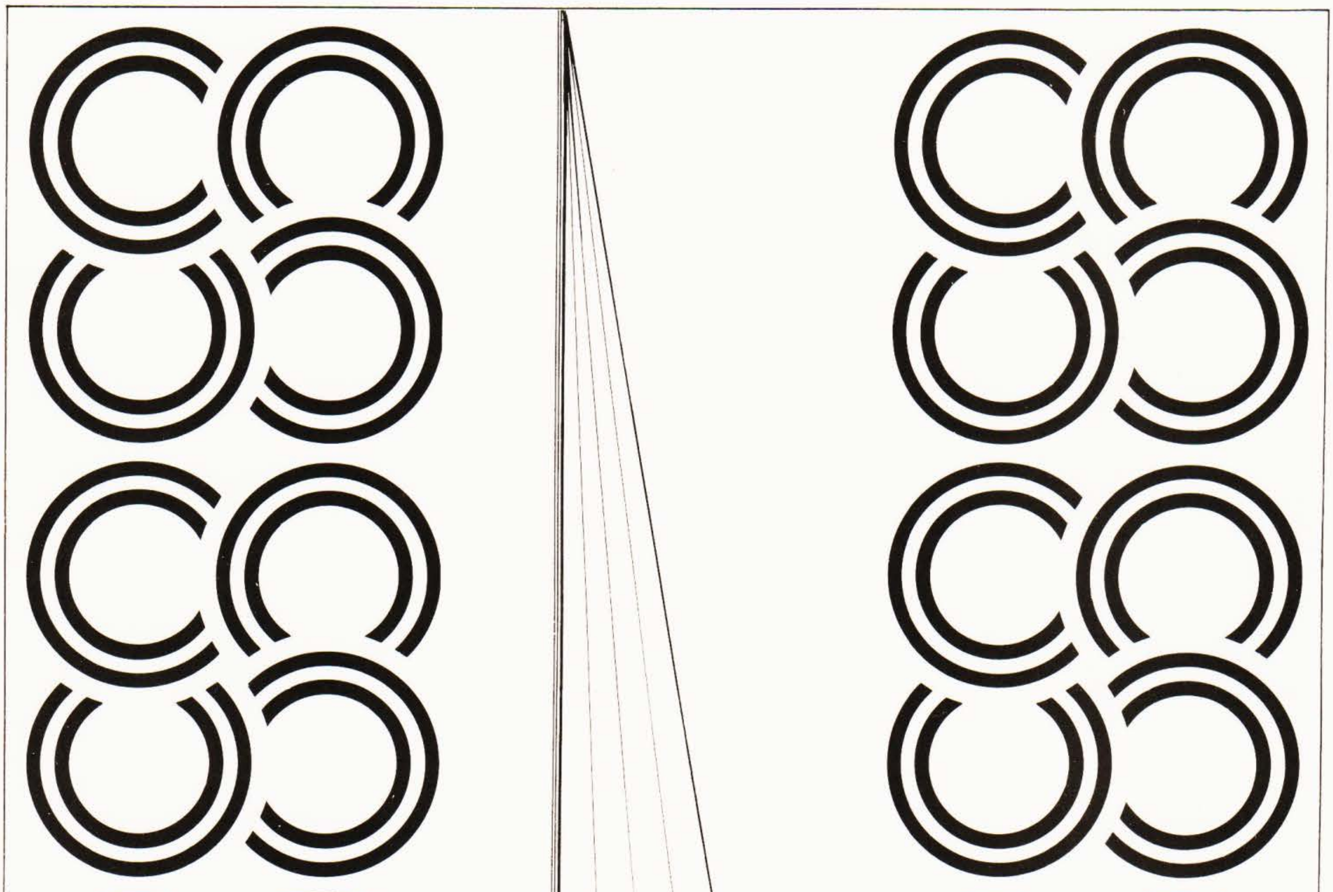
Acoustics

Longman Micro Software



Acoustics

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Preface

This computer assisted learning unit has been produced by the Computers in the Curriculum Project at Chelsea College, in conjunction with teacher groups around the country. It is designed to be incorporated into the existing curriculum and can often enhance and extend that curriculum in the classroom. The material is for use on microcomputers in the classroom and takes full advantage of the current facilities. The Unit consists of three component parts:

Teachers' guide. This provides useful information on the topic that often extends beyond the conventional material used in the classroom. It describes the educational rationale behind the development of the unit and explains how the material can be used.

Students' leaflets. These can be used as worksheets, and they provide practical suggestions and working instructions on the use of the program.

Program. This is interactive and flexible and uses graphics wherever appropriate. No previous knowledge of computing or programming is required by either the teacher or student.

The unit is especially designed to enhance the learning of the student. It has been tested with teachers and in schools to ensure that it is reliable, adaptable and valuable in the classroom. The programs have all been designed to attempt to meet the needs of different teaching methods, student abilities and class groupings.

This unit is one of a large number of computer assisted learning units being developed by the Computers in the Curriculum Project for a wide range of subjects in the school curriculum.

Margaret Cox (Dr)
Project Director
1983

Acknowledgements

The new Physics units of the Computers in the Curriculum Science materials have been developed through the Educational Computing Section, Chelsea College, supported by funds from the Microelectronics Education Programme, the Schools Council and the Educational Computing Section of Chelsea College.

The work was begun in 1979 under the direction of the former Project Director, Robert Lewis, and former Assistant Director (Science), David Want. It has been completed under the direction of Sophie McCormick, the Assistant Director (Science). Valuable help and advice has been provided by Dr Margaret Cox (Project Director), Peter Smith (former Assistant Director, Software), Professor David Johnson (Shell Professor of Mathematics Education) and Deryn Watson (Assistant Director, Humanities).

