An
Introduction to Acoustics

Mark Huckvale
Phonetics and Linguistics
University College London
www.phon.ucl.ac.uk
Fifth Edition
September 2005

Introduction to Acoustics 5th edition © 2005 Mark Huckvale University College London

Preface

This booklet has been written to accompany courses in the acoustics of speech and hearing at University College London. Its aim is to introduce the basic details of units, algebraic manipulation, number manipulation, mechanics and experimental design necessary for a good understanding of physical acoustics and laboratory work

We have produced this booklet so that you can find a single, accessible source for this information. You should find all inside comprehensible and you should make an attempt to understand it. Your tutor will help you with any difficulties you may have.

Paragraphs in grey boxes are for information only - you are not expected to memorise the detail given.

The author is pleased to accept any suggestions for improvements or additions to the booklet. We hope you find it useful.

Third edition

I have added a glossary of terms commonly found in acoustics

Fourth edition

I have revised the exercises and made minor modifications to the text. Answers to the exercises can be found on the web site: http://www.phon.ucl.ac.uk/courses/spsci/b214/.

Fifth edition

I have added two short sections on how to use a laboratory voltmeter and sinewave generator.

Mark Huckvale
September 2005

Contents

1. Measurement

This chapter introduces some basic ideas about measurement - the units in which measurements are made, how units can be combined and manipulated, how physical relationships are mirrored in the relationships between units, how measurements can be written as numbers.

1.1 Basic Units

We use the S.I. system of units (http://www.bipm.org/en/si/). In this system there are seven base units from which all others are derived. The enormous advance over previous systems is the use of a common notation, common multiplier prefixes, and the elimination of conversion factors within the system. We'll only be concerned with the three basic units:

Mass

Mass is measured in units of kilograms, written kg.

Length

Length is measured in metres, written m.

Time

Time is measured in seconds, written s.

1.2 Multiplying Prefixes

These indicate decimal multiples of units:

1,000,000,000,000×	10^{12}	tera-	T
1,000,000,000×	10^{9}	giga-	G
1,000,000×	10^{6}	mega-	M
1,000×	10^{3}	kilo-	k
100×	10^{2}	hecto-	h
10×	10^{1}	deka-	da
0.1×	10^{-1}	deci-	d
0.01×	10^{-2}	centi-	c
0.001×	10^{-3}	milli-	m
0.000001×	10^{-6}	micro-	μ
0.000000001×	10^{-9}	nano-	n
0.000000000001×	10^{-12}	pico-	p

Hence: 1km is one thousand metres. 1ms is one thousandth of a second. 1Mg is one million grams = one thousand kilograms. Unit codes are not abbreviations and should not be followed by a period, that is write "10ms" not "10ms.".

1.3 Derived Units

Repeated Events

If we are timing an event that occurs repetitively, one useful measurement is the interval between events - this is called **the period**. The period between events is clearly a measurement of time and is measured in seconds.

However a different way of measuring events that repeat is to record how many events occur within some period of time - this is called **the frequency**. In acoustics, where each repetition commonly takes much less than a second, we measure frequency in terms of the number of events that occur in one second. Thus the units of frequency are some number per second, written 1/s or s^{-1}. In fact this unit is used so commonly that we give it a special name: **hertz** written Hz.

We can express the relationship between period and frequency as:

Frequency (Hz) = 1 / Period (s)

That is the frequency of some event is equal to the reciprocal of the period between events (the shorter the period of an event, the more often it reoccurs). Notice that this expression serves two functions: it allows us to calculate a frequency give the period, and it also defines frequency and the units used for frequency.

Velocity and Acceleration

When we want to measure how fast an object is moving then we have to measure two things: a distance and a time. Clearly a faster object will cover a fixed distance in a shorter time than a slower object, or will travel a further distance in the same amount of time. The distance travelled per unit time is called the **velocity**, and is measured in **metres per second,** written m/s or ms^{-1}.

The definition of velocity is thus:

Velocity (ms^{-1}) = Distance (m) / Time Taken (s)

In air at 0C, sound travels at 332ms^{-1}. Thus for every 3 second interval after a lightning flash the sound of thunder travels approximately 1 kilometre.

The conversion factor from these units to ones you see on roads is:

1 mile per hour = 0.47 ms^{-1}
1 ms^{-1} = 2.13 miles per hour

When the velocity of an object is changing it is said to be **accelerating.** If we want to measure the rate at which the object's velocity is changing, we shall need to make two measurements of its velocity spaced by some period of time. If the object had velocity v1, at time t1, and velocity v2 at time t2, then the change in velocity is just (v2 – v1), and the interval between measurements is just (t2 - t1). Thus the acceleration is the ratio of the change in velocity to the interval between measurements: (v2 - v1) / (t2 - t1) and is measured in **metres per second per second** or ms^{-2}.

