure level has to be adjusted accordingly.



Approximation of human hearing ability

Fig. 1 Curves Showing A- and C-Weighting Responses for Sound Level Meters

A-weighting adjustment

- Total sound pressure level is calculated by adding sound pressure levels for different frequencies (after subtracting the A-weighting correction:

$$L_{tot} = 10\log(10^{Lp1/10} + 10^{Lp2/10} + \ldots + 10^{LPn/10})$$

Octave band centre frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Linear sound level	95	95	90	85	80	81	75	70	60
"A" weighted correction factor	-39.4	-26.2	-16.1	-8.6	-3.2	0	1.2	1.0	-1.1
"A" weighted sound level	55.6	68.6	73.9	76.4	76.8	81.0	76.2	71.0	63.9

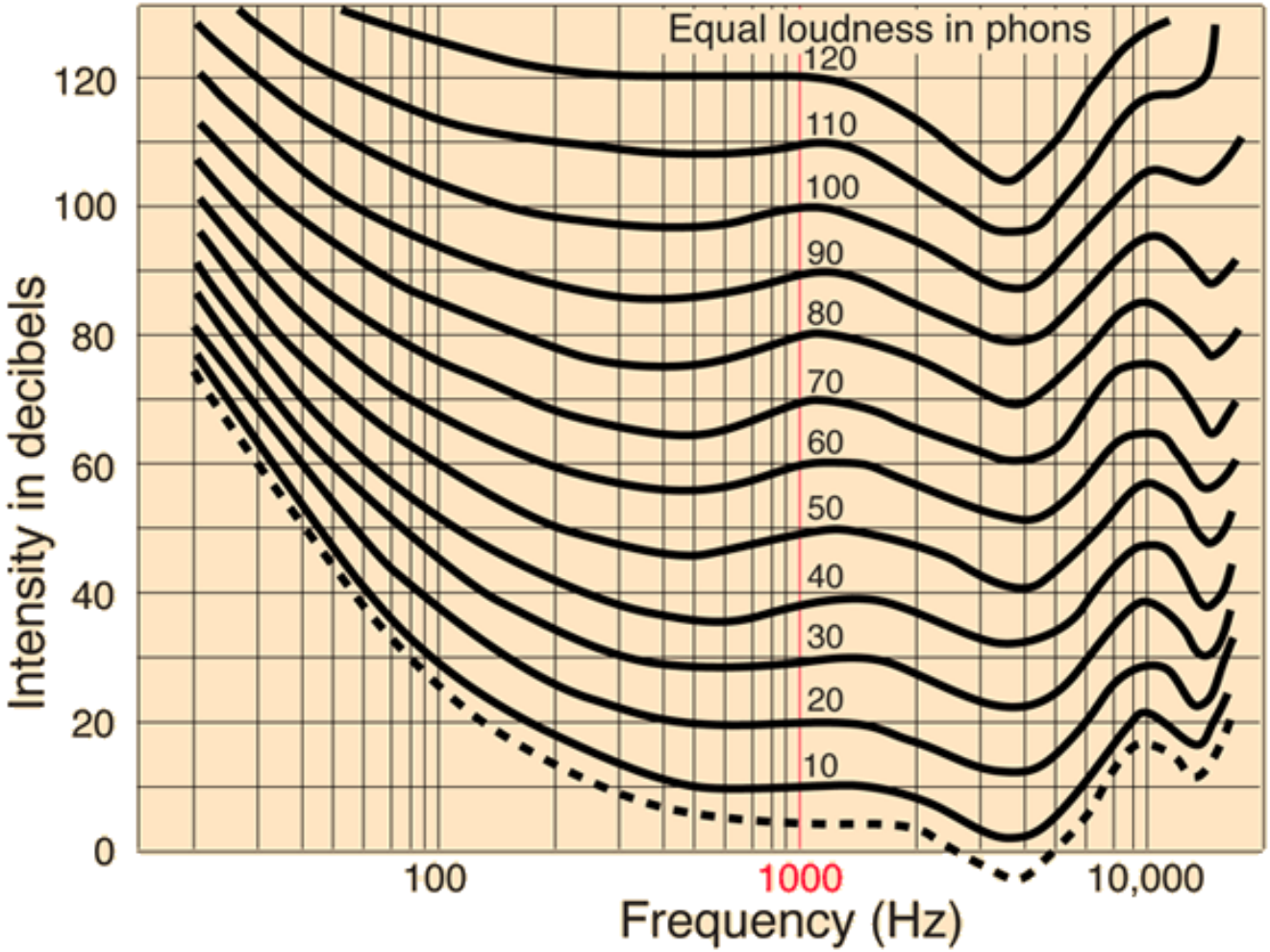
← measured

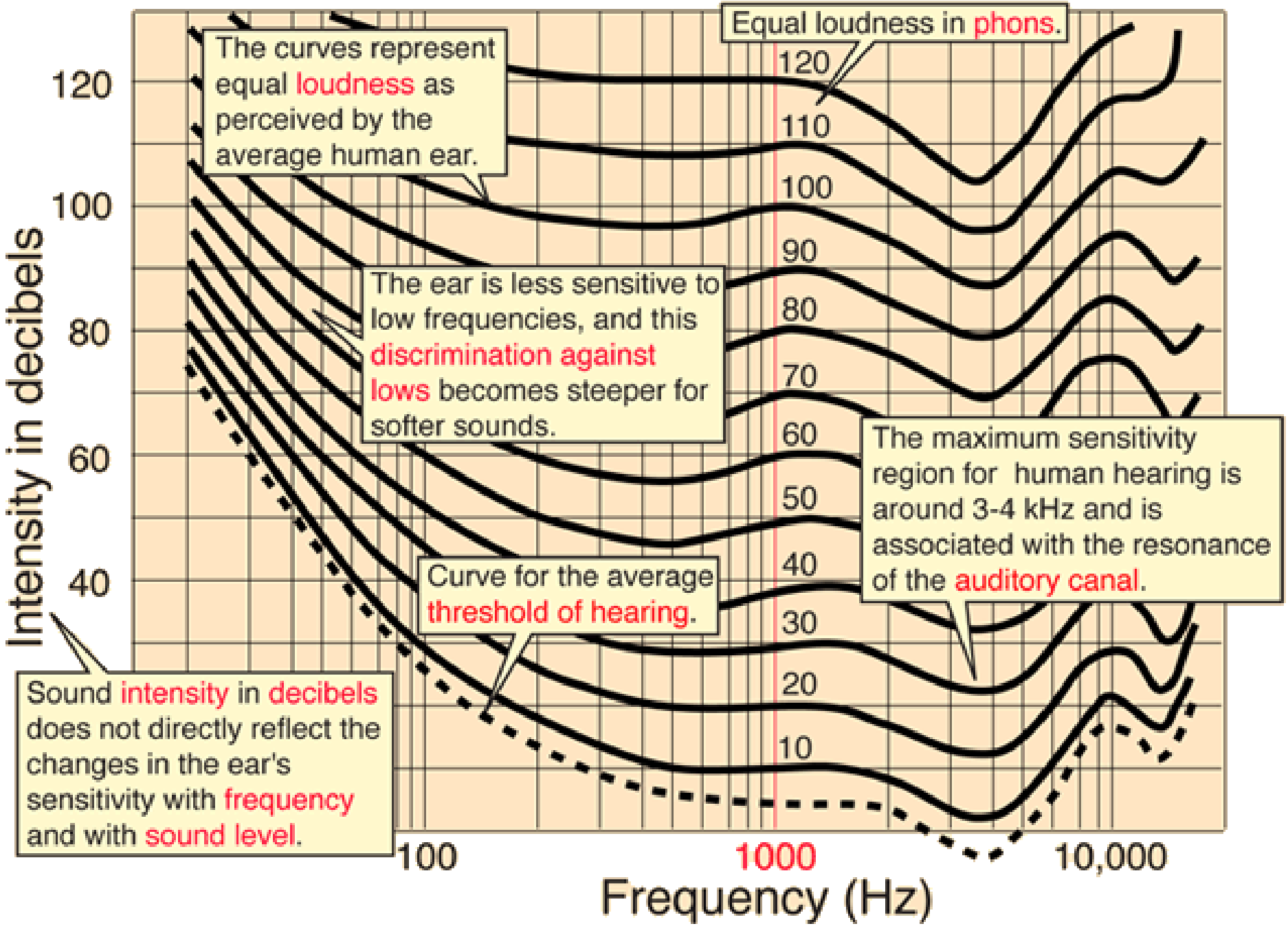
← correction

← As heard by a human (often listed as dBA or dB(A))

Isofones

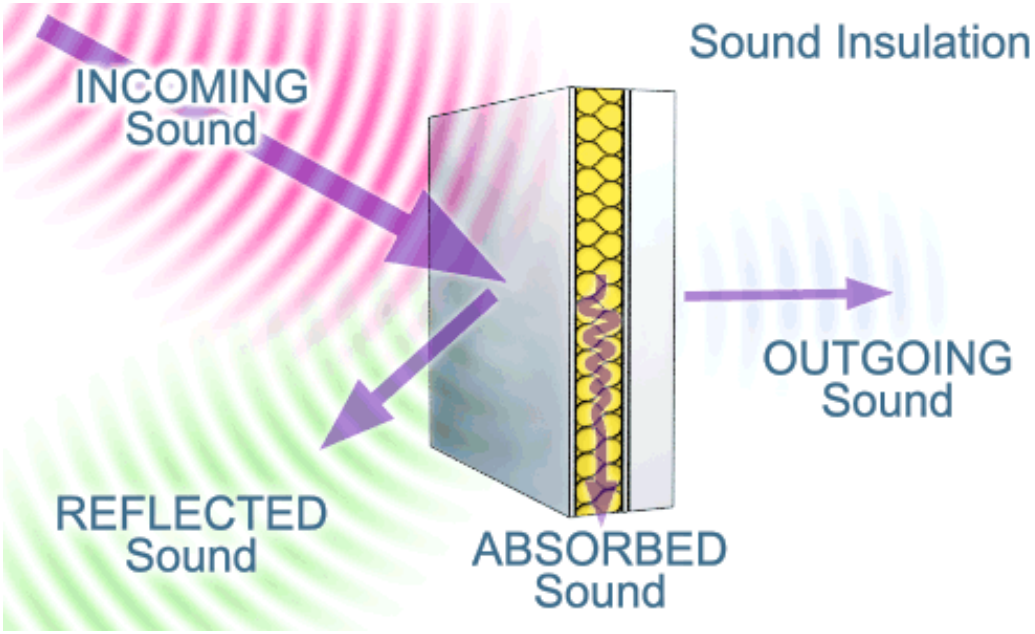
Lines of constant audible sound levels (e.g., 20 dB at 1000 Hz sounds as loud as 38 dB at 100 Hz).




Equal loudness in phons.
The curves represent equal loudness as perceived by the average human ear.
The ear is less sensitive to low frequencies, and this discrimination against lows becomes steeper for softer sounds.
The maximum sensitivity region for human hearing is around 3-4 kHz and is associated with the resonance of the auditory canal.
Curve for the average threshold of hearing.
Sound intensity in decibels does not directly reflect the changes in the ear's sensitivity with frequency and with sound level.
120
110
100
90
80
70
60
50
40
30
20
10
Intensity in decibels
100
1000
10,000
Frequency (Hz)

Absorb, reflect, transmit

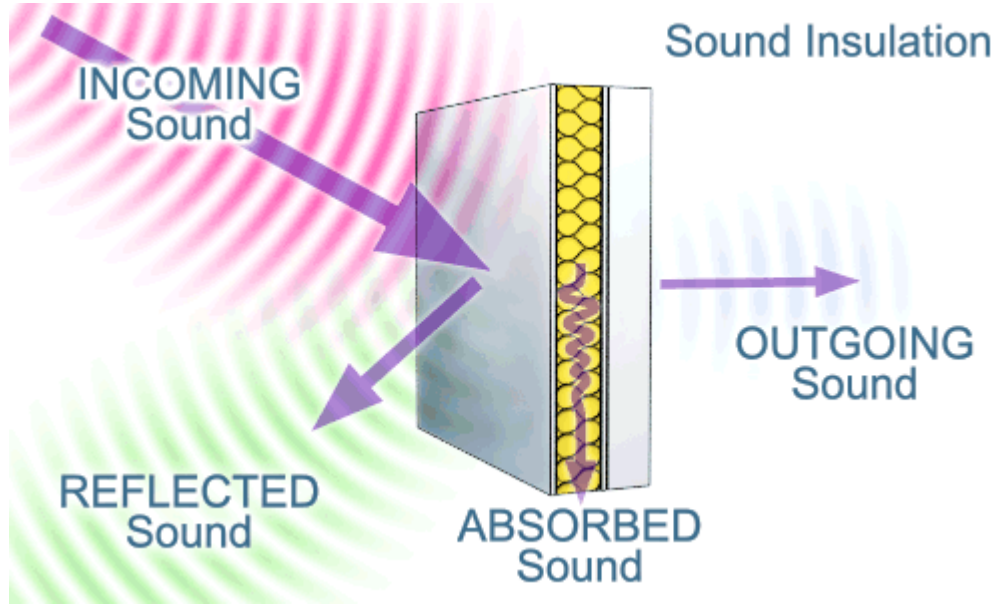
- Just like light, one of three things happens to sound when it hits a solid surface (e.g., wall).
- Sound does not transmit through a surface (technically) but instead causes the surface to vibrate, which in turn causes air on the other side to vibrate.



Reflection, absorption, transmission

- $I_i = I_\rho + I_\delta + I_\tau$

I_i



I_τ

I_ρ

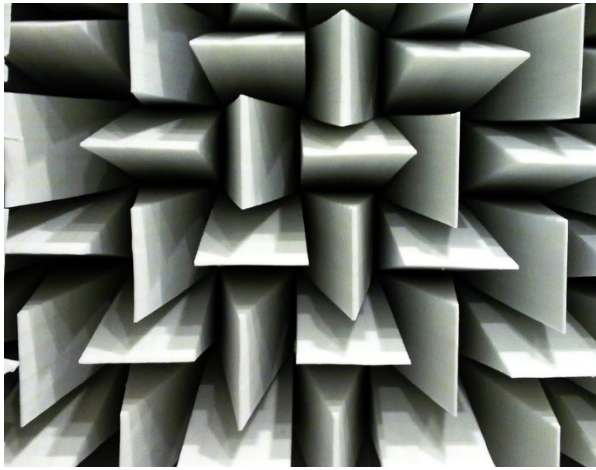
I_δ

ρ, δ, τ = reflection, dissipation, transmission coefficients.

$\alpha = 1 - \rho$ = absorption coefficient

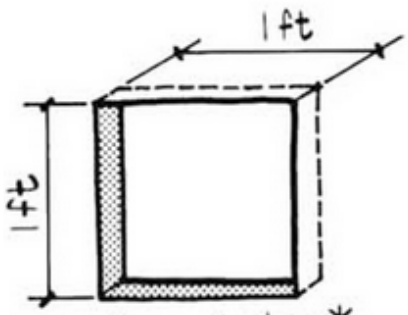
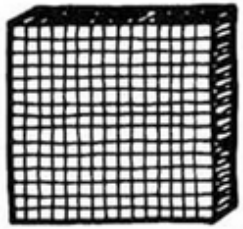
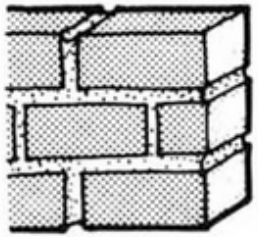
Mechanics of sound absorption

- A material is a good sound absorber if it converts a significant fraction of incident sound energy into heat
- Porous absorbers use gas-filled cells to absorb noise using friction. Key traits include:
  - Cell size, cell size irregularity, material thickness, material density
- Porous absorbers are best mid-frequency; not as good for low-frequencies.
- On the macro scale, cone-line protrusions also improve surface absorption.