Thanks are due to the central programming team for their help in producing the final versions of the programs especially the following members: David Riddle (Software Support Manager), Royston Sellman, Richard Millwood, Jan Bright, Plaxy Arthur, Mick Dodwell, Patrick Murphy, Colin Smith, Diane Moody, David Creasy, Marianne Atherton, and to Pat Dawkins and Susan Kerwin for their work in typing the manuscripts.

The Physics development work has been coordinated by David Squires (formerly at the Advisory Unit for Computer Based Education, now Adviser for Computers in Education, Devon). Thanks are due to Dr W. Tagg (Director of Advisory Unit for Computer Based Education) and C. P. Elliott (Science Adviser; Hertfordshire) for their help and advice. Acknowledgement is also due to the Advisory Unit for Computer Based Education in Hertfordshire for their continued support throughout the development.

We would also like to thank all those teachers who tested and evaluated the material in schools.

Contents

1 Introduction

A study of sound does not feature prominently in many physics syllabuses. Even fewer syllabuses make any mention of acoustics, even though it is directly relevant to everyday life. A lack of attention to the study of acoustics is not surprising, because it is a complex subject, and the acoustic properties of a building depend on a wide range of factors which are difficult to investigate experimentally in a school.

This package of computer assisted learning material is designed to provide an elementary introduction to acoustics. The package is concerned with one of the most important acoustic attributes of a room – its reverberation time. It is designed to be used by students between the ages of 15 and 18 years.

REVERB allows a rectangular room to be specified in terms of the following:

the dimensions of the room,
the type of floor,
the type of walls,
the type of ceiling,
the type and area of windows.

It is also possible to specify the number of people in the room, the number of chairs in the room, and the area and material of an acoustic panel.

The program will produce graphical or tabular output showing the variation of reverberation time with frequency for specified rooms. Values for the reverberation time are computed on the basis of the Norris–Eyring formula.

The *Students' leaflets* are designed to provide a framework for the student to use the program on an individual basis or within a small group. They can also act as preparatory reading for the students if the program is going to be used in a tutorial fashion by the teacher with a group of students. Five of the leaflets deal with the concepts of reverberation time, absorption coefficients, the effect of air on reverberation times, the effect of volume on reverberation times, and the design of auditoria. There is also a leaflet that instructs the student on how to run the program and a leaflet that lists the codes of materials or objects which can be used to specify a room.

2 Aims of the package

The fundamental aim of the package is to provide students with an introduction to elementary acoustics.

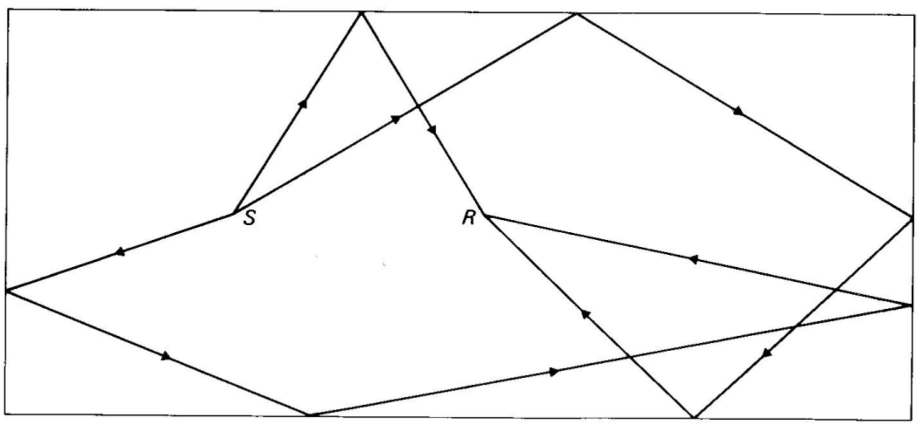
More specific aims are to:

a introduce the concept of reverberation time and its significance in acoustics;
b enable students to investigate the relationship between the construction of a room and reverberation time;
c enable students to investigate the relationship between the volume of a room and reverberation time;
d give students the opportunity to investigate the reverberation times for different types of auditoria.

3 The computer model

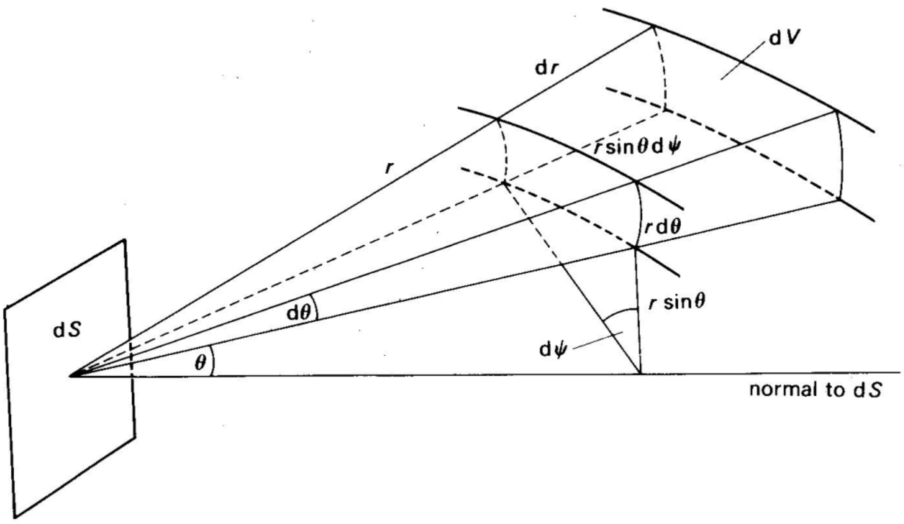
REVERB computes reverberation times on the basis of the Norris–Eyring formula. This is derived below. Consider a source, S, and receiver, R, in a room like in Figure 1 where a few of the possible reflections off the room surfaces are shown.

Figure 1



It is not difficult to imagine that in reality any small volume of space will act as though it were a source of diffuse sound. First we must assume that sound waves in a room are plane waves for which acoustic pressure and particle velocity are in phase; in such a case all the energy then contributes to the travelling wave, and the sound intensity can be calculated.