The definition of acceleration is:

Acceleration (ms^{-2}) = Change in velocity (ms^{-1}) / Time interval (s)

If a car accelerates from 0 to 60mph in 11.5 seconds, what is its acceleration (in standard units) ?

Convert units: 60 mph = 60 × 0.47 ms^{-1} = 28.2ms^{-1}
Change in velocity: (28.2 - 0) = 28.2ms^{-1}
Time interval: (11.5 - 0) = 11.5s
Acceleration: 28.2 / 11.5 = 2.45 ms^{-2}

When an object falls to the ground it is experiencing a force caused by gravity. The acceleration towards the ground caused by gravity is independent of the mass of the object (since both the gravitational force pulling it down and the object's resistance to being pulled down are both proportional to the mass of the object) and is equal to 9.81ms^{-2} (called, confusingly, *g*). Thus the car above has an acceleration of 2.45/9.81 times that due to gravity, i.e. about 1/4g.

Area, Volume, Density

To measure the area covered by some object we need to make two measurements of length. If the object is rectangular, we can simply measure its length and width. If it is some other shape then we need to count how many times some basic rectangular shape fits into the area and multiply by the area of the basic shape, see Fig 1. The unit of area is the **square metre** or **m^2**
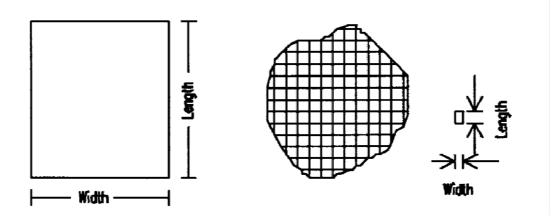

Figure 1. Measuring the area of regular and irregular shapes.

Likewise with volume: if the object is rectangular we need only to make three measurements: length, width and height. Otherwise we need to count how many basic shapes would occupy the same volume and multiply by the volume of each basic shape. The unit of volume is the **cubic metre** or $\mathbf{m^3}$.

The observation that objects made of different materials can have different masses despite being of equal volume (e.g. a milk bottle full of air or full of milk!) leads to the concept of **density**. To measure the density of a material we need to make two measurements: a measurement of mass and a measurement of volume. Mass, as we have seen is measured in kg; volume in m^3, so density is measured in kg/m^3 or kgm^{-3}.

Thus the definition of density is

> Density (kgm^{-3}) = Mass (kg) / Volume (m^3)

The density of water is $1000kgm^{-3}$ (about 1 ton per cubic metre) and the density of air is about $1kgm^{-3}$.

1.4 Algebraic Manipulation

The formulae used in the previous section perform two functions: they act as **definitions** for the derived units (e.g. the definition of density) and they may also be used to calculate a derived unit of measurement from a number of more basic units.

The ability to manipulate simple formulae is very useful, for it allows one to answer questions phrased differently from the definition: such as 'how much volume does 1kg of water occupy?' or 'what is the period of vibration of 50Hz mains electricity?'.

Lets look at some basic manipulation of such formulae. We'll start with the definition of frequency:

> Frequency (Hz) = 1 / Period (s)

or, using the convention of small letter f for frequency and capital T for period:

> f = 1 / T

The golden rule for manipulating such formulae is that you can do anything provided that you do it to both sides. So to re-arrange this formula so that is says 'T=...', then we need only take the reciprocal of both sides:

> 1 / f = 1 / (1 / T) = T

that is
> T = 1 / f
or
> Period (s) = 1 / Frequency (Hz)

There have been a number of ways in which this sort of manipulation has been taught in schools, the thing to remember is that valuable as these patterns of manipulation are - they are all versions of the golden rule above:

For example, 'when you take a symbol from one side to the other, change its sign'

i.e.

$$A = B + C$$
$$\Rightarrow A - C = B + C - C$$
$$\Rightarrow A - C = B$$

means: subtract the symbol (C) from both sides.

Or 'a divisor on one side becomes a multiplicand on the other'

i.e.

$$A = B / C$$
$$\Rightarrow A \times C = (B / C) \times C$$
$$\Rightarrow A \times C = B$$

means: multiply both sides by the symbol (C).

1.5 Numbers

Accuracy

The use of electronic calculators in the laboratory brings up the issue of how accurately one should specify a numeric value. Calculators usually represent numbers with 8 digits since they have no way of knowing how accurately the numbers in the calculation are specified. When you tap in '1.4', the calculator doesn't know whether you mean 'somewhere between 1.3 and 1.5' or 'exactly 1.4' (i.e. 1.400000000 ...).