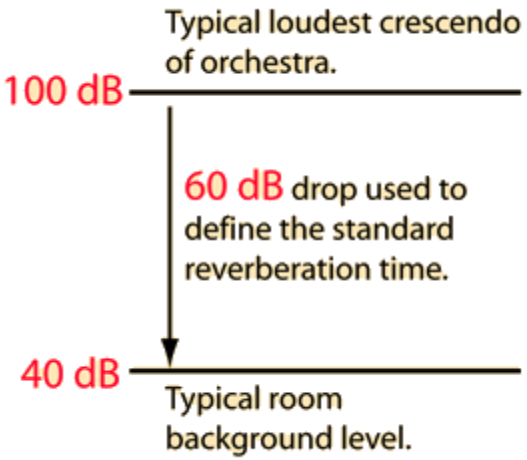
Sound absorption coefficients

$$\alpha = \frac{I_{abs}}{I_{inc}}$$

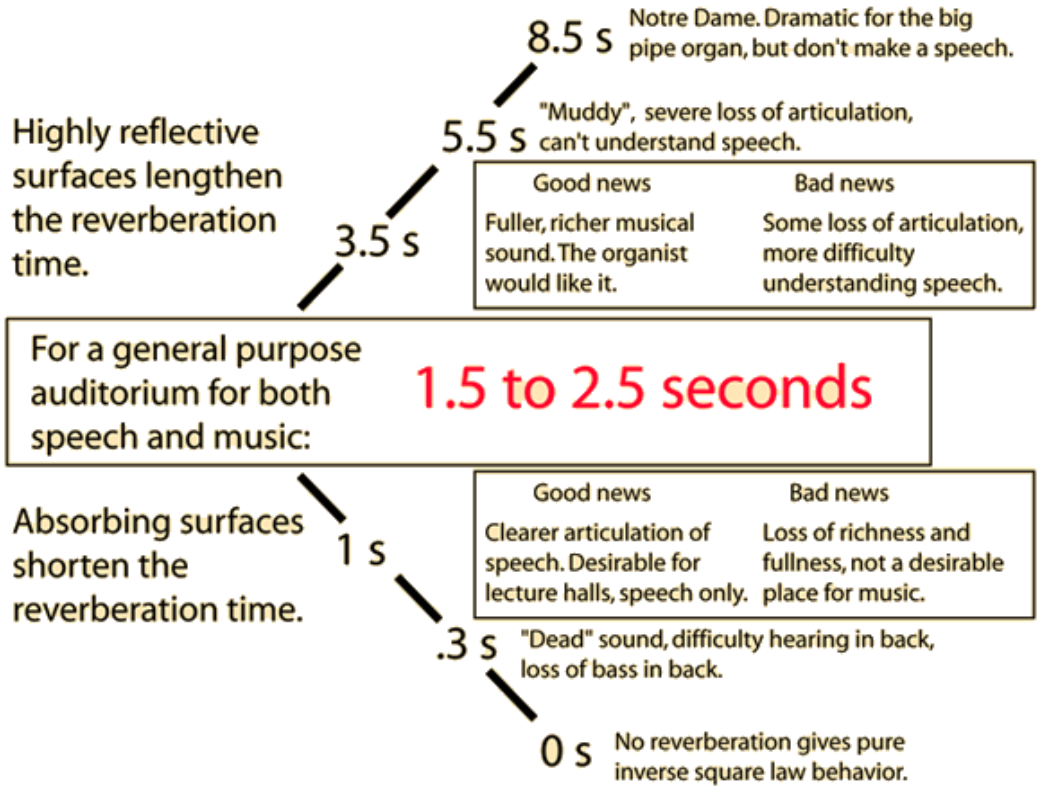
	% reflected	% absorbed and transmitted	Sound absorption coefficient (α)
 Open window *	0	100	1.0
 1½" thick glass fiber	20	80	0.80
 4" thick brick	98	2	0.02

Reverberation time

- Sound characteristic of a space
- Time lapse before sound drops by 60 dB
- $T_r = V/6A_s$ [in seconds]
  - T_r = reverberation time
  - V = room volume
  - A_s = total absorption surface area in space (m^2)
- Could vary by frequency but can be simplified using a single representative frequency (about 1000 Hz for speech)
- T_r calculator here: http://hyperphysics.phy-astr.gsu.edu/hbase/acoustic/revtim.html



Desirable Reverberation time



- Vienna, Musikvereinsaa: 2.05 seconds
- Boston, Symphony Hall: 1.8 seconds
- New York, Carnegie Hall: 1.7 seconds

	Reverberation Time			
	.8 - 1.3	1.4 - 2.0	2.1 - 3.0	Optimum**
Speech	Good	Fair - Poor	Unacceptable*	0.8 - 1.1
Contemporary music	Fair - Good	Fair	Poor	1.2 - 1.4
Choral music	Poor - Fair	Fair - Good	Good - Fair	1.8 - 2.0+

* With an adequately designed and installed sound system, speech intelligibility concerns can be mitigated.
** The optimium reverberation time can be somewhat subjective and can shift based on numerous variables.

Room sound absorption

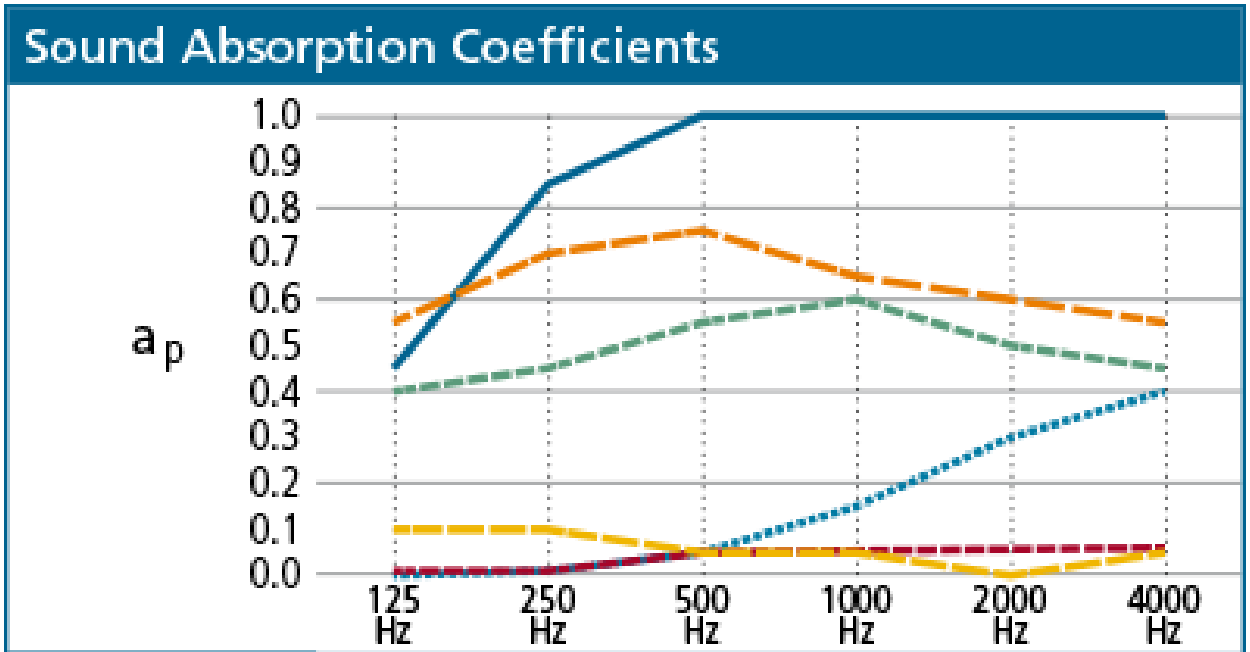
- $A_s = \alpha_w A_w + \alpha_c A_c + \alpha_f A_f + \alpha_m A_m$
  - α= absorption coefficient for surface (1 for open window; 0 for hard, smooth "acoustic mirror")
  - A = surface area
  - w, c, f, m = walls, ceiling, floor, miscellaneous (e.g., furniture)

	Sound Absorption Coefficient (α)					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Glass Fiber Ceiling Tile	0.70	0.85	0.75	0.85	0.90	0.90
Fiberglass Wall Panel - 2 inch thick	0.30	0.50	0.80	0.90	0.80	0.75
Concrete Block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Gypsum Wall Board	0.25	0.15	0.08	0.06	0.04	0.04
Plaster Wall or Ceiling	0.14	0.10	0.06	0.05	0.04	0.03
Linoleum or Tile Floor	0.02	0.03	0.03	0.03	0.03	0.02
Thin Carpet, on concrete	0.05	0.10	0.25	0.30	0.35	0.40
Wood Door	0.15	0.11	0.09	0.07	0.06	0.06
Glass	0.35	0.25	0.18	0.12	0.07	0.04
Chalkboard	0.01	0.01	0.01	0.01	0.02	0.02

FIGURE 15. Typical Absorption Coefficients for building materials commonly used in educational facilities.

Absorption coefficients and frequency

- Materials' absorption coefficients are frequency dependent.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Rockfon Sonar	0.45	0.85	1.00	1.00	1.00	1.00
Perforated Gypsum	0.55	0.70	0.75	0.65	0.60	0.55
Wetfelt Tile	0.40	0.45	0.55	0.60	0.50	0.45
Carpet	0.01	0.02	0.05	0.15	0.30	0.40
Stone/Linoleum	0.02	0.02	0.05	0.05	0.05	0.07
Unperforated Gypsum	0.10	0.10	0.05	0.05	0.00	0.05

More sound absorption coefficients

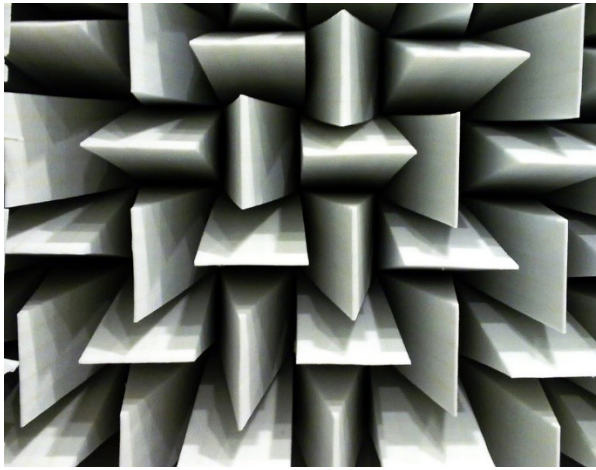
TABLE 15.1 Approximate typical absorption coefficients of various surfaces. Individual examples may vary considerably from these values.

Surface Treatment	Absorptivity at Frequency 125	250	500	1000	2000	4000
Acoustic tile, rigidly mounted	.2	.4	.7	.8	.6	.4
Acoustic tile, suspended in frames	.5	.7	.6	.7	.7	.5
Acoustical plaster	.1	.2	.5	.6	.7	.7
Ordinary plaster, on lath	.2	.15	.1	.05	.04	.05
Gypsum wallboard, $\frac{1}{2}''$ on studs	.3	.1	.05	.04	.07	.1
Plywood sheet, $\frac{1}{4}''$ on studs	.6	.3	.1	.1	.1	.1
Concrete block, unpainted	.4	.4	.3	.3	.4	.3
Concrete block, painted	.1	.05	.06	.07	.1	.1
Concrete, poured	.01	.01	.02	.02	.02	.03
Brick	.03	.03	.03	.04	.05	.07
Vinyl tile, on concrete	.02	.03	.03	.03	.03	.02
Heavy carpet, on concrete	.02	.06	.15	.4	.6	.6
Heavy carpet, on felt backing	.1	.3	.4	.5	.6	.7
Platform floor, wooden	.4	.3	.2	.2	.15	.1
Ordinary window glass	.3	.2	.2	.1	.07	.04
Heavy plate glass	.2	.06	.04	.03	.02	.02
Draperies, medium velour	.07	.3	.5	.7	.7	.6
Upholstered seating, unoccupied	.2	.4	.6	.7	.6	.6
Upholstered seating, occupied	.4	.6	.8	.9	.9	.9
Wood/metal seating, unoccupied	.02	.03	.03	.06	.06	.05
Wooden pews, occupied	.4	.4	.7	.7	.8	.7

SOURCES: Backus (p. 172) and L. Doelle, *Environmental Acoustics* (McGraw-Hill, 1972), p. 227.

Mechanics of sound absorption

- A material is a good sound absorber if it converts a significant fraction of incident sound energy into heat
- Porous absorbers use gas-filled cells to absorb noise using friction. Key traits include:
  - Cell size, cell size irregularity, material thickness, material density
- Porous absorbers are best mid-frequency; not as good for low-frequencies.
- On the macro scale, cone-line protrusions also improve surface absorption.



Anechoic Chamber

- Anechoic chambers have very high sound absorption so the reverberation time is close to 0.

Example

- Calculate the reverberation time for sound that is 1000 Hz in a classroom with the following properties.

Surface	Area (m^2)	Absorptivity (α at 1000 Hz)
Floor	200	0.03
Walls	180	0.04
Ceiling	200	0.8
Total		
Reverb. time		RT = V/6A (assume V = 600 m^2)

- What if the floor was covered with carpeting (α=0.3) or acoustic panels (α=0.9) were mounted on the walls?

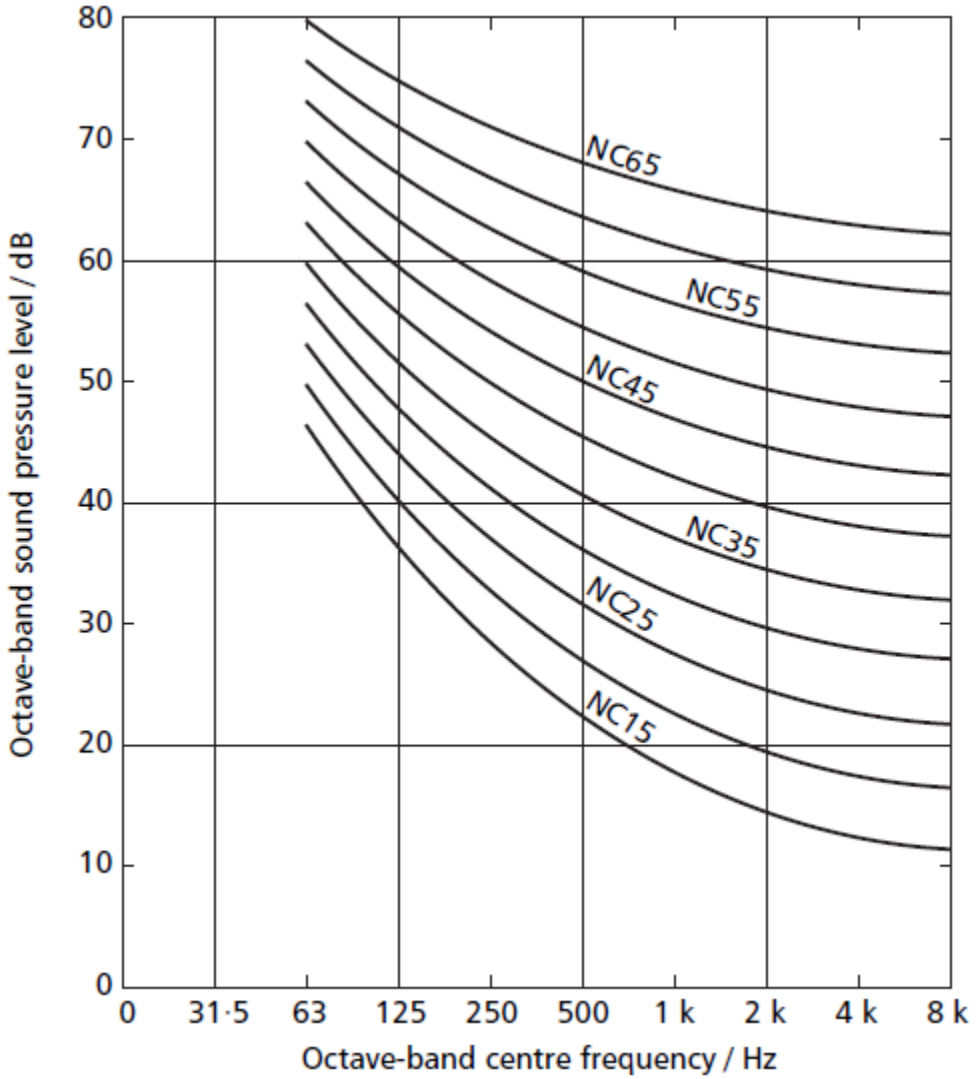
Noise Criteria limits

- Normally guidelines suggest the maximum allowable NC for a space type.

