10 ROOM ACOUSTICS

10.1.1 External Noise Climate

The external sound environment is clearly one of the factors that we need to consider when designing our buildings. This is not only because it is going to be a factor in the design of the building itself, but also because there are many instances where the external areas surrounding a building are used by occupants. Thus a garden is an important area for many dwellings and it may lose some of its amenity if it is subject to loud continuous noise. School playgrounds may be less useful if they are exposed to a loud background noise, and they may themselves be a significant source of noise in a quiet neighbourhood.

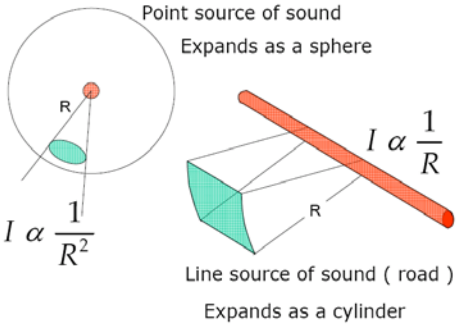


Figure 10.1 propagation of

Any sound will have to travel from its original source to the building. The nature of the sound source will be a factor in how quickly the sound source reduces in intensity as the sound travels. A sound source such as a squeal of breaks or that of a lorry accelerating away from a roundabout will be effectively a point source of sound. The intensity from such a point source will reduce as the square of the distance from the source. This is because the sound spreads as an expanding sphere centred on the source, and the area of the sphere increases as the square of the radius as is shown in Figure 1. However, a succession of cars and lorries travelling along a motorway will be effectively a line source of sound. Such a sound source will radiate sound as an expanding cylinder and therefore the intensity will reduce in relation to the distance from the source as also is shown in Figure 1. This means that the sound from the line source will carry for much greater distances than that from a point source of sound.

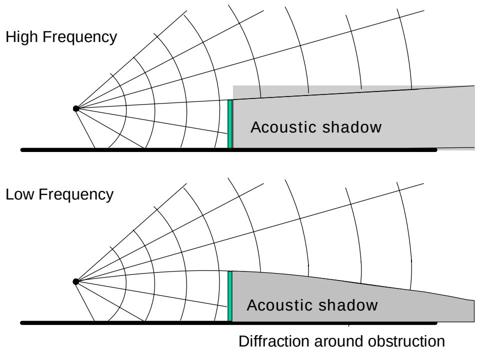


Figure 10.2 diffraction of sound

Putting distance between the user and the sound source is one way of reducing the effect of the noise, but it is possible to also make use of barriers to reduce the sound around a building. However, the effectiveness of barriers may be undermined by the phenomenon of diffraction. Diffraction is the process by which wave phenomena bend around corners as is shown diagrammatically in Figure 2. Thus, although a building might not be in direct sight of a sound source, because of diffraction around an obstruction, the façade may still experience significant levels of noise. Barriers may be specially built constructions or they may be part of the site development itself as shown in Figure 3, where blocks of flats are used to shield outside areas from the noise of passing trains.

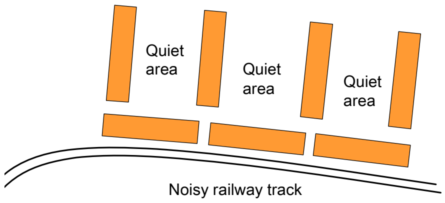


Figure 10.3 Shielding noise

A continuous noise of moderate level might be more acceptable to people than a spasmodic noise that occurs without warning. People may get used to a continuous noise and make allowances for it, but they can not prepare for unexpected sounds. Thus the nature of one sound might be more annoying than another. Because of this there is a need to be able to characterise the variability of different sounds.