Figure 2



dS is a small element of a surface, say a wall in a room. Consider a small volume of sound energy, dV, distance r from dS. Imagine dV to be a part of a hemispherical shell centred on dS, then the lengths of the sides of dV will be as shown in Figure 2. The effect of sound energy on dS from dV will depend on the projected area $dS\cos\theta$. Since we are considering the sound energy in all possible directions the fraction of the energy of dV that reaches dS will be this projected area divided by the total area around dV at the distance of dS, that is

$$\frac{dS\cos\theta}{4\pi r^2}$$

If the sound energy per unit volume is E, the total energy dE reaching dS from dV is given by

$$dE = \frac{E\,dV\,dS\cos\theta}{4\pi r^2}$$

To find the sound energy reaching dS from all such elements of the hemispherical shell, integrate dV. (Since this program deals only with enclosures and solid objects in them, sound reaches the surface from one side only, hence the *hemi*spherical shell.)

$$dV = dr.\, r\sin\theta\, d\psi\, r\, d\theta$$

$$= r^2 \sin\theta\, d\psi\, d\theta\, dr$$

$$\int_0^{2\pi} d\psi = 2\pi$$

$$\therefore dV = 2\pi r^2 \sin\theta\, dr\, d\theta$$

$$\therefore \Delta E = \int_0^{\pi/2} \frac{E\,dS\cos\theta}{4\pi r^2}.\, 2\pi r^2 \sin\theta\, dr\, d\theta$$

$$= \frac{E\,dS\,dr}{2}\int_0^{\pi/2} \sin\theta\cos\theta\, d\theta$$

$$= \frac{E\,dS\,dr}{4}$$

Let ΔE be the amount of energy which arrives at dS in the time it takes sound to travel the thickness of dV in the direction of dS – emptying dV of sound energy, so to speak.

$$\Delta t = \frac{dr}{c}$$

where c is the velocity of sound. The rate of energy arriving at $\mathrm{d}S$ is

$$\frac{\Delta E}{\Delta t} = \frac{E\,\mathrm{d}S\,\mathrm{d}r}{4} \cdot \frac{c}{\mathrm{d}r}$$

$$= \frac{E\,c}{4} \cdot \mathrm{d}S$$

Intensity is defined as the rate of energy arrival per unit surface area so

$$I = \frac{E\,c}{4}$$

It may be of interest to learn that this is one-quarter the intensity of a normally incident plane wave having the same energy density. Put another way, to provide the same intensity, a diffuse wave arriving uniformly from all directions in a hemisphere on one side of a surface must have four times the energy of a plane wave arriving normally to the surface. Once the source has stopped the sound will decay. The time will depend upon the absorption of the surfaces and the distances the sound travels between reflections. The total energy in the room is $E\,V$. The intensity at the surface is $E\,c/4$ so the rate at which energy falls on the whole interior surface, S, is $S\,E\,c/4$.

The time Δt required for the whole of the energy to reach the surface is the total energy divided by the rate at which the energy reaches the surface, i.e.

$$\Delta t = \frac{E\,V}{S\,E\,c/4} = \frac{4\,V}{S\,c}$$

This then is the average time for one reflection to occur. The distance Δl travelled by the sound in this time is

$$\Delta l = c\,\Delta t = \frac{4\,V}{S}$$

Let the average absorption coefficient of all the surfaces be $\bar{\alpha}$. If we have surfaces of areas S_1, S_2, S_3, etc., with absorption coefficients α_1, α_2, α_3, etc., then $\bar{\alpha}$ is defined as

$$\bar{\alpha} = \frac{S_1\,\alpha_1 + S_2\,\alpha_2 + S_3\,\alpha_3 + \ldots}{S_1 + S_2 + S_3 + \ldots}$$

$$= \frac{\Sigma S\,\alpha}{\Sigma S}$$

Furthermore, if there are n_{p} people of absorption coefficient α_{p}, and n_{c} chairs of absorption coefficient α_{c}, then

$$\bar{\alpha} = \frac{S_1\,\alpha_1 + S_2\,\alpha_2 + S_3\,\alpha_3 + \ldots + n_{\mathrm{p}}\,\alpha_{\mathrm{p}} + n_{\mathrm{c}}\,\alpha_{\mathrm{c}}}{S_1 + S_2 + S_3 + \ldots}$$

The proportion of energy left after one reflection is $(1 - \bar{\alpha})$ and after n reflections $(1 - \bar{\alpha})^n$. The energy left after n reflections is thus $E_o\,(1 - \bar{\alpha})^n$ where E_o is the initial energy density, i.e.

$$E = E_o\,(1 - \bar{\alpha})^n$$

One reflection takes $4\,V/S\,c$ seconds so n reflections take $4\,V\,n/S\,c$ seconds, i.e. the time for this particular decay process to reach an energy density E is

$$t = \frac{4\,V\,n}{S\,c}$$

$$\therefore n = \frac{S\,c\,t}{4\,V}$$

and $E = E_o(1 - \bar{\alpha})^{(S\,c/4\,V)t}$

Since we have already shown that the energy density and the intensity at any point are directly related

$$I = I_o(1 - \bar{\alpha})^{(S\,c/4\,V)t}$$

$$\ln(I/I_o) = (S\,c/4\,V)\,t\ln(1 - \bar{\alpha})$$

$$2.303\log(I/I_o) = (S\,c/4\,V)\,t\ln(1 - \bar{\alpha})$$

Now reverberation time, T is defined such that

$$10\log(I/I_o) = -60$$

So if we write

$$10\log(I/I_o) = \frac{10}{2.303}(S\,c/4\,V)\,t\ln(1 - \bar{\alpha})$$

$$-60 = \frac{10}{2.303}(S\,c/4\,V)\,T\ln(1 - \bar{\alpha})$$

which, on rearranging, simplifying and putting $c = 343\ \mathrm{m\,s^{-1}}$ becomes

$$T = \frac{0.161\,V}{-S\ln(1 - \bar{\alpha})}$$

This is the Norris–Eyring formula for reverberation time. If absorption by the air is significant (very large rooms at higher frequencies), this equation becomes

$$T = \frac{0.161\,V}{-S\ln(1 - \bar{\alpha}) + xV}$$

where x is the absorption coefficient for air.