Situation	Noise rating (NR)
Studios and auditoria:	
— sound broadcasting (drama)	15
— sound broadcasting (general), television (general), sound recording	20
— television (audience studio)	25
— concert hall, theatre	20–25
— lecture theatre, cinema	25–30
Hospitals:	
— audiometric room	20–25
— operating theatre, single bed ward	30–35
— multi–bed ward, waiting room	35
— corridor, laboratory	35–40
— wash room, toilet, kitchen	35–40
— staff room, recreation room	30–40
Hotels:	
— individual room, suite	20–30
— ballroom, banquet room	30–35
— corridor, lobby	35–40
— kitchen, laundry	40–45
Restaurants, shops and stores:	
— restaurant, department store (upper floors)	35–40
— night club, public house, cafeteria, canteen, department store (main floors)	40–45

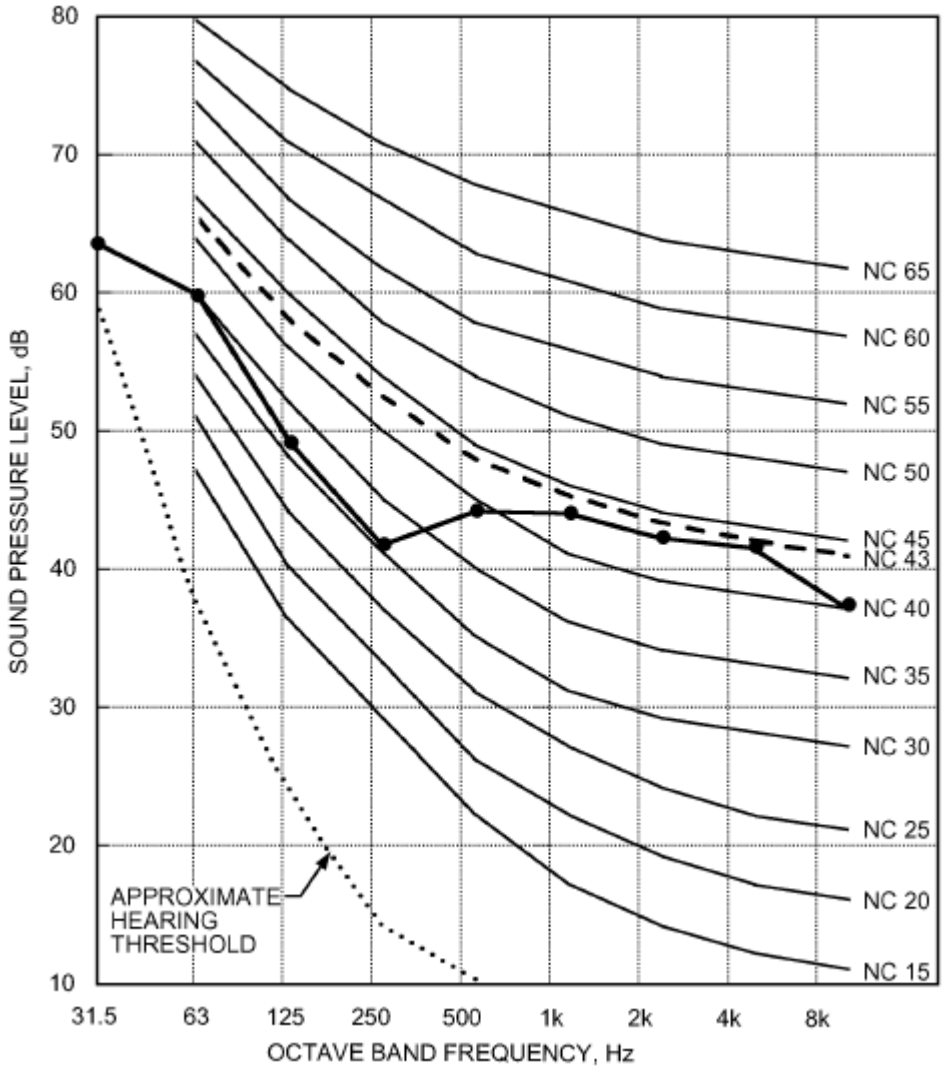
Noise Criteria (NC) curves

- A space achieves NC[X] if the sound pressure level is entirely below

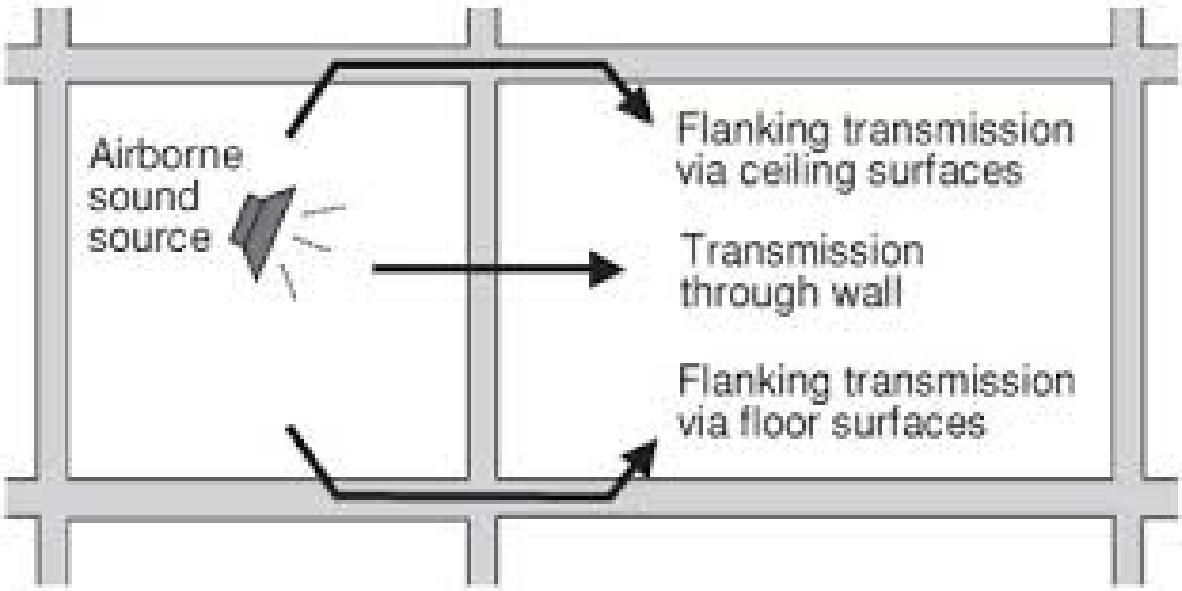


How to measure NC Rating

- To achieve a certain NC, all measured SPLs at the octave frequencies must be below a NC.



Types of sound barriers & the physical phenomena



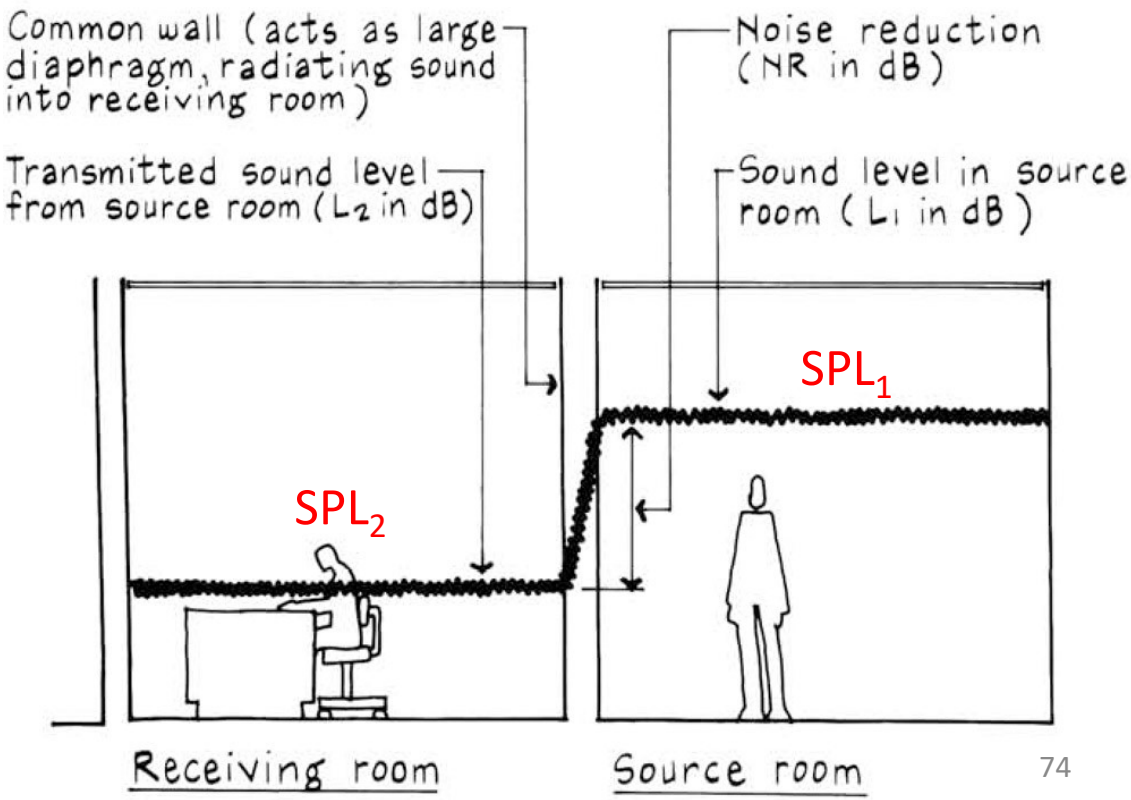
Also: through openings, ducts, plenum, gaps under doors, etc.

Wall sound insulation

- Transmission loss (TL) (AKA Sound transmission loss (STL)) indicates the sound loudness reduction through a surface.
  - It has units of dB
- $TL = 10\log(1/\tau)$
- τ = sound transmittance of a surface

Noise reduction between rooms

- Sound is reduced arithmetically between rooms according to the noise reduction (NR)
- It includes the effect of absorption in the receiving room
- NR = SPL_1 - SPL_2



Noise Reduction

Noise reduction depends on three things:

1. Area of the wall dividing the spaces (e.g., between source and receiving room)
2. The absorption of the receiving room (in sabins or $\Sigma(A_i \cdot \alpha_i)$)
3. The transmission loss (TL) of the wall (in dB)

$NR = TL + 10\log(\Sigma A_2\alpha_2/S)$

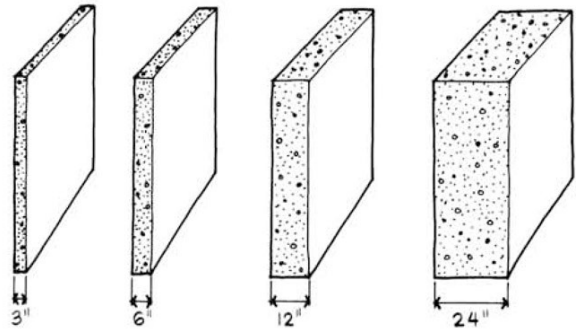
$A_2\alpha_2$ = absorption in receiving room (sabins)

S = dividing wall area (m^2)

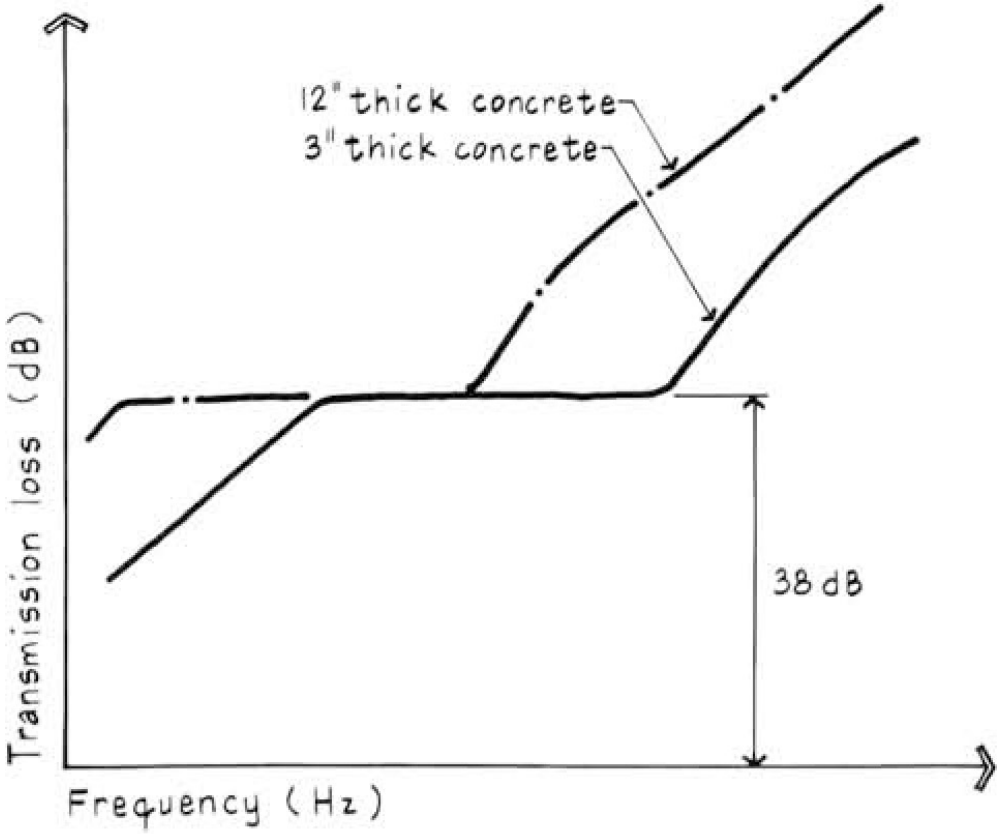
Example

In an condo building, two adjacent living rooms have a party wall constructed of 10 cm thick brick which has a TL of 40 dB at 500 Hz. The surface area S of the wall is 20 m^2, and both rooms have 30 $m^2 \cdot$sabins of absorption A_2 at 500 Hz. Find the sound level SPL_2 in room 2 if the sound pressure level SPL_1 in room 1 (noise source room) is 74 dB.