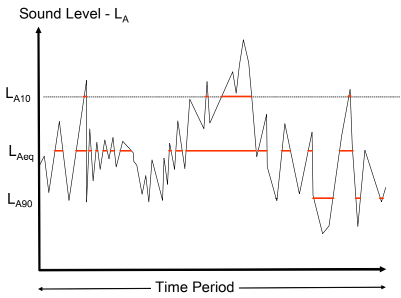


Figure 10.4 variability of sound

This can be done by using one of a number of different measures to characterise the sound in the environment. Some of these are listed in Figure 4. A continuous sound is best characterised by an average sound level, whereas a sound that is increasingly intermittent is better characterised by a measure of the level exceeded for ever shorter periods of time.

10.1.2 Planning

Within a particular site it is therefore beneficial to consider:

placing buildings as far as possible from a noise source,

ii) using screens to limit the direct sound to the façade,
iii) using buildings themselves to create an acoustic shadow on site,
iv) using noisy areas to shield quiet areas.

These general principles may also be applied to the overall planning of the building itself:

i) grouping noisy areas together and away from quiet areas,
ii) putting distance between areas of different sound environments.

Additionally it is worthwhile considering separately the two modes of noise propagation;

10.1.3 Air borne sound,

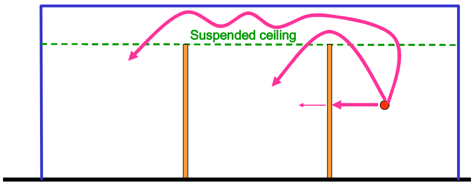


Figure 10.5 Loss of sound insulation

i) Air borne sound requires air paths. Holes in partitions, gaps between different forms of construction and open windows allow the free passage of air and of sound waves across structural boundaries.

   It is important to recognise that there are often sound paths that are not immediately apparent. Thus in Figure 5 the void above a lightweight false ceiling can act as a sound path across heavy weight partitions, and in Figure 6 the air route through ductwork can similarly act to transmit sound between rooms and from noisy to quiet areas. This additional sound path to the direct route is sometimes called flanking.

ii) Distance will diminish the intensity of sound and circuitous routes will also provide opportunities for the sound to be absorbed along its route.

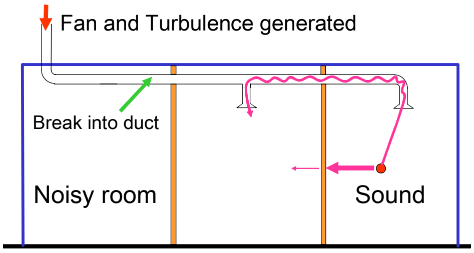


Figure 10.6 Loss of sound insulation

iii) The surface of a partition or structure needs to be moved in order for the sound energy to enter into the structure. A thin light flexible structure is easily flexed and sound energy thus can easily enter into it. However, the stiffer a structure is then the more difficult it is for the compressible air to move the surface of the structure. Thus the sound insulation of a partition is primarily determined by the surface mass of the partition.

The sound loss across a partition is given by the Sound Reduction Index (SRI) that will be defined later. Theoretically the SRI for a single partition is given by,

$$SRI = Constant + 20 \times log_{10}(m \times f)$$

Where, m is surface mass in kg/m² and f is frequency.

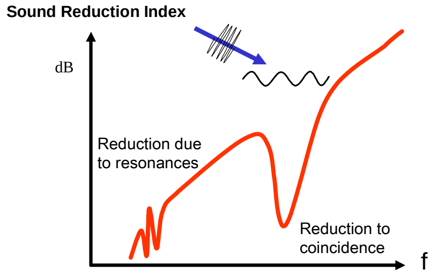


Figure 10.7 Deviation from Mass Law

However, this theoretical relationship is compromised by the different modes of vibration that can transmit sound through a partition as is shown in Figure 7. At low frequencies the panel itself might resonate and therefore transmit sound, whilst at higher frequencies, obliquely incident sound can instigate flexural waves that also allow energy to enter into the panel and therefore transmit sound to the other side of the panel. Thus the sound transmission through and across structures is really rather complex and may need careful thought to predict accurately. This will be covered in acoustics courses in later years.