4 Using the program REVERB

REVERB is run by using a series of keywords. The program prompts for the use of a keyword with the prompt 'Option?'

The keyword DEMO will demonstrate the program. No values need to be entered.

The following keywords can be used to specify a room and its contents.

SIZE Specification of the length, breadth and height of a room in metres.

WALLS Specification of a material code for the walls.

CEILING Specification of a material code for the ceiling.

FLOOR Specification of a material code for the floor.

WINDOWS Specification of the area of and material code for windows.

PANEL Specification of the area and material code for an acoustic panel.

CHAIRS Specification of the number and type of chairs in the room.

CARPET Specification of the area and material of a carpet.

PEOPLE Specification of the number of people in the room.

The program will produce results when one of the following keywords is used.

GRAPH A bar graph of reverberation times at frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The bar graph will be superimposed on top of the last bar graph drawn for a previously defined room. Superimposed bar graphs for two different rooms are shown in Figure 3.

Figure 3

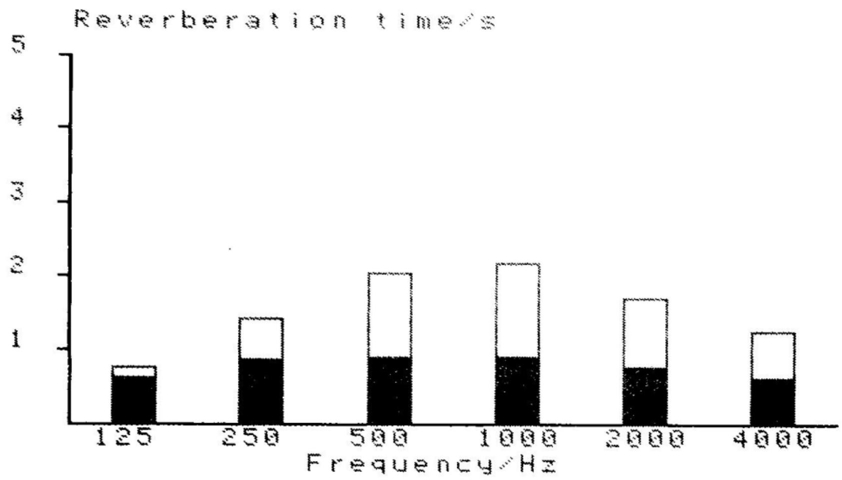


TABLE A table of reverberation time at frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. An example of a tabular display is shown in Figure 4.

Figure 4

Frequency/Hz	Reverberation time/s
125	.74
250	1.42
500	2.04
1000	2.18
2000	1.69
4000	1.23

In some cases it may be easier to use the keyword START which leads into a predetermined route. The user is automatically asked a series of questions to specify the room, and the results are calculated and tabulated.

In addition, the following keywords may be used.

DEFINE Definition of the absorption coefficients of a material at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The defined material is named by the program user. It is permissible to use a defined material on any surface of the room.

LIST Display of the materials and objects which can be specified. The code number and absorption coefficients of each material or object are shown in the display.

RESET Return of all the values to those of a 'default' room which are

size 6 m × 4 m × 2.5 m

floor	wood
ceiling	plasterboard
walls	plaster

There are no windows or people in the room. Use of the GRAPH or TABLE keyword will produce results for this room immediately the program is loaded.

SUMMARY Summary of the values which have been used to specify a room.

HELP Advice on how to run the program.

FINISH Ends the program.

5 Outline of the students' material

It is assumed that the students:

a appreciate that sound is a wave motion;
b understand that wavefronts can be represented by rays;
c are familiar with the reflection of waves from a plane surface;
d understand the meaning of intensity.

The students' material consists of seven leaflets.

A Reverberation time
B Absorption coefficients
C The effect of air on reverberation time
D The relationship between volume and reverberation time
E The design of auditoria
F A list of codes for the materials and objects which can be used to specify a room
Z A list of keywords available to run the program

Students' leaflets A to *E* are designed to be used in order. *Leaflets F* and *Z* are reference leaflets which can be used when the program is being run.

A brief description of *Students' leaflets A* to *E* is given below.

A Reverberation time

This leaflet introduces the concept of reverberation time. The formation of reverberant sound due to reflections off the surfaces in a room is discussed and the definition of reverberation time is introduced.

The students are asked a series of questions about reflections of a sound wave in two dimensions in a room in which all the surfaces are covered with the same material. These questions are designed to enable students to work out an approximate reverberation time for the room. In this way it is hoped that the students will develop an understanding of the physical significance of reverberation time.

B Absorption coefficients

The idea of an absorption coefficient is introduced. Instructions are given on how to use the DEFINE keyword to define materials which have absorption coefficients that vary in different ways with frequency. The students are requested to use these defined materials to study the way the absorption coefficients of the materials covering a room's surfaces affect the reverberation times of the room.

C The effect of air on reverberation time

This leaflet introduces the idea of an anechoic chamber. The students investigate the reverberation times for a small anechoic chamber and see what effect air has on the reverberation times of the chamber as the volume is increased.

D The relationship between volume and reverberation time

This leaflet attempts to explain why the reverberation times of a room are dependent on volume. The students are asked to consider what happens to the way a two-dimensional wave is reflected off a room's surface as the room is enlarged.

E The design of auditoria

The students are given acoustic data on three types of auditoria: a concert hall, an opera house and a debating hall. They are then requested to use the program to investigate the effect on the room's reverberation times when it is filled with an audience.