Mass law and diminishing returns

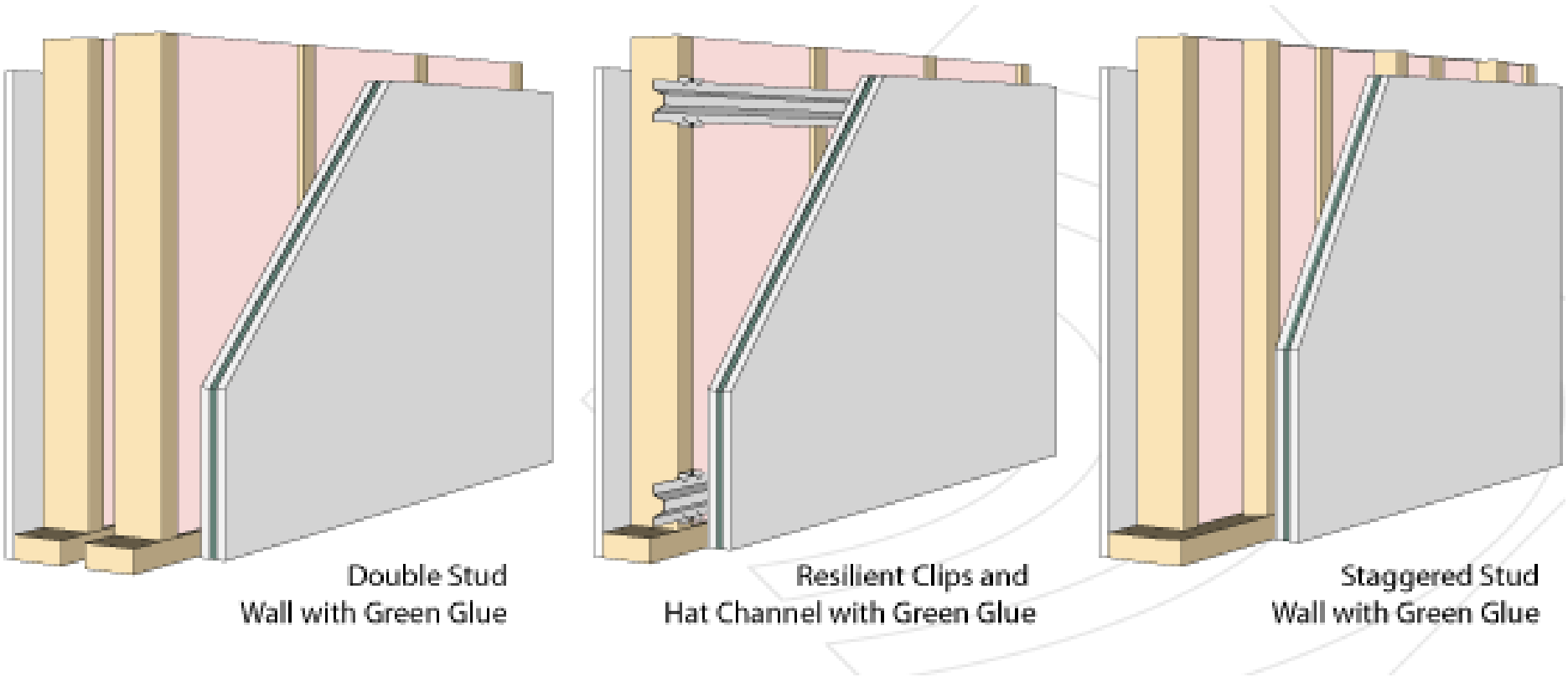


Weight (lb/ft²):	36	72	144	288
STC:	42	46	51	58

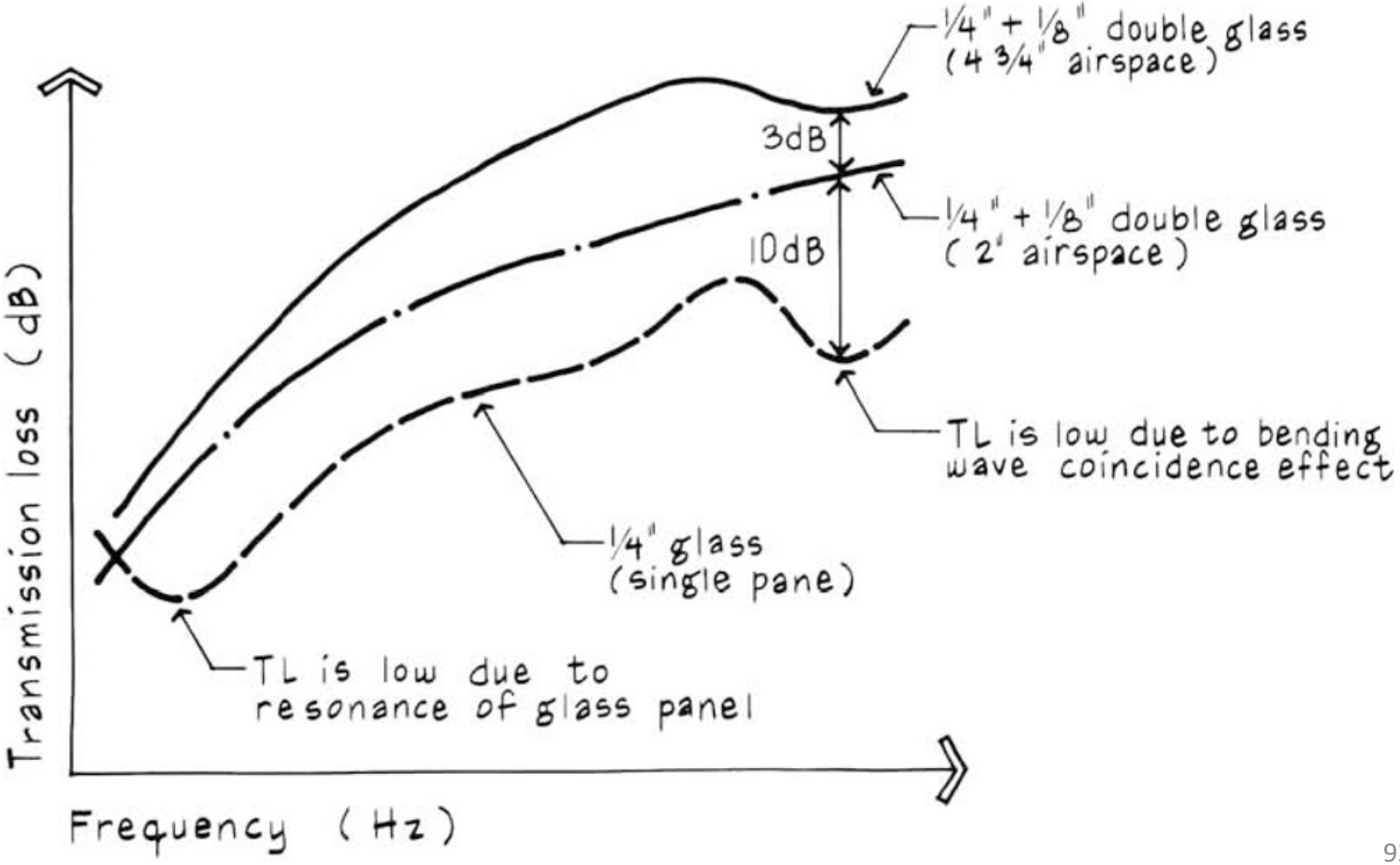


Roadside barriers transmission loss

Stud wall strategies



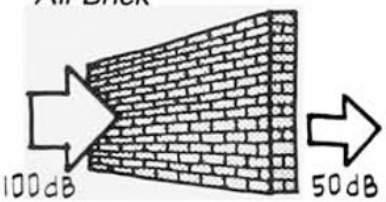
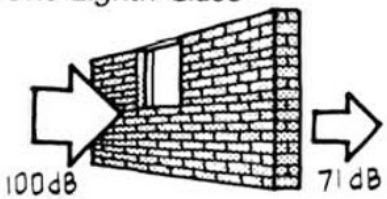
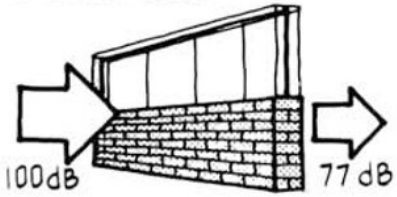
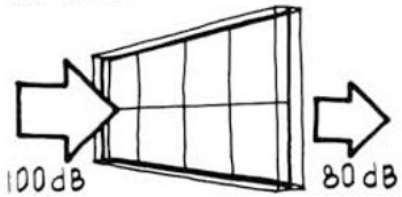
Transmission loss through windows



Composite walls and TL

- Even small holes are areas of high-transmittance materials cause a wall to have relatively high transmittance.

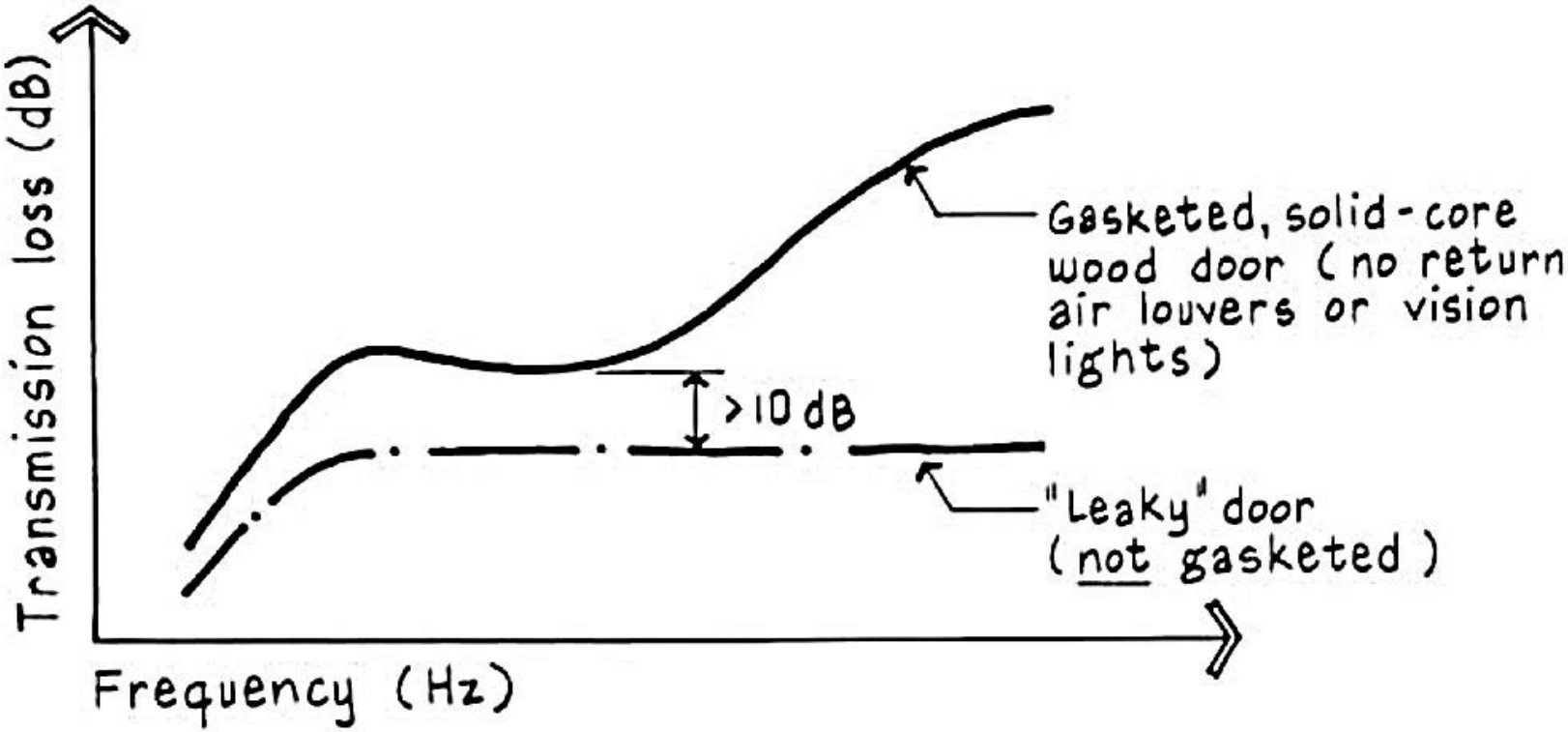
$$Composite\ \mathrm{TL} = 10\log\frac{\sum S}{\sum \tau S}$$

Wall	Composite TL (dB)
All Brick 	50
One-Eighth Glass 	29
One-Fourth Glass	26
One-Half Glass 	23
All Glass 	20

Example

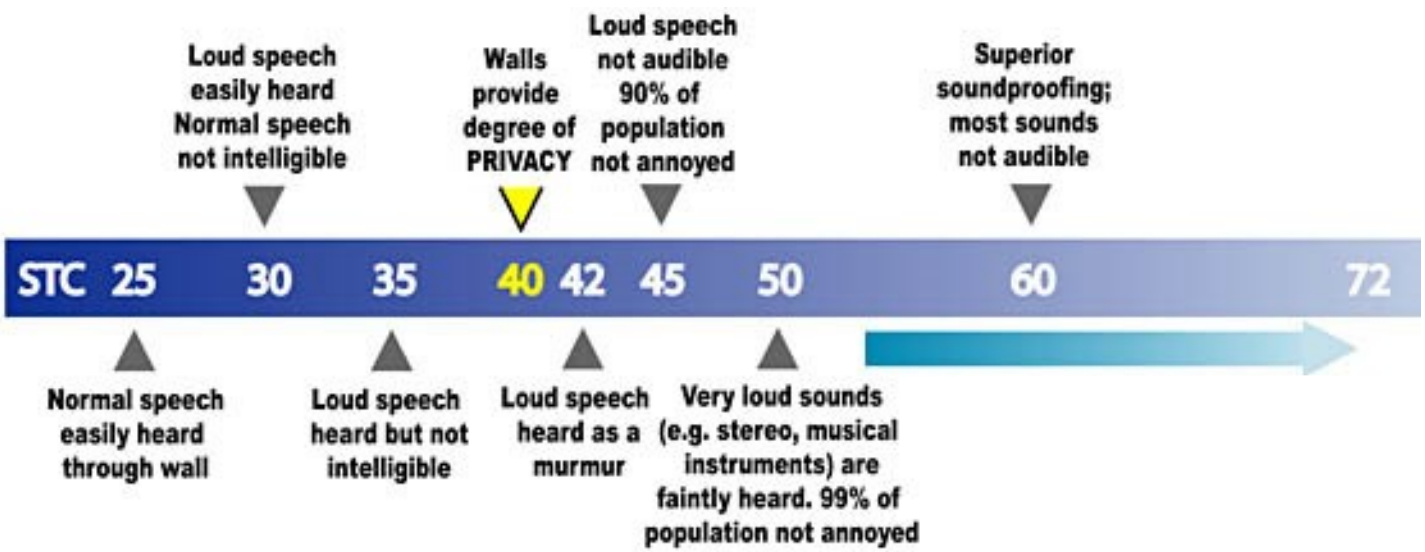
- A 10 m^2 exterior wall material with a nominal τ of 0.1% (or 0.001), and a 10% WWR (with an open window). Calculate the transmission loss (TL) and effective transmittance of the composite wall.
- (Answer: TL=9.96 dB; τ = 10.09%)

Sound leaks


Transmission loss (dB)
Frequency (Hz)
Gasketed, solid-core wood door (no return air louvers or vision lights)
>10 dB
"Leaky" door (not gasketed)

Sound Transmission Class (STC)

- A rating system to indicate a surface's ability to block (attenuate) sound from 125 to 4,000 Hz. (whereas TL is for a single frequency)

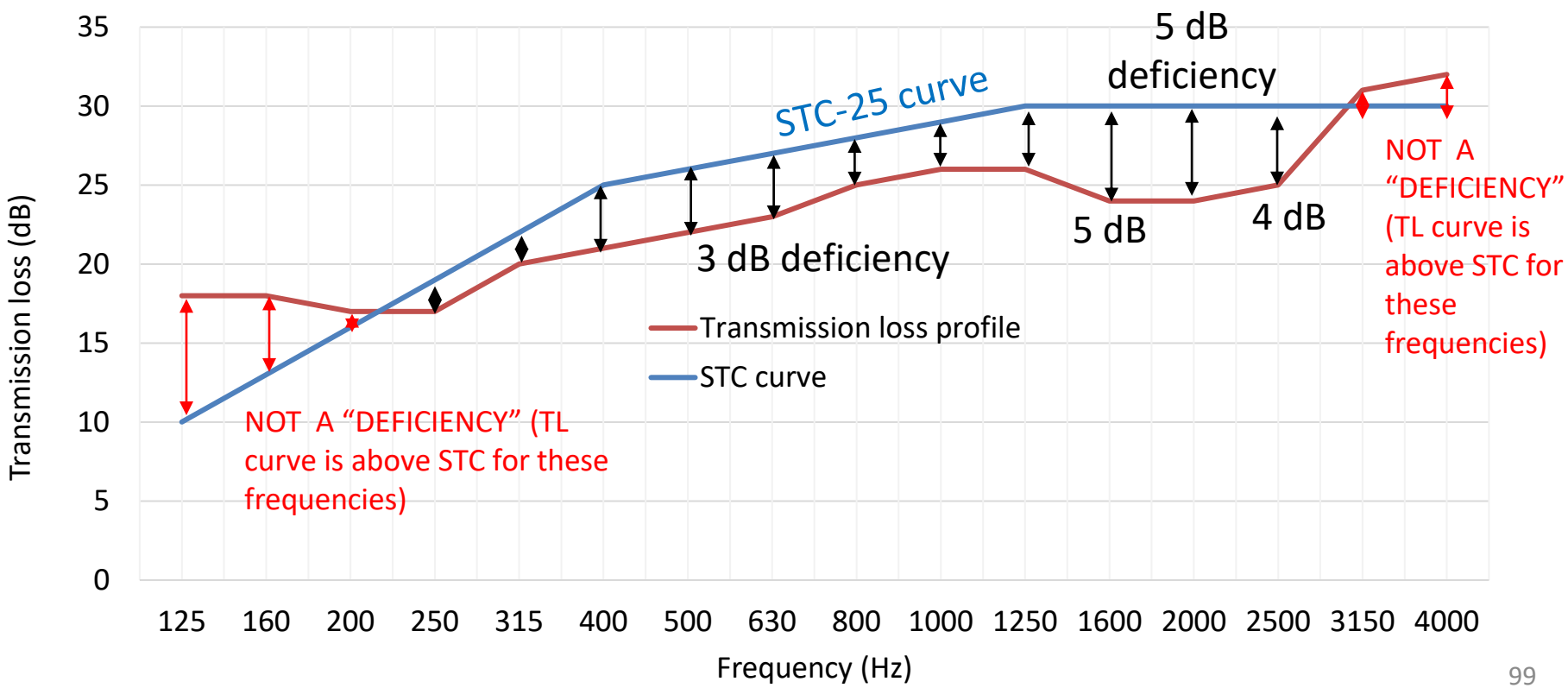


Sound Transmission Class (STC)

The STC level is indicative of TL; it's selected according to two rules.

The two STC Conditions:

1. No single frequency band may have more than 8 deficiencies (8 dB)
2. The total deficiencies for the 16 frequencies may not exceed 32 (dB)



Sound Transmission Class (STC)

The STC level is indicative of TL; it's selected according to two rules.

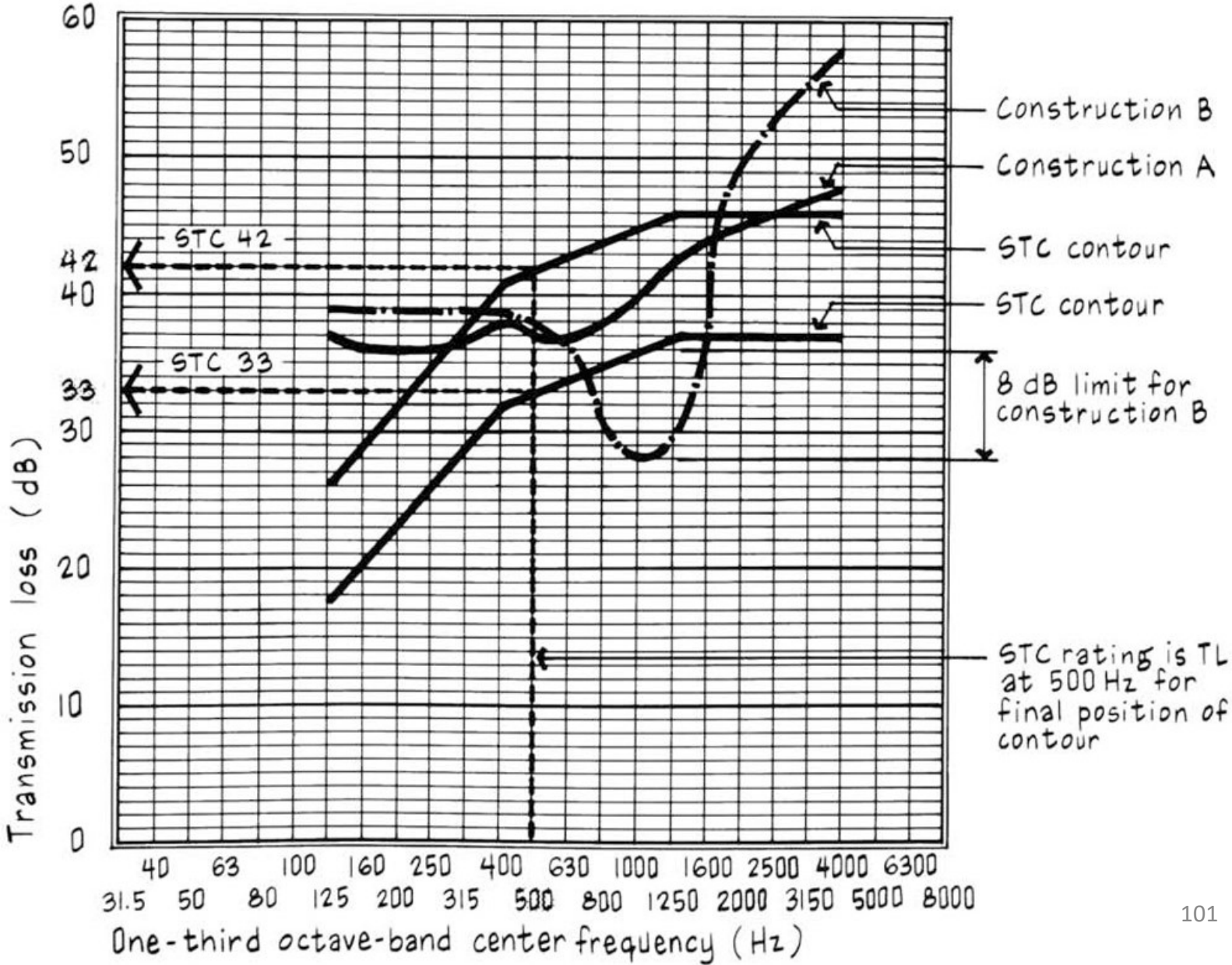
The two STC Conditions:

1. No single frequency band may have more than 8 deficiencies (8 dB)
2. The total deficiencies may not exceed 32 (dB)

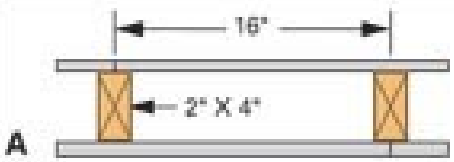
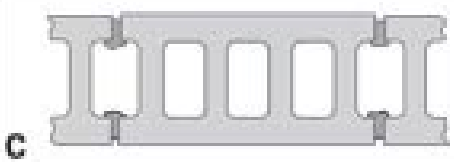
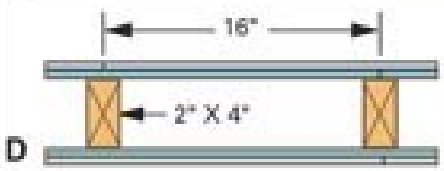
Similar to A-weighting correction

Frequency (Hz)	STC Contour Adjustment	Transmission Loss	Transmission Loss - Adjusted[A]	STC you wish to test	Deficiencies[B]
125	+16	**35**	51	55	4
160	+13	**41**	54	55	1
200	+10	**42**	52	55	3
250	+7	**45**	52	55	3
315	+4	**47**	51	55	4
400	+1	**50**	51	55	4
500	0	**53**	53	55	2
630	-1	**56**	55	55	0
800	-2	**59**	57	55	0
1000	-3	**60**	57	55	0
1250	-4	**59**	55	55	0
1600	-4	**61**	57	55	0
2000	-4	**61**	57	55	0
2500	-4	**62**	58	55	0
3150	-4	**67**	63	55	0
4000	-4	**70**	66	55	0
				Total deficiencies	21

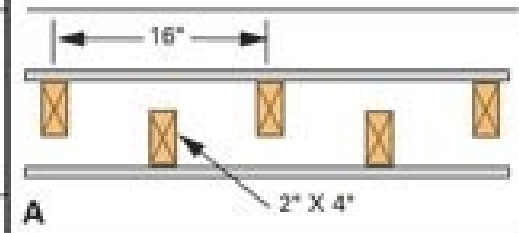
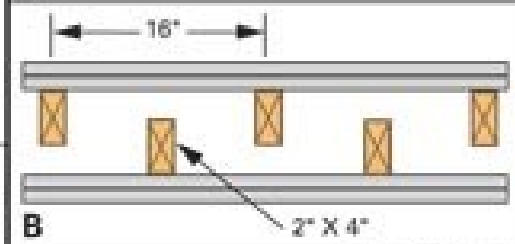
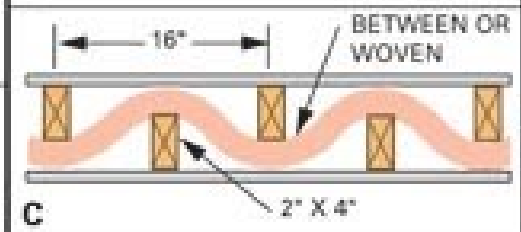
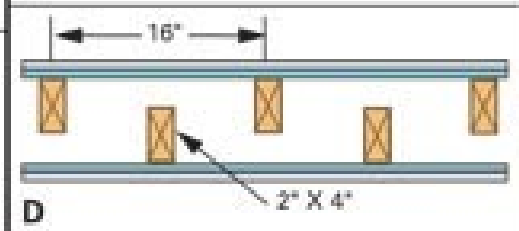
STC Example


60
50
42
40
33
30
20
10
0
STC 42
STC 33
Transmission loss (dB)
Construction B
Construction A
STC contour
STC contour
8 dB limit for construction B
STC rating is TL at 500 Hz for final position of contour
40 63 100 160 250 400 630 1000 1600 2500 4000 6300
31.5 50 80 125 200 315 500 800 1250 2000 3150 5000 8000
One-third octave-band center frequency (Hz)

SOUND INSULATION OF SINGLE WALLS

DETAIL	DESCRIPTION	STC RATING
	1/2" GYPSUM WALL - BOARD 5/8" GYPSUM WALL - BOARD	32 37
	3/8" GYPSUM LATH (NAILED) PLUS 1/2" GYPSUM PLASTER WITH WHITECOAT FINISH (EACH SIDE)	39
	8" CONCRETE BLOCK	45
	1/2" SOUND DEADENING BOARD (NAILED) 1/2" GYPSUM WALLBOARD (LAMINATED) (EACH SIDE)	46
	RESILIENT CLIPS TO 3/8" GYPSUM BACKER BOARD 1/2" FIBERBOARD (LAMINATED) (EACH SIDE)	52

SOUND INSULATION OF DOUBLE WALLS

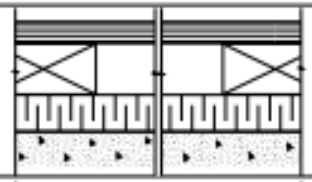
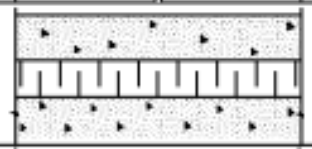
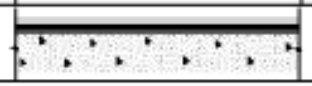
DETAIL	DESCRIPTION	STC RATING
	1/2" GYPSUM WALLBOARD	38
	5/8" GYPSUM WALLBOARD (DOUBLE LAYER EACH SIDE)	45
	1/2" GYPSUM WALLBOARD 1 1/2" FIBROUS INSULATION	49
	1/2" SOUND DEADENING BOARD (NAILED) 1/2" GYPSUM WALLBOARD (LAMINATED)	50

Floor sound transmission

IIC = Impact Insulation Class

Minimum IIC recommended for residential buildings

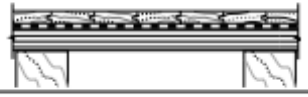
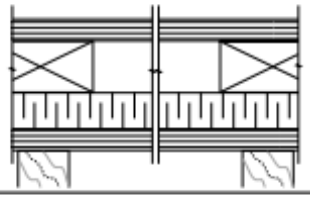
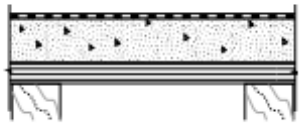
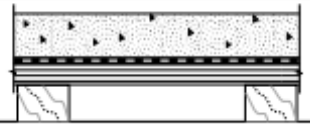
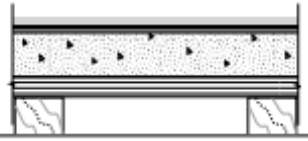
Table 1. Approximate IIC ratings for a 150-mm-thick concrete slab with various kinds of toppings. (Only part of the basic assembly is shown.)

Table 1		Topping	IIC
I-1		None, or ceramic or marble tiles	28
I-2		Vinyl flooring	35-40
I-3		Hardwood flooring	30-35
I-4		9-mm-thick hardwood on 6-mm-thick resilient layer	45-50
I-5		16-mm plywood or OSB on 40- x 90-mm wood strapping on 25-mm mineral fibre board	50-55
I-6		35-mm concrete on 25-mm mineral fibre board	60-65
I-7		Carpet and underlay	75-85

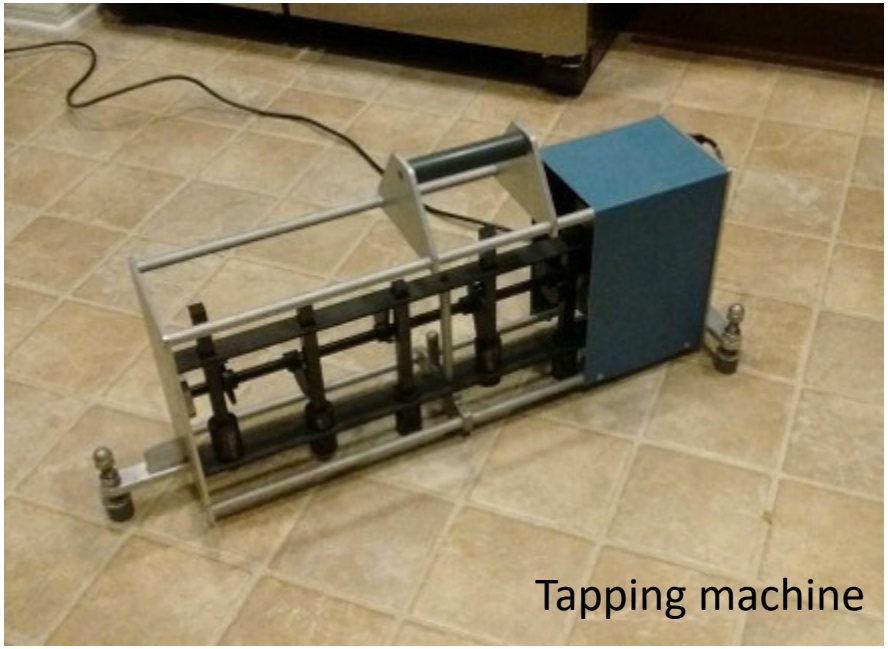
https://www.nrc-cnrc.gc.ca/ctu-sc/files/doc/ctu-sc/ctu-n35_eng.pdf

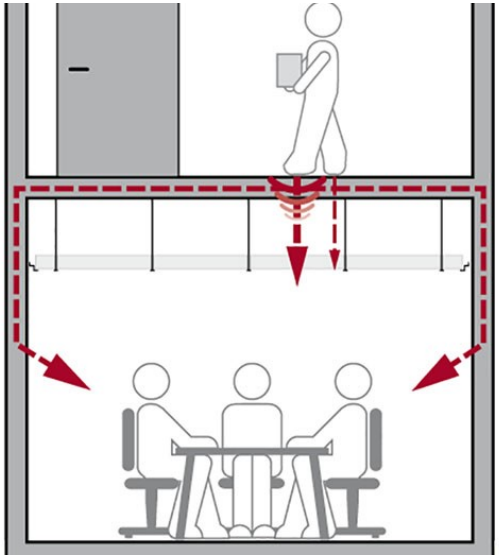
IIC for wood floors

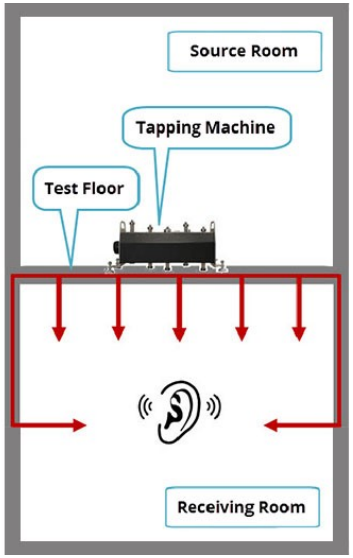
Table 2. Approximate IIC ratings for a basic joist floor (IIC 45) with different floor toppings. (Only part of the basic assembly is shown.)

Table 2		Topping	IIC
II-1		Ceramic or marble tiles	40
II-2		Vinyl flooring	47
II-3		Hardwood flooring	47
II-4		9-mm-thick hardwood on 6-mm-thick resilient layer	47
II-5		16-mm plywood or OSB on 40- x 90-mm wood strapping on 25-mm mineral fibre board	55-58
II-6		Resilient flooring on 35-mm concrete	52
II-7		35-mm concrete on resilient layer	55-65
II-8		Carpet and underlay	75-85
II-9		Carpet and underlay on 35-mm concrete	>85

Testing impact noise

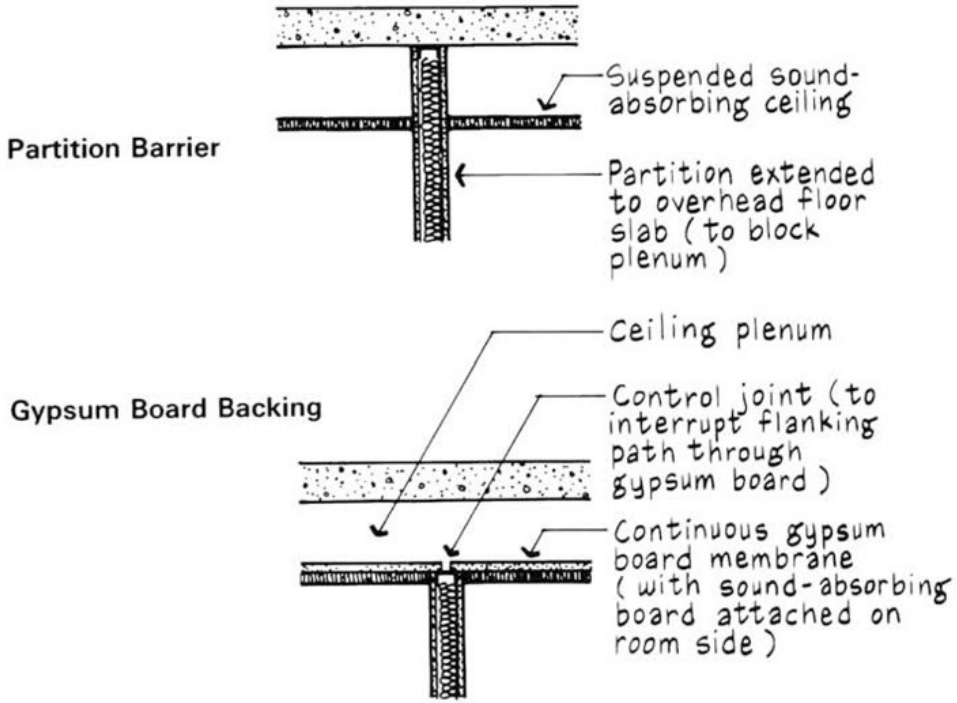


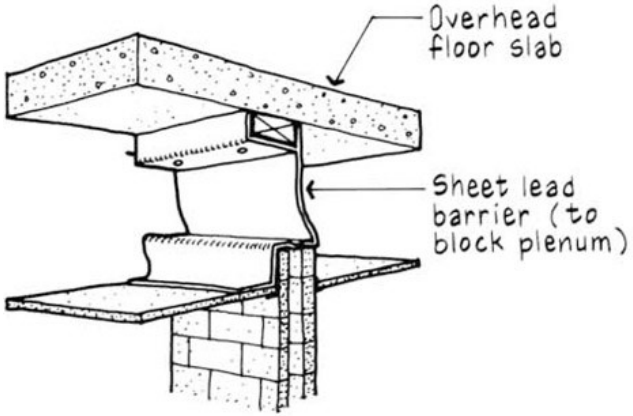




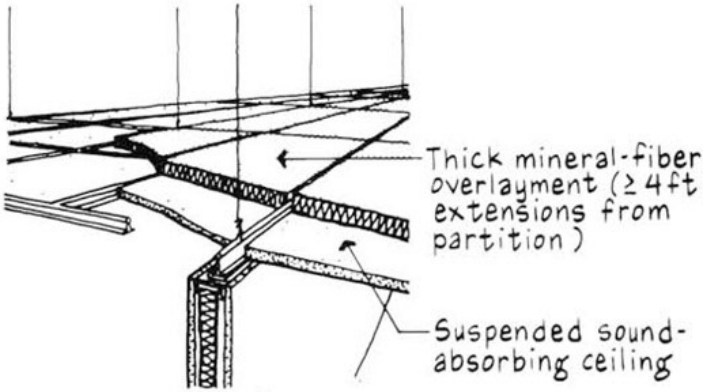
Demonstration of tapping machine:
https://www.youtube.com/watch?v=BzYUW8k4NHA

Plenum barriers





Sheet Lead (or Vinyl) Barrier

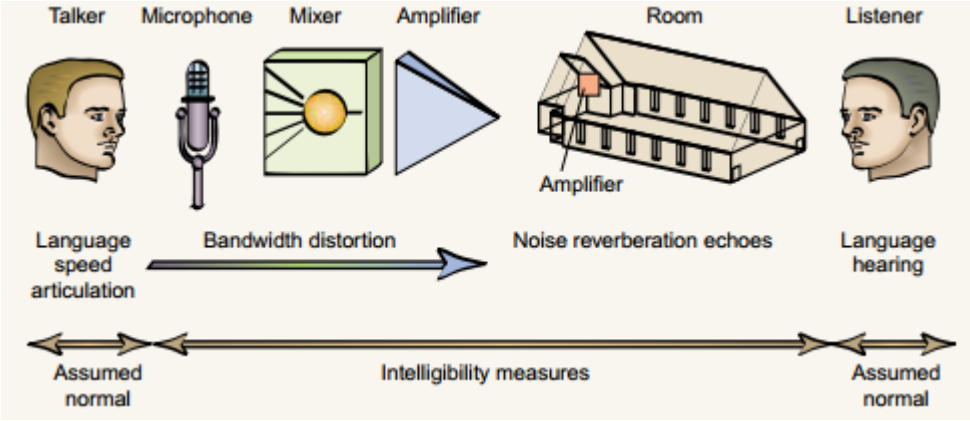


Mineral-Fiber Overlayment

Speech Intelligibility Index (SII)