Keep this in mind when using the much simplified method given above. Where information is available, it is more practical to use curves based upon experience to determine the SRI of a single layer of structure. A simplified curve which is generally applicable for frequencies between 100 Hz and 3000 Hz is shown in Figure 8.

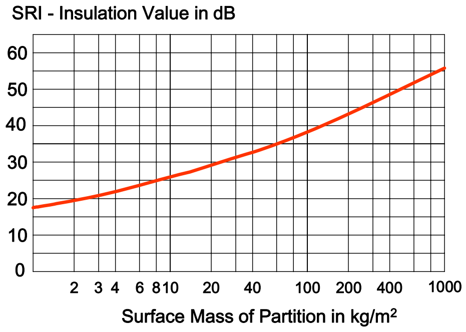


Figure 10.8 Practical Values of Mass Law

10.1.4 Structure borne sound.

i) For structure borne sound to be a problem, the sound must first enter into the structure. The first task is therefore to avoid or minimise the degree to which sound enters into the structure. This is done by ensuring that machinery that is noisy is isolated from the structure by using isolation mountings as shown diagrammatically in Figure 9.

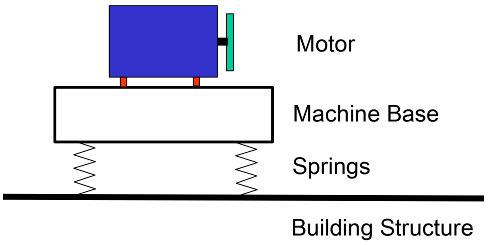


Figure 10.9 Isolate source from structure

The difficulty of isolating heavy machinery from structural floors may be a contributory factor in choosing to locate heavy vibrating machinery on the ground floor. The presence of vibrating machinery in a building may also affect the choice of structural system.

Private offices, libraries	< 47 dBA
Lecture theatres, meeting rooms	< 42 dBA
Bedrooms at night	< 35 dBA

Figure 10.10 Limiting sound levels

ii) Structure borne sound does not decay easily because in a rigid structure there is little flexing to absorb and dampen the sound. Therefore the noise path has to be broken in order to prevent the propagation of the sound. This will of course create a break or gap in the structure. Structurally this might be inconvenient and therefore it needs to be considered at an early stage of the structural design. Introducing breaks in the structure at a late stage of construction can be costly.

Ensuring that structural breaks are not bridged may require considerable thought being put into constructional details. Even connecting separated structures by a single bolt can cause a breakdown of the isolation.

iii) Where sound is transmitted across a partition, it must necessarily have entered into the structure. A continuous structure may then transmit that structural sound which can then be radiated into a room via an adjacent wall as is shown in Figure 9A. This process is also sometimes called flanking.

Air-borne sound

Mass law – surface density of enclosure
Air gaps around joints as small as possible
Avoid weak links such as flanking

Structure-borne sound

prevent entering structure
break the sound path
consider structure borne flanking

Figure 10.11 Limiting sound levels

In terms of planning the building layout, the main objective is to control the level of sound and vibration that enters into particular spaces. This sound may arise from noise in the external environment or from activities within the building that themselves generate noise. Some rooms require quiet whilst in others the ambient sound level is not so critical. Figure 10 gives the background noise level appropriate in a number of situations.

10.1.5 Noise Transmission

Figure 11 summarises aspects of noise transmission in buildings.

The sound insulation required by a partition may be found quite easily by subtracting the required sound level from the sound level on the other side of the partition as shown in Figure 12.