6 Answers to students' questions

Students' leaflet A

A1 During the first reflection $\frac{1}{2}$ of the wave's sound energy will be absorbed.

A2 After the first reflection $\frac{1}{2}$ of the wave's sound energy will be reflected.

A3 After the second reflection $(\frac{1}{2} - \frac{1}{4})$, i.e. $\frac{1}{4}$, of the initial energy of the sound wave will have been reflected.

A4 After the fourth reflection $(\frac{1}{8} - \frac{1}{16})$ of the initial energy of the sound wave will have been reflected.

A5 As it takes 20 reflections to reduce the sound energy by a factor of 10^6, 20 reflections of the wave take place during the reverberation time.

A6 The average time between the reflections is given by the average distance between them divided by the speed of the sound, i.e. $3\,\text{m}/300\,\text{m}\,\text{s}^{-1} = 0.01\,\text{s}$.

A7 A rough estimate of the reverberation time of the room will be 0.01 s.

Students' leaflet B

B1 The best absorber at low frequencies is material B.

B2 The best absorber at high frequencies is material A.

B3 The reverberation times of a room with surfaces covered with material A will decrease as frequency increases.

B4 The reverberation times of a room with surfaces covered with material B will increase as frequency increases.

B5 There will be a significant change in reverberation times.

B6 The reverberation times of plaster increase with frequency. The reverberation times of glass decrease with frequency. Therefore the effect of the windows on the room's reverberation times will be more pronounced at low frequencies.

Students' leaflet C

C1 The reverberation times of the room will be large.

C2 The reverberation times will be equal.

C3 The effect of air at frequencies of 125 Hz, 250 Hz and 500 Hz will be zero as the absorption coefficients of air at these frequencies are zero. Effects will be observed at the higher frequencies. The reverberation times will be reduced for these frequencies.

C4 As the absorption coefficients of air are very small, the effect on reverberation times produced by the air will be small.

Students' leaflet D

D1 The surface area of the room will be increased by a factor of 4.

D2 The volume of the room will be increased by a factor of 8.

D3 The area of the reflected wave surface will be increased by a factor of 4.

D4 The intensity of the wave surface coming into contact with the room's surfaces will be $\frac{1}{4}$ of the intensity in the original room.

D5 The amount of absorbing material the wave surface comes into contact with will be increased by a factor of 4.

D6 The average time between reflections of the wave surface will be doubled.

D7 The combined effect on the room's reverberation times of the changes produced by surface area and volume changes will be a factor given by $4 \times \frac{1}{4} \times 2 = 2$.

D8 The total surface area of this enlarged room will be greater than the total surface area of the previously enlarged room.

D9 The increase in reverberation times will be less.

D10 As the volume of a room is increased the reverberation times of the room will tend to increase.

Students' leaflet E

E1 If the reverberation times were too long in a room, i.e. greater than a second, speech would sound slurred.

E2 The reverberation times in a room designed for the performance of music will be longer than those in a room designed for speech. The typical reverberation times in a concert hall would be of the order of two seconds.

7 Extending the use of the program

This program contains a number of options and each option is controlled by a keyword. These are listed below with their option numbers, the input required by the user and the data structure within the program. An * is used to show that the user must enter a value.

Option	*Keyword*	*Input and limits*	*Data structure*
1	SIZE	dimensions of room (limits 80 m × 40 m × 20 m)	"1,*,*,*"
2	WALLS	material code for walls (1–13,15,20)	"2,*"
3	CEILING	material code for ceiling (1–13,20)	"3,*"
4	FLOOR	material code for floor (1–5,14,20)	"4,*"
5	WINDOWS	area of window code for window type (6,7,15,20)	"5,*,*"
6	PANEL	panel area code for panel type (1–13,15,20)	"6,*,*"
7	CARPET	area of carpet code for carpet type (14,16,20)	"7,*,*"
8	CHAIRS	number of chairs code for chair type (18–20)	"8,*,*"
9	PEOPLE	number of people	"9,*"
10	DEFINE	name of surface (anything) 6 coefficients for absorption at 125,250,500,1000,2000,4000 Hz	"10,*,*,*,*,*,*,*"
11	TABLE	none	"11"
12	GRAPH	none	"12"
13	SUMMARY	none	"13"
14	LIST	none	"14"
15	HELP	none	"15"

16	RESET	none	"16"
17	PAUSE	none	"17"
0	FINISH	none	"0"

The keyword data lines are 4999–5150. To change a keyword simply replace the keyword listed above with the new one: e.g. to change SIZE to DIMENSIONS type

```
5010 DATA "DIMENSIONS, to set the dimensions of the room"
```

To add an alternative keyword two data lines must be added to the program in the keyword block in the spare lines 5120–5150: e.g. to allow the single letter W to call option 2 as well as WALLS type

```
5120 DATA "W, to choose the wall material"
5122 DATA "2,*"
```

Certain keywords included within the program control not only one option but a sequence of options thus providing particular pathways through the program. For example in this program START is defined as follows.

```
5110 DATA "START"
5112 DATA "1,*,*,*, 2,*, 3,*, 4,*, 9,*, 17, 11"
```

Therefore the following sequence occurs when START is used.

1 The user is asked to set the dimensions of the room.
2 The user is asked to select the wall material.
3 The user is asked to select the ceiling material.
4 The user is asked to select the floor material.
9 The user is asked to state the number of people.
17 The user is asked to press return to continue.
11 The results are calculated and displayed in a table.

In another example using the keyword DEMO, the user is not required to enter any values since these have been provided.

```
5115 DATA "DEMO"
5117 DATA "1,15,10,4, 2,9, 3,11, 4,4, 9,30, 17, 11, 17, 12"
```

Here the dimensions of the room are set at 15 × 10 × 4. The walls are plaster, the ceiling fibreboard, the floor parquet and the room contains 30 people. The results are calculated and displayed as a table. The user is asked to press return and the results are displayed as a graph. In a similar way any useful sequence of keywords with or without values can be defined to fit into any particular teaching scheme. These can only be entered in the spare lines of the keyword block and should be carefully tested before use. For permanent alterations the programs should be resaved.