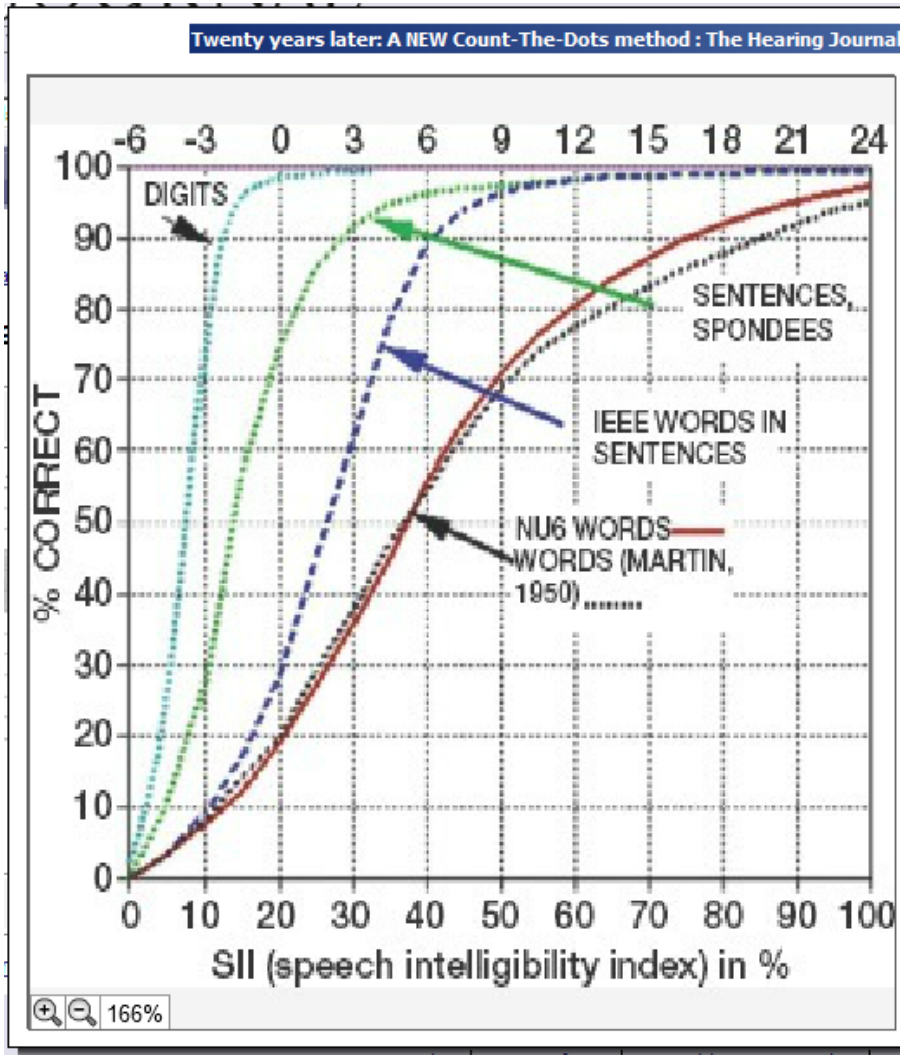
- An indication of the ability for spoken words to be heard and understood in a room.
- 0 means unintelligible; 1 means perfect clarity
- It indicates the signal-to-noise ratio, but is quite complicated to calculate.
- Factors include: speech loudness, background noise, reverberation time/echoes, etc.
- Details here, for the curious:

http://dare.uva.nl/document/2/45240



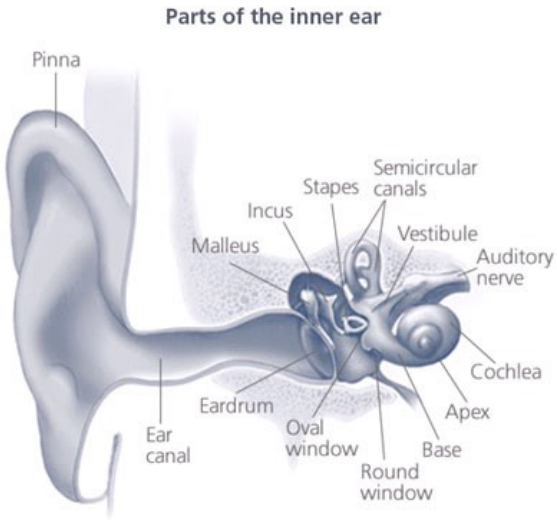
Speech Intelligibility Index (SII)

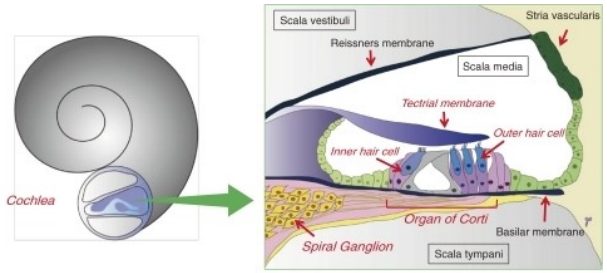
- SII indicates the fraction of "speech cues" that are heard correctly.
- Our brains are able to fill in some gaps; so % of correct words understood is higher than SII.

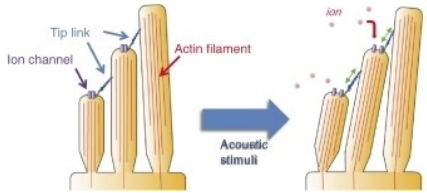


Hearing Damage/Noise-Induced Hearing Loss (NIHL)

- About 3% of the population suffers from NIHL
- 12% of population has some sort of hearing loss
- Hearing loss is an increasing problem because of exposure to noise from work (e.g., machinery) and recreation (e.g., music, hunting)
- Cause: chronic loud noise damages tiny hair cells called stereocilia







Safe limits to noise

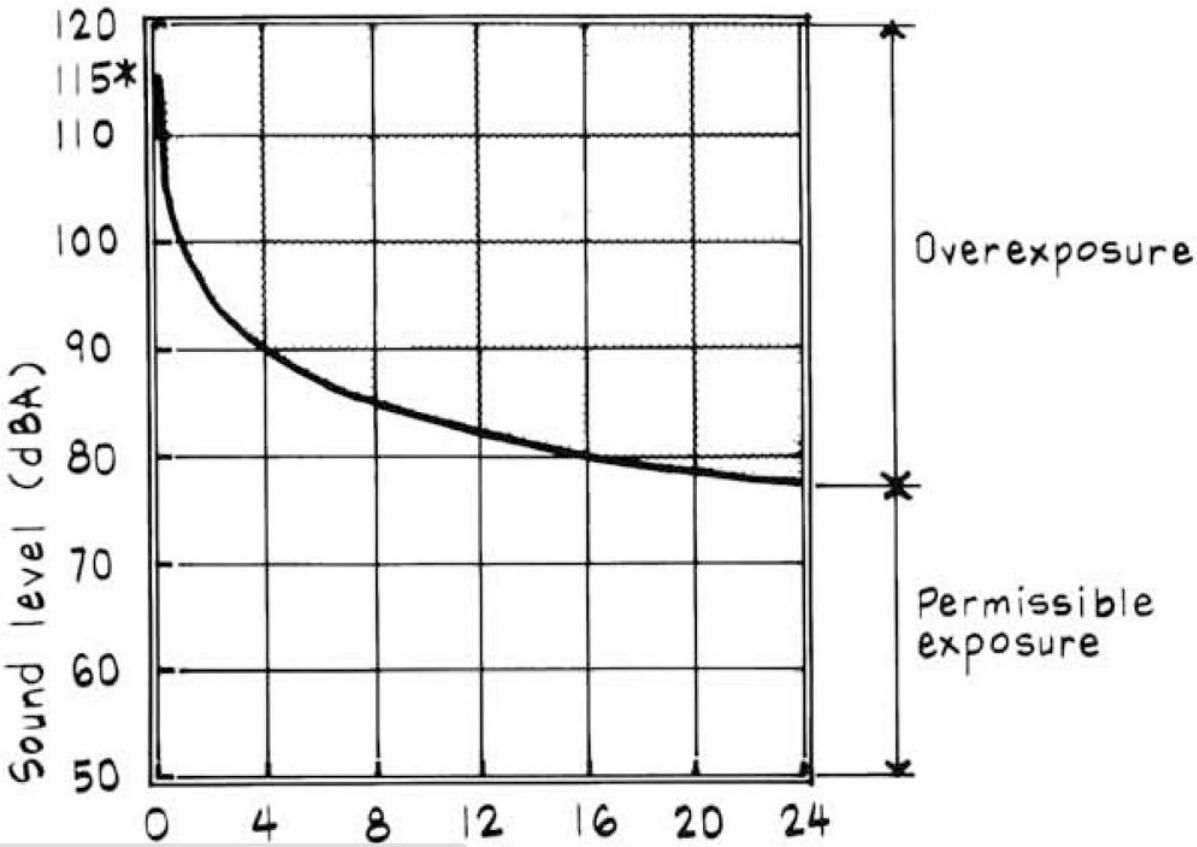
- Safe limits depend on exposure
- Remember that a change of 3 dB in SPL means a halving/doubling of sound pressure.

Canada Labour Code, Part II, (R.S.C. 1985, c. L-2)
Canada Occupational Safety and Health Regulations, (SOR/86-304)
Section 7.4(1)(b)

Quebec has a limit of 87 dB; the Federal limit is 90 dB.

3 dB(A) Exchange Rate Allowable Level dB(A)	Maximum Permitted Daily Duration (hours)	
85	8	Beside busy road
88	4	
91	2	
94	1	10 m from diesel truck
97	0.5	
100	0.25	1 m from speaker at dance club

Noise exposure limits



Music Professor Sues Smashing Pumpkins Over Hearing Loss

A Princeton University professor of music is suing members of the Smashing Pumpkins, claiming that he sustained permanent hearing damage after attending a Smashing Pumpkins concert. Peter Jeffrey, who specializes in Gregorian chants and folk music, attended the Pumpkins' show, his first rock concert, at Connecticut's New Haven Coliseum in January 1997. The 45-year-old professor, who

Smashing Pumpkins

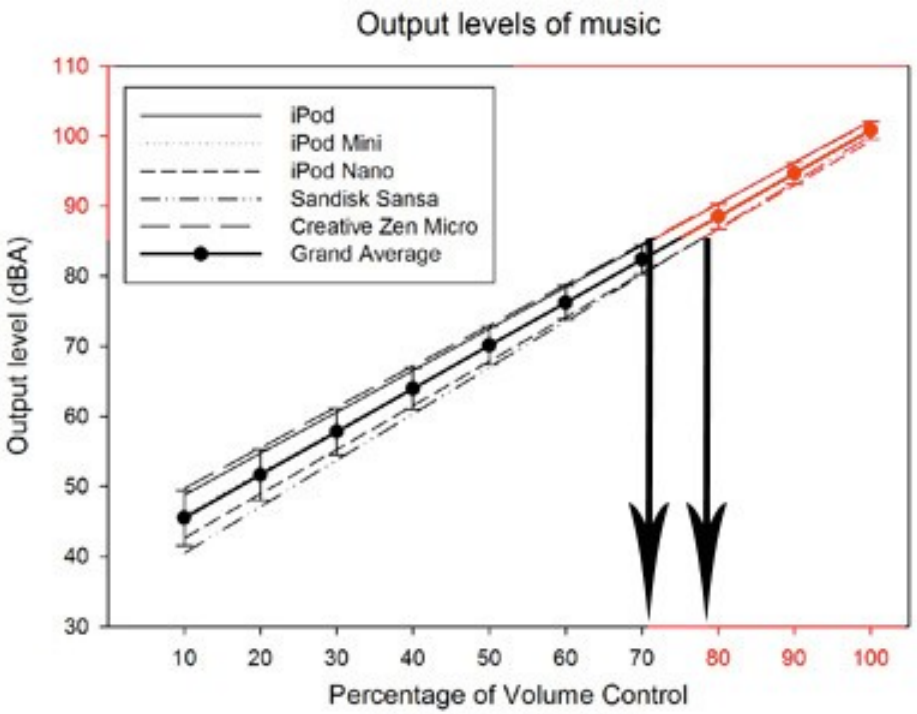
Ear protection

- Ear plugs are cheaper, easier, less hot than earmuffs, but may provide less protection – especially at SPL > 105 dB(A)
- Effective noise level (ENL)

  = SPL (in dB(A)) – derated NRR (noise reduction rating)

Maximum protection provided by non-continuous use of Hearing Protection	
Percent time used	**Maximum Protection**
50%	3 dB
60%	4 dB
70%	5 dB
80%	7 dB
90%	10 dB
95%	13 dB
99%	20 dB
99.9%	30 dB

Loud Music



(Fligor and Portnuff, 2006)

Figure 1. Free-field equivalent output levels of 5 MP3 players, using stock earphones, as a function of volume control settings. The Grand Average is the mean of all music genres across all players. Error bars represent 1 standard deviation around the Grand Average.

MAXIMUM iPOD LISTENING TIME PER DAY GUIDE
(Table Based on Figor and Portnuff, 2006)

% of Volume with Headphones	
100	5 Minutes
90	18 Minutes
80	1.2 Hours
70	4.6 Hours
60	18 Hours
10-50	No Limit

A-B-Cs of Building Acoustics

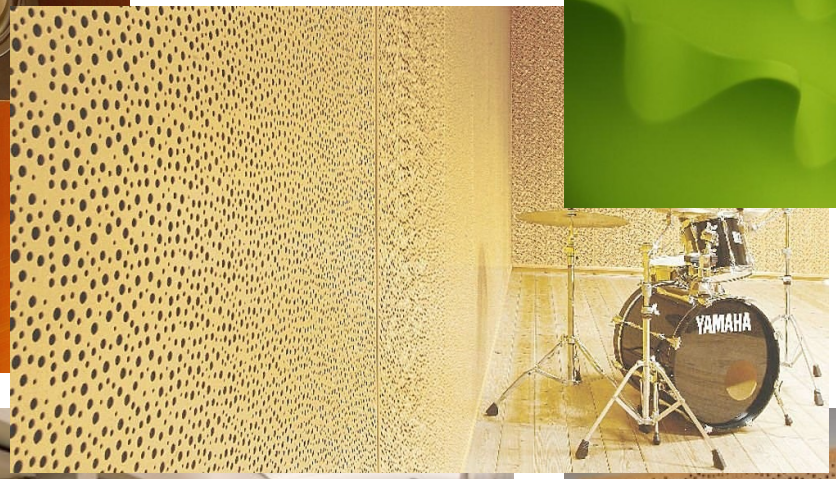
Given that a source exists and that personal ear protection is not an option, there are three options for mitigation:

1. **A**bsorb (use absorptive materials)
2. **B**lock (isolate sound)
3. **C**over/mask (e.g., white noise)

Design Strategies

At least one absorptive surface in each room should be used.

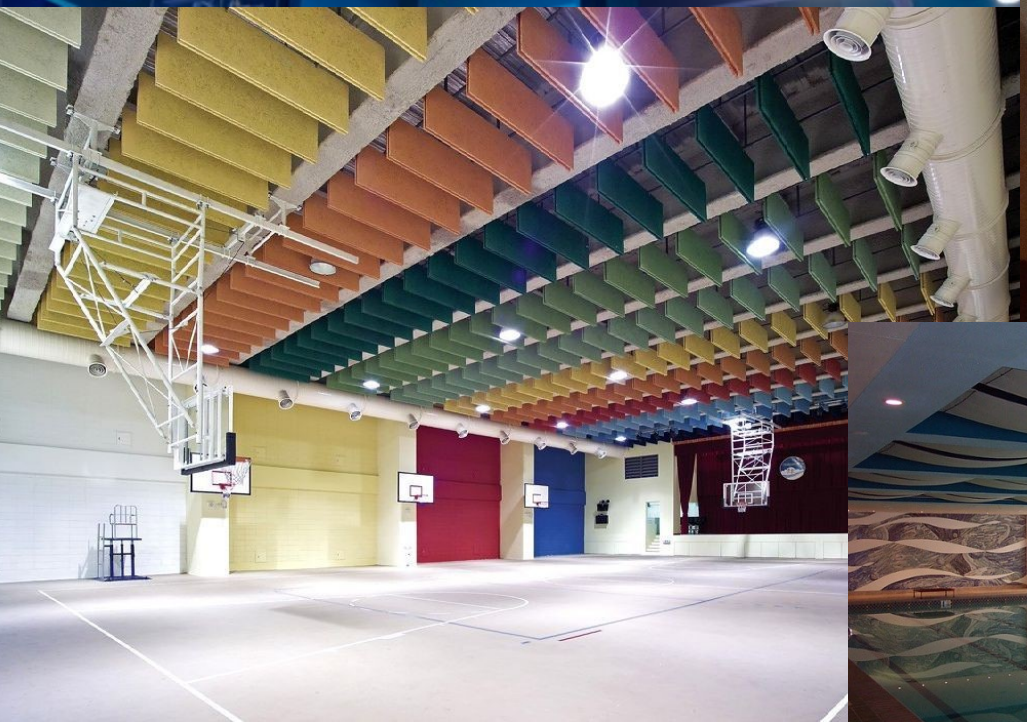
Sound absorbing concepts



UPPER
CANADA

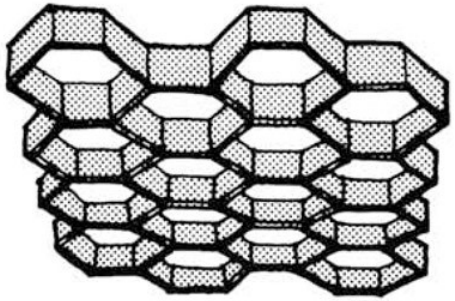
HOT! NEW!
Materials just arrived!
kyyrö quinn