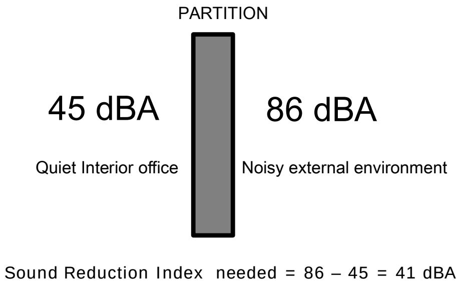


Figure 10.12 Sound Reduction Index

The sound insulation provided by a partition is called the Sound Reduction Index of the partition and is defined as:

$$SRI = 10\log_{10}\left(\frac{1}{\tau}\right) \; dB = -10\log_{10}(\tau) \; dB$$

Where, τ is the Sound Transmission Co-efficient which is itself defined as:

$$\tau = \frac{\text{sound power transmitted}}{\text{incident sound power}}.$$

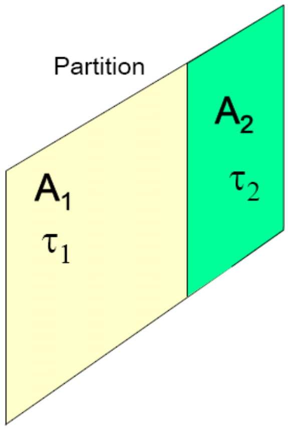


Figure 10.13 Two materials in panel

Where a panel between two rooms comprises a number of different materials e.g. a door within a partition, or a window within a wall, then there are a number of parallel paths that the sound might take. This can be taken into account by using the average sound transmission co-efficient. This is an area weighted average sound transmission co-efficient and where there are two materials making up the panel as shown in Figure 13,

$$\tau_{Average} = \frac{A_1 \times \tau_1 + A_2 \times \tau_2}{A_1 + A_2}.$$

It should be noted that this is an average of power transmission coefficients. The properties of particular materials are given in terms of the Sound Reduction Index measured in decibels and these need to be converted into sound transmission coefficients in order to calculate the average value of τ. Using the definition of the Sound Reduction Index given earlier:

$$\begin{aligned} -10log_{10}(\tau) &= SRI\ dB \\ log_{10}(\tau) &= -\frac{SRI}{10}\ dB \\ \tau &= 10^{-\frac{SRI}{10}} \end{aligned}$$

10.1.6 An example of a door within a wall

Using the example given in Figure 14 where a wall partition with a SRI of 50 dB has a door within it that has a SRI of 18 dB.

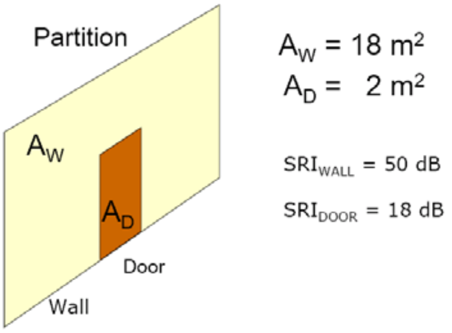


Figure 10.14 Door in partition wall

For the wall,

$$\tau = 10^{-\frac{50}{10}} = 10^{-5} = 0.00001$$

For the door

$$\tau = 10^{-\frac{18}{10}} = 10^{-1.8} = 0.01585$$

Using these two sound transmission coefficients to calculate the average $\tau_{Average}$,

$$\tau_{Average} = \frac{A_{Door} \times \tau_{Door} + A_{Wall} \times \tau_{Wall}}{A_{Door} + A_{Wall}}$$

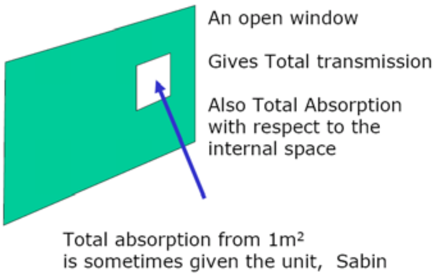
$$\begin{aligned} \tau_{Average} &= \frac{2 \times 0.01585 + 18 \times 0.00001}{2 + 18} \\ &= 0.001594 \end{aligned}$$

giving an overall Sound Reduction Index of,

$$\begin{aligned} SRI_{Overall} &= -10 \log_{10} 0.001594 = -10 \times -2.798 \\ &= 28\ \text{dB} \end{aligned}$$

10.1.7 An example of gaps in a wall

It is instructive to undertake this calculation using an open gap rather than a door. Consider a partition with a hole in it as is shown in Figure 15.