8 References

Background reading for the teacher

Smith B J 1971 *Acoustics*. Longman
Ginn K B, Denmark *Architectural acoustics*. Briiel and Kjaer, Denmark
Ford R D 1970 *Introduction to acoustics*. Applied Science Publishers Ltd
Kuttruff H 1979 *Room acoustics*. Applied Science Publishers Ltd

Data on absorption coefficients

Evans and Bazley 1960 *Sound absorbing materials*. HMSO

Background reading for the student

Waves and vibrations 1975 Schools Council/Loughborough University of Technology Engineering Science Project, Macmillan Education
Knudsen V O 1963 Architectural acoustics *Scientific American*, November

Students' leaflet A
Reverberation time

When sound is produced in a room it does not die away instantly. It will continue to be heard because of reflections from the walls, the ceiling, the floor and any other surfaces in the room.

The time the sound takes to die away is one of the most important acoustic properties of a room. The human ear finds it very difficult to detect a sound which has decayed to 10^{-6} of its original intensity. Therefore, reverberation time is defined as the time taken for a sound to decay by this factor. The reverberation time of a room will be different at different frequences.

Figure A1

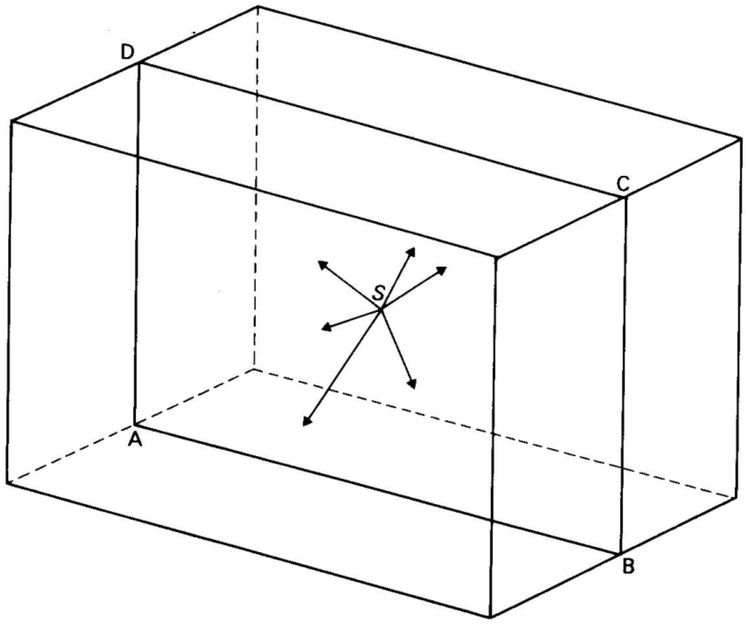
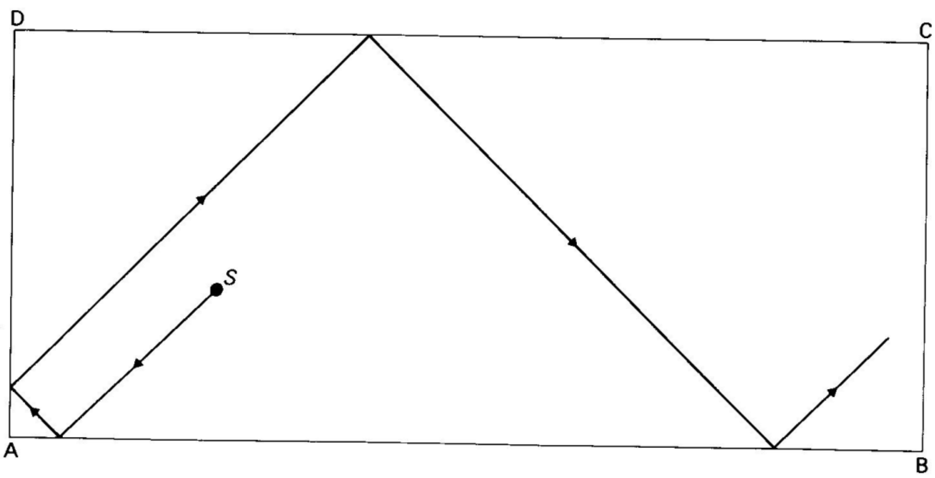


Figure A1 represents a room with a source of sound at S. Waves will be given off in all directions. We are only going to consider one wave which is always moving parallel to the side wall. This wave is shown in the side view of the room drawn in Figure A2. The first four reflections of the wave are shown.

Figure A2



Each time the wave is reflected off the floor, the ceiling or a wall some of the wave's energy will be absorbed.

Assume that the floor, wall and ceiling are all made of the same material.

Obviously this is unrealistic, but it should help you to develop some ideas about reverberation time.

Assume that each time the wave is reflected, half of its energy is absorbed by the surface.

A1 During the first reflection what fraction of the wave's sound energy will be absorbed?

A2 After the first reflection what fraction of the wave's sound energy will be reflected?

You should be able to see that $\frac{1}{2} \times \frac{1}{2}$, i.e. $\frac{1}{4}$, of the wave's initial sound energy will be absorbed during the second reflection.

A3 What fraction of the initial sound energy will be reflected after the second reflection?

A4 What fraction of the initial sound energy will be reflected after the fourth reflection?

If you worked out the fraction of sound energy that was reflected after twenty reflections of the sound wave it would be approximately 10^{-6}.

A5 How many reflections of the sound wave take place during the reverberation time?

It is possible to work out a rough value for the reverberation time from an average value for the time between reflections. The average distance that the wave travels between reflections is of the same order as the average dimension of the room. In the two dimensional view of the room we are considering this is $(4 + 2)/2 = 3\,\text{m}$.