Ceiling treatments

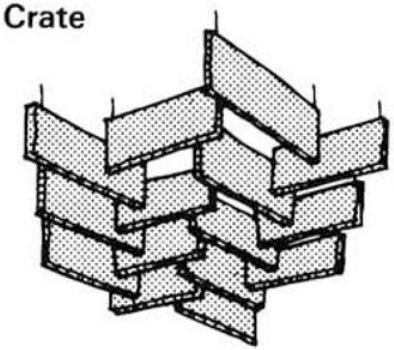


Parallel

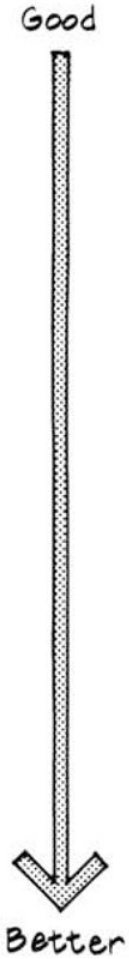
Honeycomb



Egg Crate

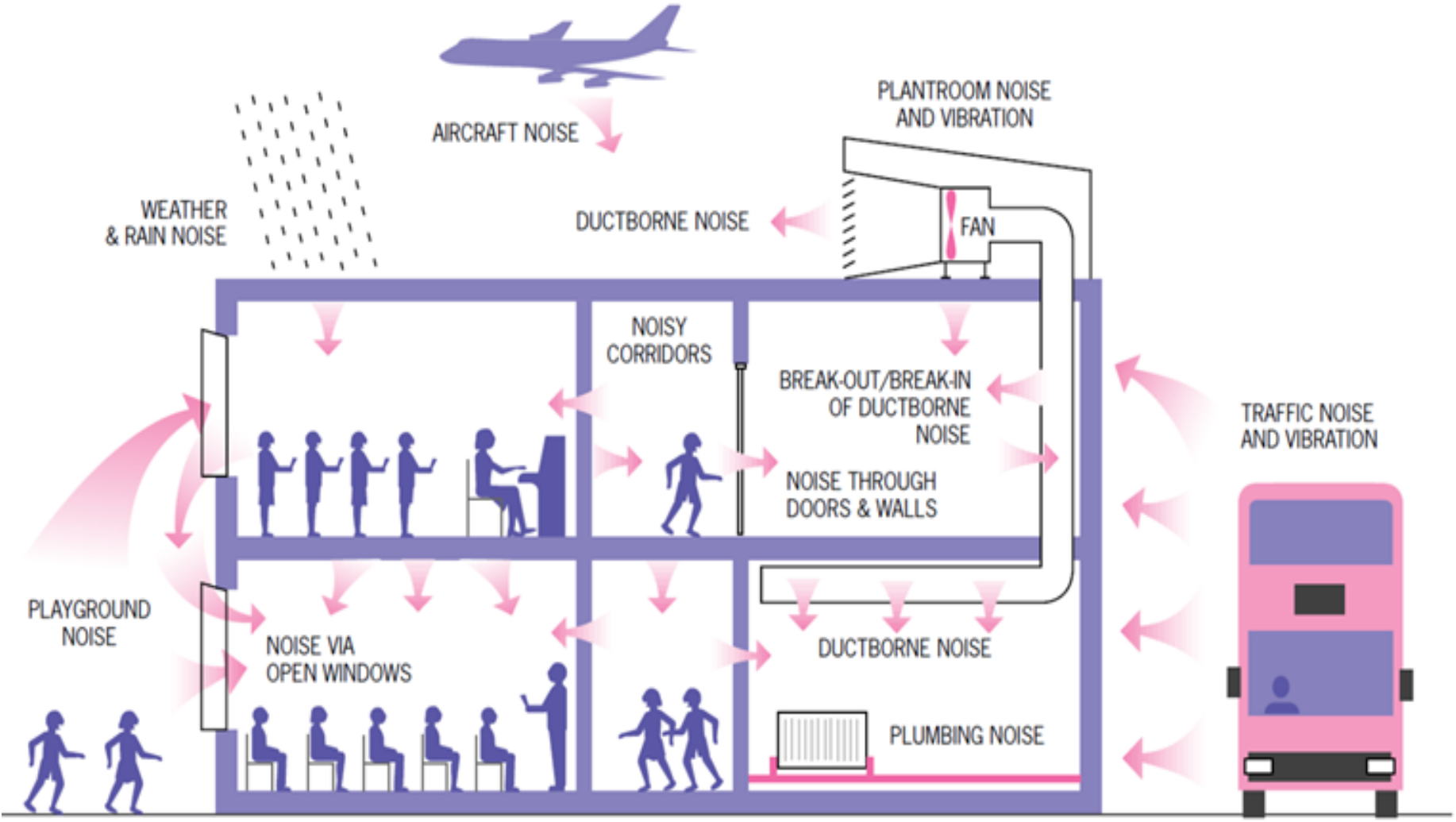


Sound Absorption Efficiency



Floor treatments

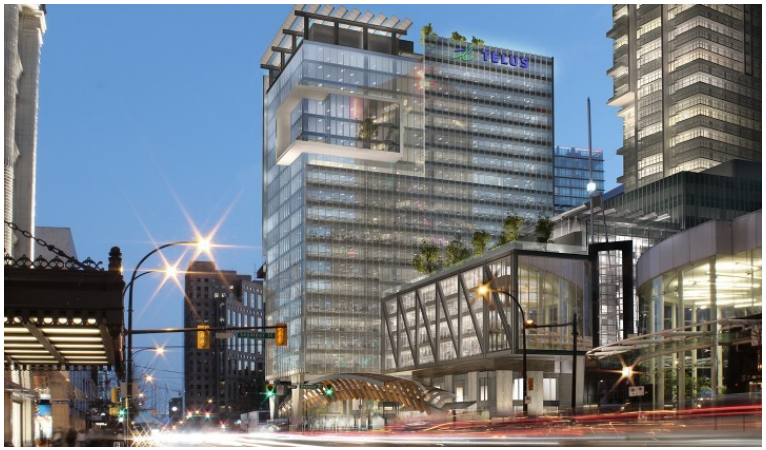
Sound isolation concepts

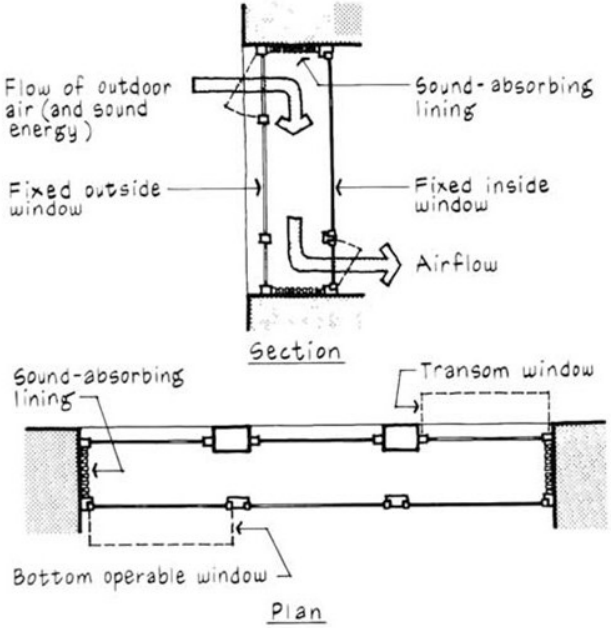


Source (e.g., traffic) → Path (e.g., through a wall) → Receiver (e.g., ear)

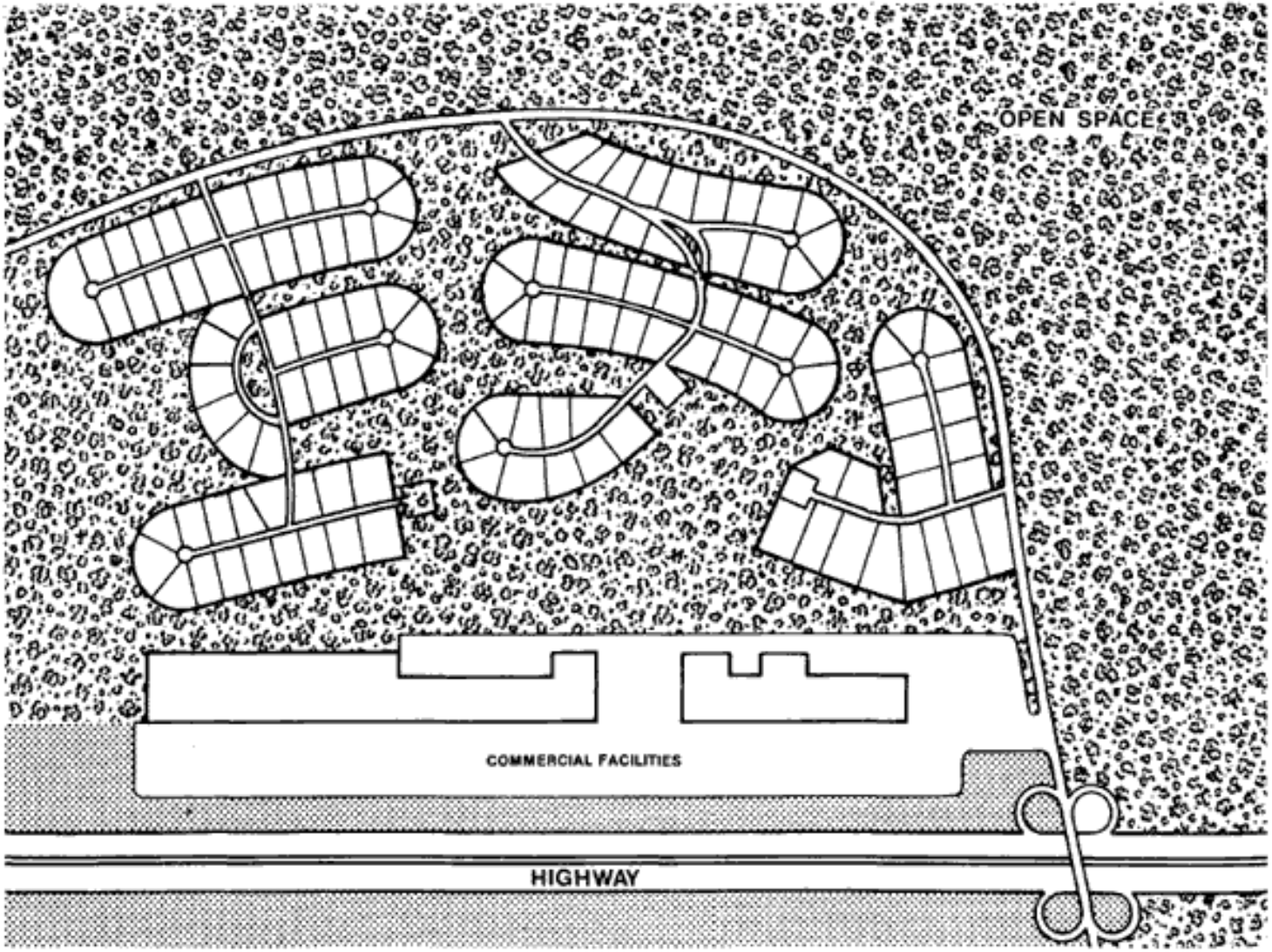
Double-skin Facades

- Urban areas tend to be noisy and no natural ventilation (open windows) comes at the cost of noise. One solution is “double-skin facades”.

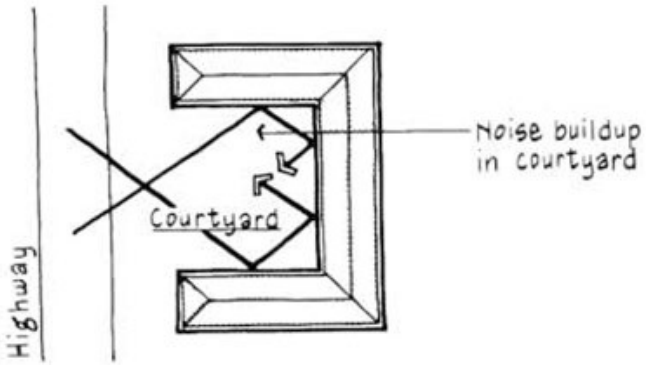


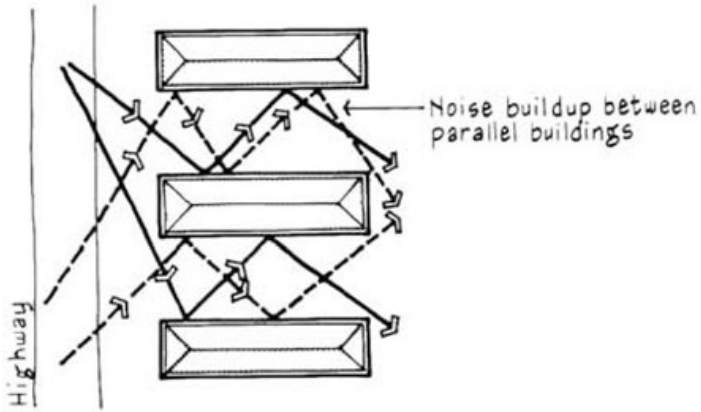


Locate residential away from highway

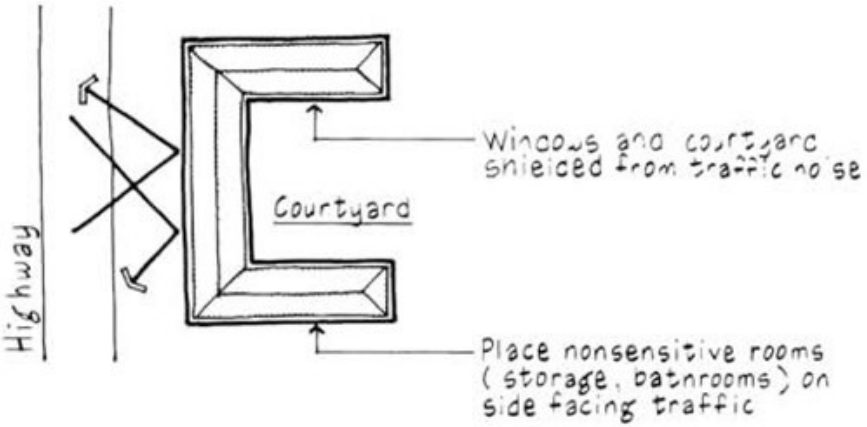


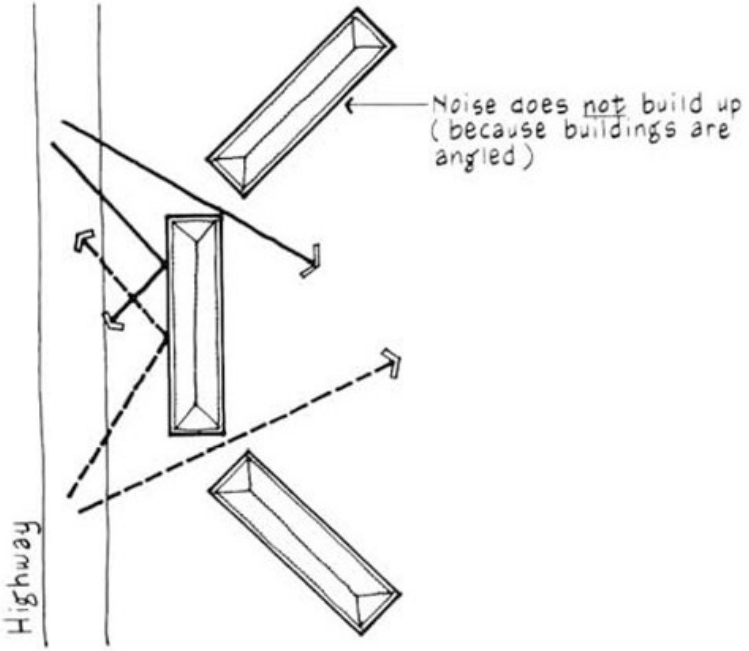
Poor


Highway
Courtyard
Noise buildup in courtyard

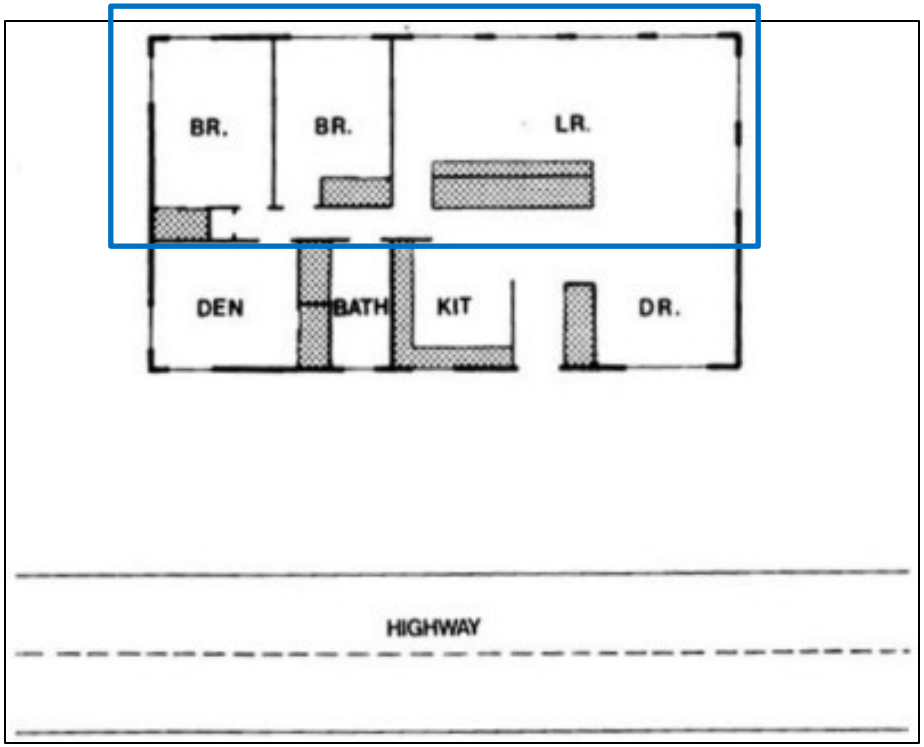

Highway
Noise buildup between parallel buildings

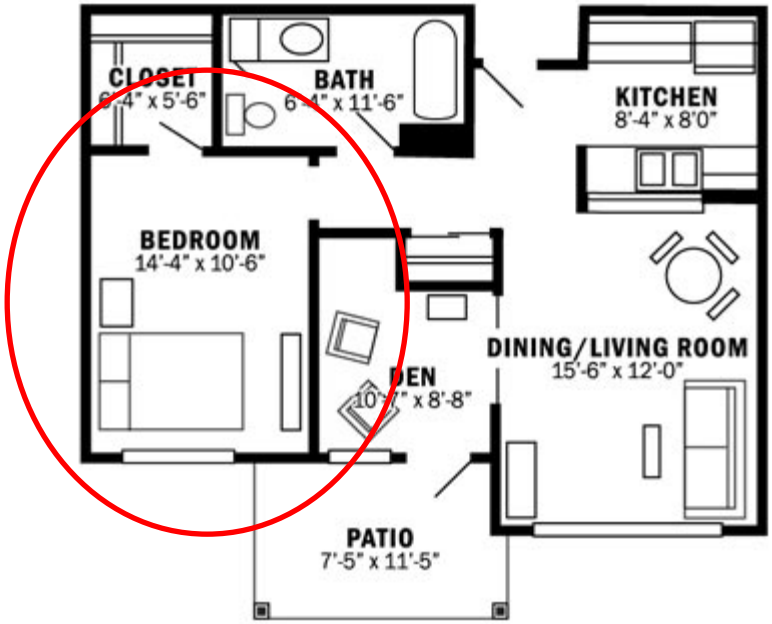
Better


Highway
Courtyard
Windows and courtyard shielded from traffic noise
Place nonsensitive rooms (storage, bathrooms) on side facing traffic