An open window

Gives Total transmission

Also Total Absorption with respect to the internal space

Total absorption from 1m² is sometimes given the unit, Sabin

Figure 10.15 Gaps in partition wall

Simplify the example by assuming the following:

The wall transmits no sound through it, so $\tau_{WALL} = 0$,

The hole transmits all sound incident on it, so $\tau_{HOLE} = 1$.

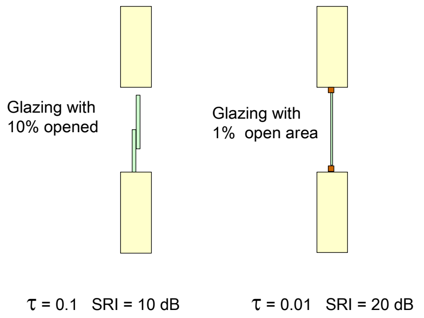


Figure 10.16 Constructions with Gaps

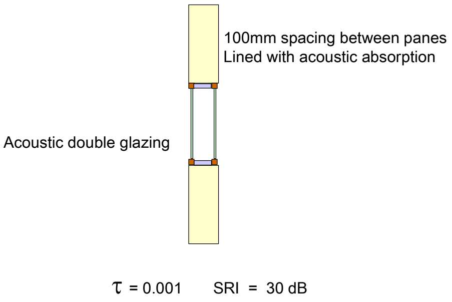


Figure 10.17 Constructions with Gaps

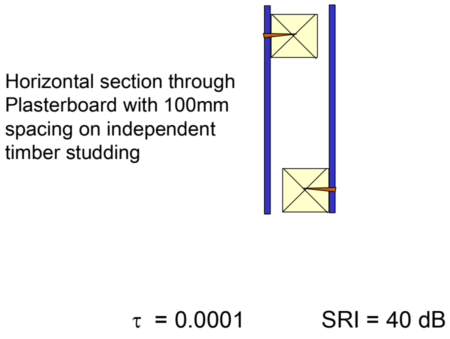


Figure 10.18 Constructions with Gaps

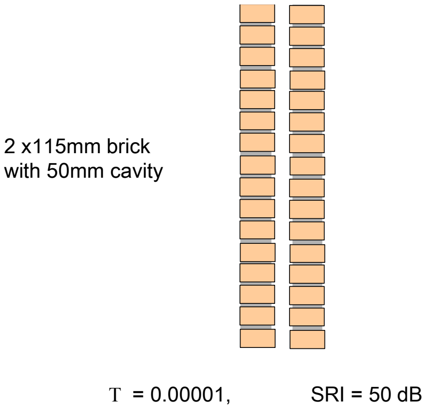


Figure 10.19 Cavity wall

Using,

$$\tau_{Overall} = \frac{A_{Wall}\tau_{Wall} + A_{Hole}\tau_{Hole}}{A_{Wall} + A_{Hole}}$$

And as the hole is small, $A_{Wall} \approx A_{Wall} + A_{Hole}$, then,

$$\tau_{Overall} = \frac{A_{Hole}}{A_{Wall}}$$

And the overall SRI is given by,

$$SRI_{Overall} = 10\log_{10}\left(\frac{A_{Wall}}{A_{Hole}}\right) \text{ dB.}$$

and using this for a number of different area ratios gives Table 1.

$\frac{1}{\tau} = \frac{A_{Wall}}{A_{Hole}}$	$SRI_{Overall} = 10\log_{10}\left(\frac{A_{Wall}}{A_{Hole}}\right)$ dB
0.1	10
0.01	20
0.001	30
0.0001	40
0.00001	50

Table 1 – SRI - Sound Reduction Indices

Figures 16 to 19 show how these relate to different constructions.