A6 If you take the speed of sound in air to be about $300\ \text{m}\,\text{s}^{-1}$ what is the average time between reflections?

A7 What is a rough estimate of the reverberation time of the room?

Of course, this is a very approximate value for reverberation time. Three dimensions should be considered and the walls, ceiling and floor would typically be made of different materials.

It is much more difficult to calculate the reverberation time of a realistic room. The computer program REVERB enables you to obtain values for reverberation times using a formula which has been developed to deal with realistic rooms.

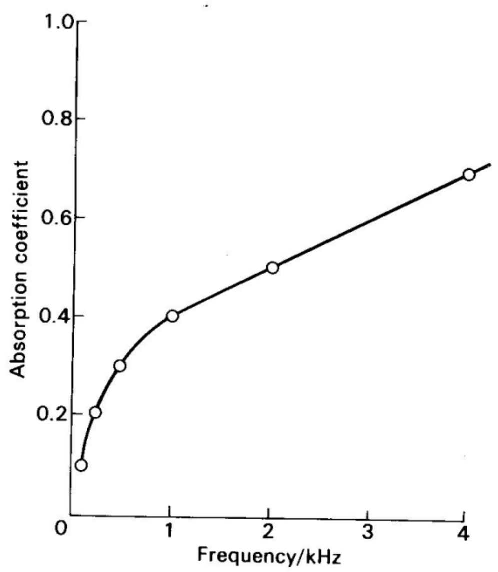
Students' leaflet B
Absorption coefficients

Different materials will absorb sound energy by different amounts. The extent to which a material absorbs sound energy is usually expressed in terms of an absorption coefficient.

The absorption coefficient of a material at a given frequency is defined as the sound energy absorbed by a given area of the material divided by the sound energy incident on the same area.

Figure B1 shows, in graphical and tabular form, how the reverberation time of a 'make-believe' material A varies with frequency. Figure B2 shows how reverberation time varies with frequency for a 'make-believe' material B.

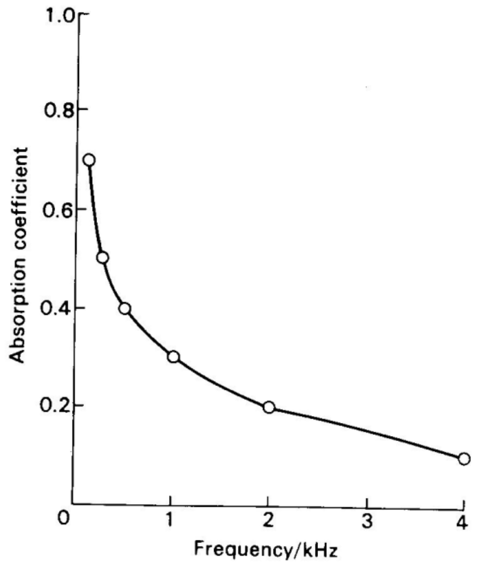
Figure B1



Frequency/Hz	*Coefficient*
125	0.1
250	0.2
500	0.3
1000	0.4
2000	0.5
4000	0.7

Material A

Figure B2



Frequency/Hz	*Coefficient*
125	0.7
250	0.5
500	0.4
1000	0.3
2000	0.2
4000	0.1

Material B

B1 Which material is the best absorber at low frequencies?

B2 Which material is the best absorber at high frequencies?

Define material A by using the DEFINE keyword. Specify a room of length 6 m, breadth 4 m, and height 2.5 m in which the walls, floor and ceiling are covered with material A.

B3 Do you think the reverberation times of this room will increase or decrease with frequency?

Check your answer by using the TABLE or GRAPH keywords.

Use the DEFINE keyword to define material B. Specify a room of the same dimensions as before with the walls, floor and ceiling covered with material B.

B4 For this room do you think that reverberation time will increase or decrease with frequency?

Check your answer by using the TABLE or GRAPH keywords.

Use the RESET keyword to return to the 'default' room with plaster walls, a wood floor and a plasterboard ceiling. The dimensions of this room are the same as the room you have already been considering.

Use the GRAPH keyword to see how the reverberation time of this room varies with frequency.

Incorporate windows into the room specification by using the WINDOWS keyword. Specify windows of total area 25 m^2 which are made of normal glass.

Use the LIST keyword to compare how the absorption coefficients of plaster and glass vary with frequency.

B5 Do you think the reverberation time of the room with windows will be significantly different from that of the room without windows?

B6 Will any difference in the reverberation times of each room be more pronounced at high or low frequencies?

Use the GRAPH keyword to compare the reverberation times of these rooms.

Students' leaflet C
The effect of air on reverberation time

Imagine a small room in which all the surfaces are covered with a material which has an absorption coefficient of 0.4 at all frequencies. If the room is small the sound energy absorbed by the air in the room will be negligible, i.e. the air will not affect the reverberation time of the room.

C1 Do you think the reverberation times of the room at different frequencies will be large or small?

C2 Will the room's reverberation times at different frequencies be equal to each other?

Use the DEFINE keyword to define a material with an absorption coefficient of 1.0 for all the specified frequencies. Specify this as a covering for the walls, floor and ceiling of a room of length 4 m, breadth 4 m, and height 2.5 m.

Use the TABLE keyword to obtain values for the reverberation time of this room. Do these values agree with your predictions?

If the volume of a room is increased the air in the room will start to have a significant effect on the room's reverberation times.

The absorption coefficients of air are given in Table C1.

Frequency/Hz	125	250	500	1000	2000	4000
Reverberation time/s	0	0	0	0.0003	0.007	0.02

C3 Will the room's reverberation times be equal to each other or will there be some differences in their values?

C4 Do you expect any effect to be large?

By using the SIZE keyword change the specified dimensions of the room to the following values: length 25 m, breadth 20 m, height 10 m.

Use the TABLE keyword to check your answers to questions C3 and C4.