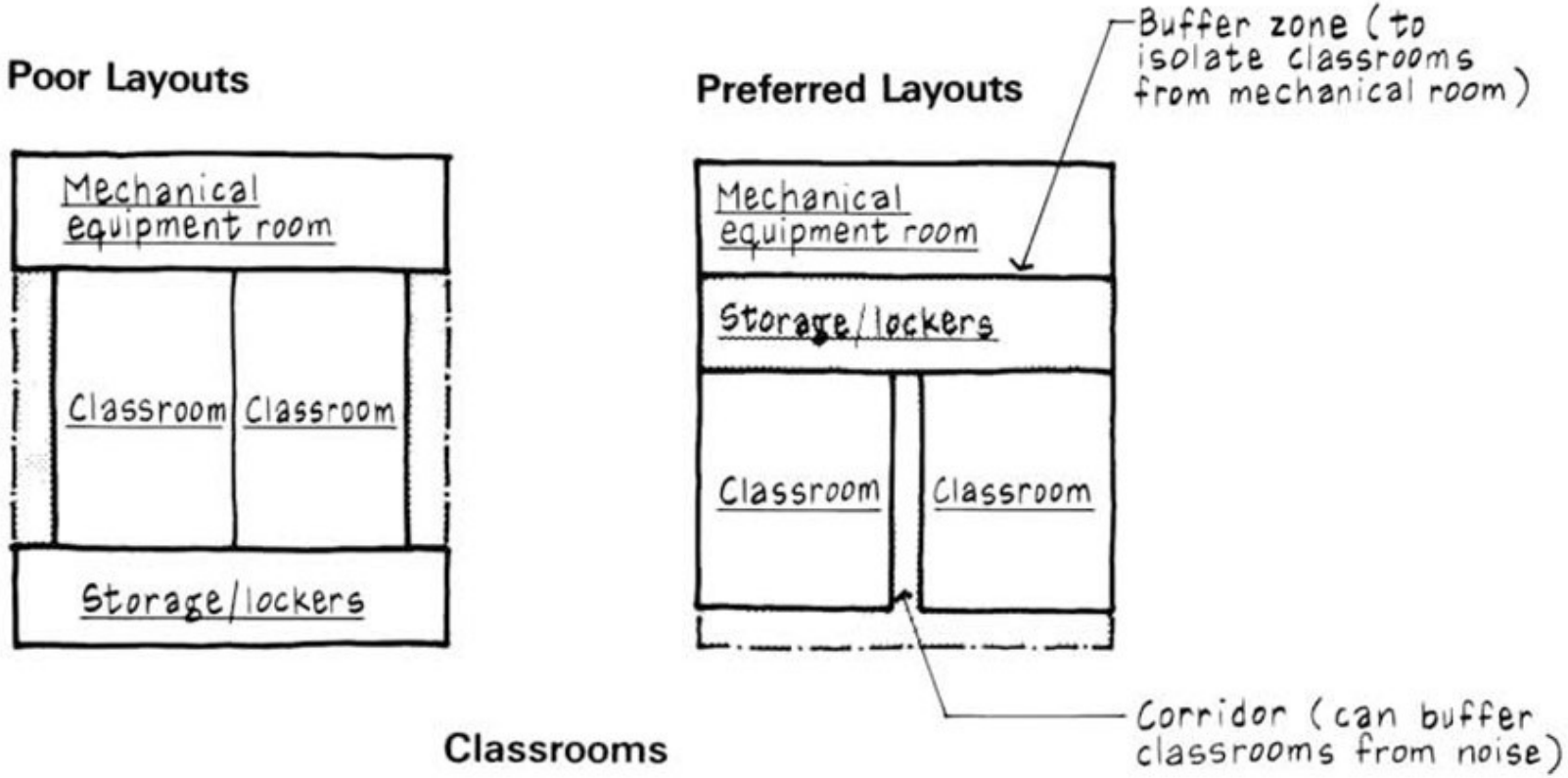

Highway
Noise does not build up (because buildings are angled)

Home layout for acoustics

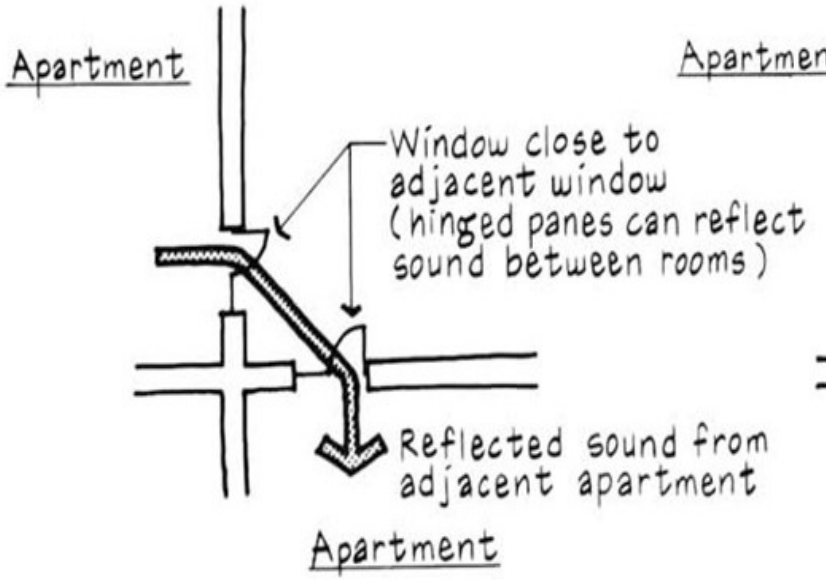




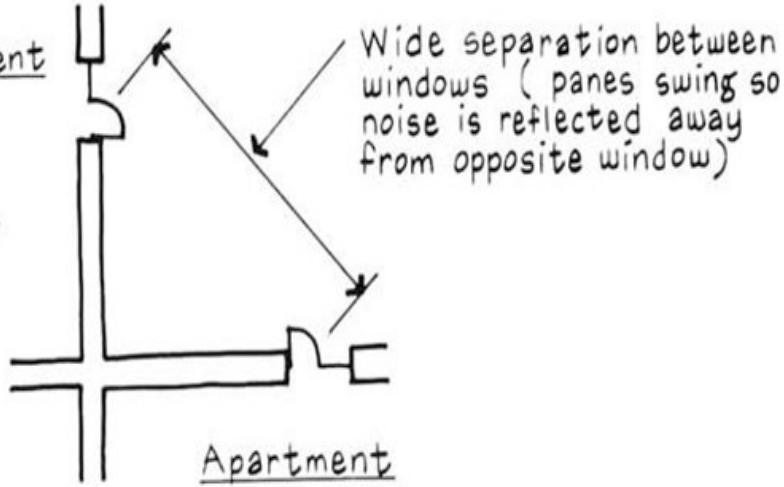
Space layouts for acoustics



Window placement



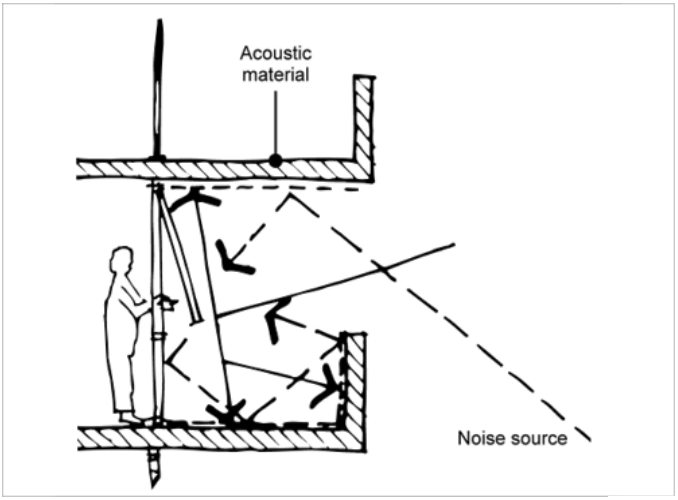
Poor Window Layout

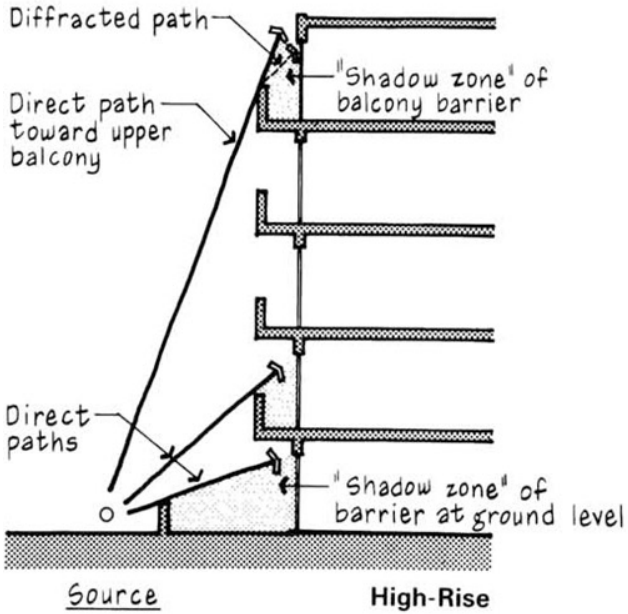


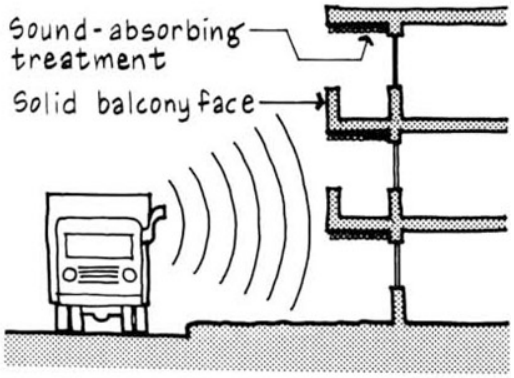
Preferred Window Layout

LIBERTYVILLAGECONDO.COM

Balconies and sound



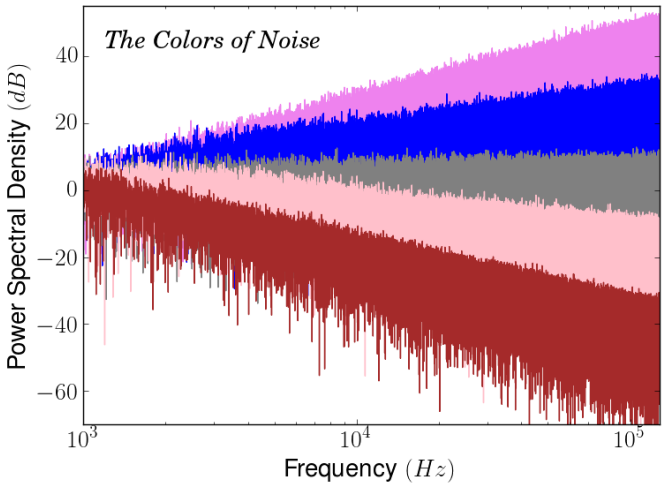




Balcony Protection

Sound making (Cover)

- **White noise** has a continuous frequency spectrum with equal energy per hertz over a specified frequency range. Because octave bands double in width for each successive band, for white noise the energy also doubles in each successive octave band. Thus white noise displayed on a 1/3 octave or octave band chart increases in level by 3 dB per octave.
- **Pink noise** has a continuous frequency spectrum with equal energy per constant-percentage bandwidth, such as per octave or 1/3 octave band. Thus pink noise appears on a 1/3 octave or octave band chart as a horizontal line.
- **Red noise** has a continuous frequency spectrum with octave band levels that decrease at a rate of 4 to 5 dB per octave with increasing frequency. Red noise is typical of noise from well-designed HVAC systems.



(ASHRAE 2013)

Samples here: https://en.wikipedia.org/wiki/Colors_of_noise

Standards on acoustics

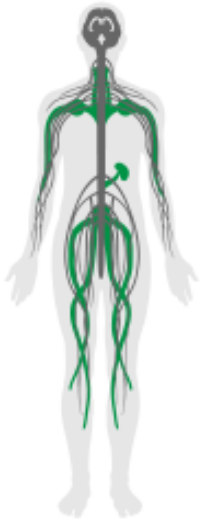
- LEED: http://www.usgbc.org/credits/eq10
- WELL: https://www.wellcertified.com/standard

WELL on Sound Masking

SOUND MASKING

Ambient silence can be just as distracting as a loud environment as it highlights acoustical disturbances and decreases speech privacy. Overhearing private conversations is reported as a specific cause of employee acoustic dissatisfaction in open offices. Sound masking systems supply a low level of background noise to provide workers with a degree of confidentiality in their communications and can decrease distraction associated with aural interruptions.

This feature aims to mitigate uncomfortable acoustic disruptions and increase speech privacy by providing low background noise through the use of sound masks.



Immune
Nervous

	Core and Shell	New and Existing Interiors	New and Existing Buildings
PART 1: SOUND MASKING USE	-	O	O
PART 2: SOUND MASKING LIMITS	-	O	O

PART 1: SOUND MASKING USE

All open workspaces use the following:

a.[90] Sound masking systems.

PART 2: SOUND MASKING LIMITS

If sound masking systems are used, sound levels fall within the following range, when measured from the nearest workspace:

a.[90] Open workspaces: 45 - 48 dBA.

b.[90] Enclosed offices: 40 - 42 dBA.

WELL on Sound reducing surfaces

SOUND REDUCING SURFACES

Proper design and construction are not always enough to achieve acoustic comfort in buildings. Sources that contribute to acoustic dissatisfaction such as sound transmission from internal and external sources, footfall noise and voices from adjacent spaces are difficult to control. However, sound reduction treatments that incorporate absorptive surfaces such as wall panels, ceiling baffles and surface enhancements can help with reverberation management and improve acoustic comfort.

This feature requires spaces to incorporate absorptive surfaces in order to reduce unwanted noise reverberation. The noise reduction coefficient (NRC) is an average value that determines the absorptive properties of materials. The larger the NRC value, the better the material is at absorbing sound under standardized conditions.

Cardiovascular
Endocrine
Nervous

	Core and Shell	New and Existing Interiors	New and Existing Buildings
PART 1: CEILINGS	-	O	O
PART 2: WALLS	-	O	O

The following spaces, if present, have ceilings that meet the specifications described:

a.[90] Open workspaces: minimum NRC of 0.9 for the entire surface area of the ceiling (excluding lights, skylights, diffusers and grilles).

b.[90] Conference and teleconference rooms: minimum NRC of 0.8 on at least 50% of the surface area of the ceiling (excluding lights, skylights, diffusers and grilles).

The following spaces, if present, have walls that meet the NRC specifications described:

a.[90] Enclosed offices, conference and teleconference rooms: minimum NRC of 0.8 on at least 25% of the surface area of the surrounding walls.

b.[90] Open workspaces: minimum NRC of 0.8 on at least 25% of the surface area of the surrounding walls.

c.[90] Partitioned office spaces: partitions reach at least 1.2 m [48 inches] and have a minimum NRC of 0.8.

Example Auralization

- Auralization is the acoustic equivalent to daylight rendering
- https://www.youtube.com/watch?v=zUYdCTdkWdg