10.1.7.1Multiple layer partitions

The cavity wall construction shown in Figure 19 merits further consideration. Although it might be imagined that, as shown in Figure 20, putting an absorbing layer within the cavity would much reduce the sound transmitted through the wall, it does not in fact make a great difference. This is because the sound insulation provided by a partition is principally determined by the difficulty that the compressible air has in moving the more rigid surface of the partition. The dampening effect of an absorbing layer that absorbs even 50% of the sound power is insignificant in comparison with that rejected at the surface of the partition.

For lighter weight partitions that are more flexural, then the addition of sound absorbing materials within a cavity can have an effect and be worthwhile including.

It might appear that all that needs to be done in order to improve sound insulation, is to increase the number of rigid surfaces that the sound has to cross. This will increase the number of times the sound has to cross the difficult boundary from compressible air to rigid solid. Indeed it is found that multi layer partitions do have better sound insulation than single layer partitions. However, the effects of multiple layers is quite complex and does not provide all the benefit that might be expected.

The theoretical sound insulating effect of a single leaf, will be given by the mass law,

$$SRI = Constant + 20 \times log_{10}(m \times f).$$

Because the constant will apply to each case to be considered, it is omitted for simplicity and,

$$SRI = 20 \times log_{10}(m \times f)$$

If a single leaf of brick by itself has a SRI of 43 dB, then two bricks built into a single leaf, as shown in Figure 22, will have twice the surface mass of the single leaf, and its theoretical SRI will be calculated as shown in Column 2 of Table 2.

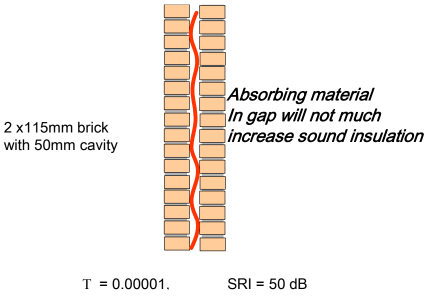


Figure 10.20 Cavity wall + insulation

Single Leaf	Double Density	Two Independent leaves
$SRI_{SINGLE} = 20log_{10}(m \times f)$	$SRI_{DOUBLE} = 20log_{10}(2m \times f)$ $SRI_{DOUBLE} = 20log_{10}(m \times f) \times (2)$ $= 20log_{10}(m \times f) + 20log_{10}(2)$ $SRI_{DOUBLE} = SRI_{SINGLE} + 6$	$SRI_{TWICE} = SRI_{SINGLE} + SRI_{SINGLE}$ Theoretical – not found in practice.
43dB	49 dB	86 dB

Table 2 - Calculation of SRI's

However, two completely independent leaves would have an SRI that was simply the sum of the two separate SRI's, as shown in column 3 of Table 2.

The SRI of 50 dB that is found in practice for a cavity wall is indeed better than the 49 dB that would be expected from doubling the surface density, but it is nowhere near the SRI of 86 that might be expected theoretically from two independent leaves.

This is due to the fact that the air in the cavity is captive, and cannot expand and contract freely. This increases the stiffness of the air and allows the vibrations of one leaf to be more easily transferred to the second leaf. This means that the two leaves are effectively coupled together and not entirely independent.

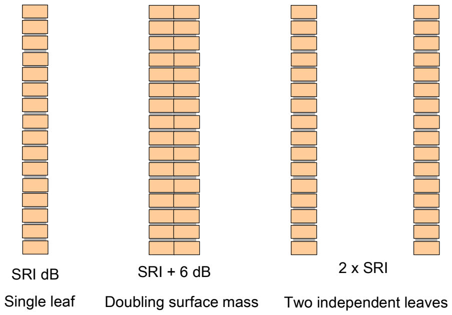


Figure 10.22 Multiple leaves

10.1.8 Room Acoustics

Within a room there can be distinguished three different elements of a sound field as shown in Figure 23.