Students' leaflet D
The relationship between volume and reverberation time

Imagine a room whose dimensions are doubled.

D1 What change will take place in the total surface area of the room?

D2 What change will take place in the volume of the room?

Think about how the way in which the sound is reflected by the room's surfaces will be affected by this change in area.

D3 By what factor will the area of the wave surface which comes into contact with the room's surfaces be changed?

D4 Remembering that the total energy emitted by the sound source will not change when the room size changes, by what factor will the intensity of the sound energy reaching the walls change?

D5 By what factor will the amount of absorbing material that the wave comes into contact with change?

Think about the way in which the sound reflection will be affected by the change in volume.

D6 What change will occur in the average time between reflections of the wave off the surfaces of the enlarged room?

Think about the combined effect that the change in intensity, the change in the amount of absorbing material the wave is reflected from and the change in time between reflections will have on the rate at which sound energy will be absorbed by the room's surfaces.

D7 By what factor do you think the reverberation times of the room will be changed when the average linear dimension is doubled?

Use the GRAPH keyword to obtain a graph of reverberation times against frequency for the default room. By using the SIZE keyword change the dimensions of the room to specify one with twice the length, breadth and height of this room. Compare the reverberation times of these two rooms by using the GRAPH keyword again.

Use the SIZE keyword to change the dimensions of the room to 12 m × 10 m × 4 m. The volume of this room will still be eight times the volume of the default room.

D8 Will the total surface area of the room have changed by the same amount?

D9 Do you think the change in the room's reverberation times will change by the same factor as before?

Check your answers by using the GRAPH keyword.

D10 Does the reverberation time of a room tend to increase or decrease as the volume of the room is increased?

Students' leaflet E
The design of auditoria

In a room designed for speech, e.g. a debating hall or an opera house, it is obviously important that each syllable is clearly heard. Speech consists of a rapid succession of syllables.

E1 What would speech sound like in a room with a long reverberation time?

In large halls designed for speech the intensity of the sound reaching the section of the audience a long way from the speaker will not be very high. The intensity of the sound reaching the audience will be increased by sound reflected off the room's surfaces. The reverberation time should be long enough to enhance the intensity of the sound but short enough to ensure that the speech is distinct.

Rooms designed for music have different acoustic criteria from those designed for speech. When music is performed it is desirable to emphasise the notes that are produced. The relative emphasis that a room gives to different frequencies will affect the sound of the performance.

E2 Do you think the reverberation time for a room designed for music should be greater or less than the reverberation time of a room designed for speech?

Most concert halls and opera houses are not rectangular in shape. They are often horseshoe shaped, fan shaped or dome shaped. In addition modern halls often make use of electronic devices which assist reverberation at specific frequencies. Acoustic reflectors may also be suspended from the ceiling to modify the acoustics of the room.

NOISE can only deal with rectangular rooms and it cannot simulate the effects of 'electronic resonators' or acoustic reflectors. However, by specifying the simple 'make believe' rooms detailed in Table E1, you should be able to use the program to get some idea of the different reverberation times of auditoria designed for three quite different purposes.

Table E1

	Concert hall	*Opera house*	*Conference room*
Length	45	35	10
Breadth	30	25	8
Height	15	12	3
Walls	plaster	plaster	plaster
Ceiling	plaster	plaster	acoustic plaster
Floor	wood	carpet	carpet
Audience capacity	2000	1000	50

The reverberation times for concert halls are usually in the region 1.5 s to 2.0 s; for an opera house they are approximately 1.1 s; and in a debating room they will be about 0.6 s. In order to obtain reverberation times of this order you will have to specify acoustic panels.

You may like to define the material for these panels by using the DEFINE keyword. You may also want to see the effect of changing the specifications of the walls, ceiling and floor material. It is worthwhile investigating the effects that an audience will have on each auditorium's reverberation times.

Students' leaflet F
Room construction codes

A tick indicates a valid code for a given surface.

Code	*Material*	*Walls*	*Ceiling*	*Floor*	*Windows*	*Panel*	*Carpet*	*Chairs*	*People*
1	brick	√	√	√		√			
2	concrete	√	√	√		√			
3	tiles	√	√	√		√			
4	parquet	√	√	√		√			
5	wood	√	√	√		√			
6	plate glass	√	√		√	√			
7	glass	√	√		√	√			
8	plasterboard	√	√			√			
9	plaster	√	√			√			
10	acoustic plaster	√	√			√			
11	fibreboard	√	√			√			
12	glass wool	√	√			√			
13	perforated hardboard	√	√			√			
14	carpet			√			√		
15	curtains	√			√	√			
16	water						√		
17	people								√
18	soft chairs							√	
19	hard seats							√	
20	defined	√	√	√	√	√	√	√	√

Students' leaflet Z
How to run the program

The program is run by using a series of keywords which are typed in response to the prompt 'Option?'

Keyword	*Function*
	The following keywords are concerned with the specification of a room.
SIZE	Specification of the length, breadth and height of a room in metres.
WALLS	Specification of the type of wall covering.
CEILING	Specification of the type of ceiling covering.
FLOOR	Specification of the type of floor covering.
WINDOWS	Specification of the area and type of windows.
PANEL	Specification of the area and material for an acoustic panel.
CARPET	Specification of the area and material of a carpet.
CHAIRS	Specification of the number and type of chairs in the room.
PEOPLE	Specification of the number of people in a room.
	Values for the reverberation times of the room may be obtained by using the following keywords.
TABLE	Production of a table of reverberation times at different frequencies.
GRAPH	Production of a graph of reverberation times at different frequencies.
	In addition the following keywords can be used.
DEFINE	Definition of the absorption coefficients of a surface.
SUMMARY	Summary of the current room specification.
LIST	List of the materials which can be specified together with their codes and adsorption coefficients.
RESET	Return of all values to the initial 'default' values for a room.
HELP	Produces a list of keywords with a brief explanation of each one.
FINISH	Ends the program.

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