There is the direct sound that arrives at the listener directly from the source, there are those first reflections from walls and ceiling that reinforce the direct sound, and there is a reverberant sound field that reaches the listeners ears after multiple reflections from the room surfaces.

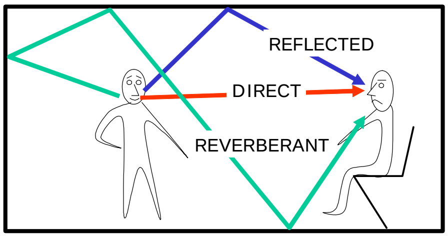


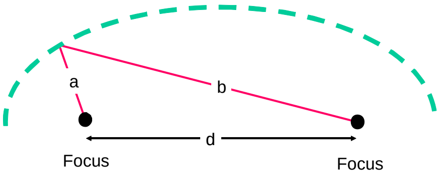
Figure 10.23 Sou

Where it is expected that an audience should clearly hear a speaker, then it is important that there is sufficient direct sound arriving at a listener's ears. Thus in lecture rooms and concert halls, as shown in Figure 24, the seats are raked in order that those at the back of the room can receive direct sound from the speaker or orchestra. Generally, providing good 'sight lines' will ensure good direct sound.

Figure 10.24 Direct Sound

A reflected sound heard less than 30-50ms after the initial sound will tend to reinforce the initial sound. This will improve the definition of the sound and increase its loudness. Reflected sounds arriving later than 80 ms will tend to muddy the clarity of the sound and may even be heard as a distinct echo if the time delay is as much as 1 second.

This means that surfaces that are intended to reflect sound to reinforce a speaker need to be positioned so that reflected sound arrives no later than 50 ms after the initial sound. Because sound travels at 343 m/s, this means that the reflected sound path from speaker to audience position should exceed the direct sound path by no more than 14m.

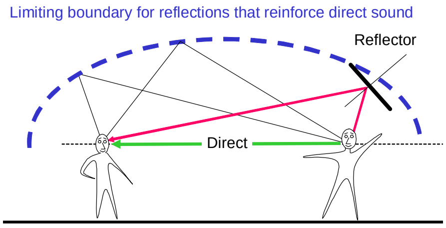


a + b = constant - draws out an ellipse

For reinforcement to occur: a + b = d +14

Figure 10.25 Properties of ellipse

There is a geometrical way of ensuring this using the properties of an ellipse. One property of an ellipse is that the path length between the ellipse and the two foci is constant as shown in Figure 25. Thus using a piece of string with a scale length of (14 + D)m, and fixing the two ends at an audience position and speaker's position, a pencil line drawn whilst keeping the string taught will draw out an ellipse. Any reflector within this ellipse will therefore automatically be positioned to give reflections that arrive early enough to reinforce the original sound, as indicated in Figure 26.



Difference in Path length < 17m i.e. time delay < 50 ms

Figure 10.26 Sound path difference

The reverberant sound in a room gives it a particular acoustic. A room intended for speech would prove rather unsuccessful if it were too reverberant because the reverberant sound would mask the definition of the speaker's voice. This effect is common in large spaces such as we find in Bath Abbey. Those who talk in such spaces will deliberately slow down their speech and articulate their words very clearly in order that a congregation can hear and understand what they say.

However, that very same long reverberation time in Bath Abbey also substantially increases the sound level of song, and adds to the quality of the sound heard from the choir.

It should therefore not be surprising to find that rooms intended for different purposes are designed to have different levels of reverberant sound.

10.1.8.1Reverberation time

The level of reverberant sound in a space is characterised by its Reverberation Time. This is defined as the time it takes for a sound field to decay to one millionth of the original sound intensity. The reverberation times required for a number of different spaces are given in Figure 27.

Type of Sound or Type of room	Reverberation time in Seconds	
	Room Volume of 500 m^3	Room Volume of 10 000 m^3
Speech	0.7	1.0
Church music	2.0	3.0
Classical Concert	1.9	2.0
Pop Concert	0.8	0.8
Opera House	1.5	1.8

Figure 10.27 Reverberation Times

Reverberation time may be calculated using a quite simple relationship known as Sabines Formula and named after the academic who first determined it through measurement,

$$RT = \frac{0.16V}{A} \text{ secs.}$$

Where V is the volume of the space in m^3,
And   A is the total acoustic absorption, $\sum \alpha S$ in sabin.
  α is the surface absorptance of the material,
  S   is the surface area of the material.

It is important to appreciate that when acousticians talk about absorption they refer to the surface absorption in relation to what is happening in the room. Consider Figure 28 that shows a wall with a 1 m^2 open window. This open window has a transmittance to sound of 100%, but also an effective surface absorptance of 100% and an absorption of 1 Sabin.

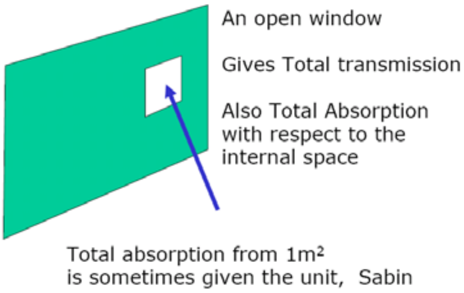


Figure 10.28 Open Windows

In order to estimate the total absorptance of a room, the absorptance of all the surfaces needs to be summed. In a real building this will be done at a number of different frequencies because the acoustic properties of materials change with frequency.

10.1.8.2Calculation of Reverberation time

Consider a lecture theatre for 120 people that is 20m long by 12m wide by 3m high. It is assumed to be occupied by 80 people and the doors have a surface area of $5m^2$.

A lecture theatre is recommended to have a reverberation time of 0.8 secs, and therefore taking Sabine's formula,

$$RT = \frac{0.16 \times V}{\sum \alpha S}$$

and re-arranging it to find the total absorption that is needed within the lecture theatre in order to give a reverberation time of 0.8 sec gives:

$$\sum \alpha S = \frac{0.16 \times (20 \times 12 \times 3)}{0.8} = 144 \text{ Sabin.}$$

	Absorption coefficient α		
Room element	125 Hz	500 Hz	2000 Hz
Person on seat	0.16	0.4	0.44
Unoccupd. seat	0.08	0.15	0.18
Air abs./m^3	0	0	0.01
Walls	0.02	0.02	0.04
Doors	0.3	0.1	0.1
Ceiling	0.2	0.1	0.04
Floor	0.05	0.05	0.1

Figure 10.29 Absorption factor

The absorption actually provided by the lecture theatre needs to be calculated. Because of the varying properties of different materials at different frequencies, this calculation should be done over a number of Octaves. It is a calculation that is convenient to arrange in tabular form as is shown in Table 3.

The absorption coefficients for the different materials are shown in Figure 29.

Tabulating the absorption data for three frequencies,

Room, Content	Num.	125 Hz		500 Hz		2000 Hz	
	Area	α	α x S	α	α x S	α	α x S
	S						
Persons on seats	80	0.16	12.8	0.4	32.0	0.44	35.2
Unocc. seats	40	0.08	3.2	0.15	6.0	0.18	7.2
Room Air	720	-		-		0.01	7.2
Walls	204	0.02	4.08	0.02	4.08	0.04	8.16
Doors	4.8	0.3	1.44	0.1	0.48	0.1	0.48
Ceiling	240	0.2	48.0	0.1	24.0	0.04	9.6
Floor	240	0.05	12.0	0.05	12.0	0.1	24.0
Total			81.5		78.6		91.8

Table 3 – Tabulation of the total absorption within an auditorium

Across all the Octaves considered, additional absorption will be required in order to achieve a RT of 0.8 secs. because less than the required 144 sabin absorption is available. The two most likely places to add absorption are at the back of the side walls and the back wall. The back wall provides a substantial surface area onto which treatment can be applied but it does not affect directly the acoustics of many of the audience.