When you are measuring things in the laboratory, it is unlikely that you will be able to measure any more accurately than one part in a thousand, that is with an accuracy greater than 0.1%. Thus any calculation you do in the laboratory should reflect this: if you measure 15 swings of a pendulum at 18.2 seconds then its period is 1.21 seconds, and its frequency is 0.824 swings per second. Note that your calculator might say a period of 1.213333 and a frequency of 0.8241758 (why not check?), but these numbers are too precise. To measure the period to an accuracy of 7 digits, such as above, we would have to measure the time taken to within 0.00001% (1 part in 10million), that is we would have to measure our 15 swings to within a microsecond. Such a thing might be possible with suitable apparatus, but not with a stopwatch!

There is a simple rule of thumb that we can follow. An accuracy of about 0.1% means that we can quote numbers with three digits in them fairly reliably. The formal name for this is **three significant figures.** The word 'significant' is used because leading zeros in numbers smaller than 1 are not counted. Thus all of the following have an accuracy of three significant figures:

$1.23, 0.340, 0.00000000631, 143 \times 10^6, 7.89 \times 10^{-3}$

while these numbers have a greater accuracy:

$1.234, 1.340, 0.99999999631, 143000000$

To convert numbers of greater accuracy to three significant figures we look at the fourth significant digit in the number (skipping leading zeros). If that digit is 0,1,2,3 or 4, we simply truncate the number after the third digit. If the digit is 5,6,7,8 or 9 we add one to the third digit (and carry 1 if it becomes 10, etc) and then truncate after the third digit. Hence:

1.233	becomes	1.23
1.235	becomes	1.24
1.237	becomes	1.24
1.299	becomes	1.30
0.9995	becomes	1.00

Scientific Notation

Another problem that tends to be raised rather than solved by electronic calculators is the use of **scientific notation** for numbers. When numbers grow to more than the eight figures that calculators can display (because the calculation has grown rather large or rather small), the calculator switches to a display format in which the number is divided into two parts: the first (called the **mantissa**) is a number between 1 and 10, the second part (called the **exponent**) is the numbers of powers of ten that the mantissa needs to be multiplied by to get the number represented. This is called scientific notation and familiarity with it will help you with formulae that contain very large and very small numbers.

Thus if you divide 1 by 88888888 on your calculator, it will probably display 1.125-08 (i.e. 1.125×10^{-8}), where 1.125 is the mantissa and -8 is the exponent.

Some more examples:

1234	is	1.234×10^3
20.0	is	2.0×10^1
0.3	is	3.0×10^{-1}
0.025	is	2.5×10^{-2}
1000000000	is	1.0×10^9
0.00000001	is	1.0×10^{-8}

How do we perform arithmetic on numbers in scientific notation? For addition (or subtraction), it is first necessary to convert both numbers to the same exponent - the same numbers of powers of ten - then add (or subtract) the mantissas. Thus:

$$2.0 \times 10^3 + 1.2 \times 10^2$$
$$= 2.0 \times 10^3 + 0.12 \times 10^3$$
$$= 2.12 \times 10^3$$

i.e. $2000 + 120 = 2120$

$$1.5 \times 10^3 - 6.5 \times 10^2$$
$$= 15.0 \times 10^2 - 6.5 \times 10^2$$
$$= 8.5 \times 10^2$$

i.e. 1500 - 650 = 850

For multiplication, the mantissas are individually multiplied and the exponents added. For division, the mantissas are individually divided and the exponents subtracted. Thus:

$$2.0 \times 10^3 \times 1.2 \times 10^2$$
$$= (2.0 \times 1.2) \times 10^{(3+2)}$$
$$= 2.4 \times 10^5$$

i.e. 2000 x 120 = 240000

$$1.5 \times 10^3 / 2.5 \times 10^2$$
$$= (1.5 / 2.5) \times 10^{(3-2)}$$
$$= 0.6 \times 10^1$$
$$= 6$$

i.e. 1500 / 250 = 6

You may find this summary useful:

$$10^a \times 10^b = 10^{a+b}$$
$$10^a / 10^b = 10^{a-b}$$
$$1 / 10^a = 10^{-a}$$

Large and small quantities

A common problem when drawing up a table of figures or a graph, is that the numbers may be very large or very small when expressed in the standard units. Thus we might have a table of periods of vibration of an acoustic resonator:

Length (m)	Period (s)
0.25	0.0062
0.30	0.0086
0.35	0.011
0.40	0.023

(the numbers used are for demonstration only) We can achieve a much neater form of table by heading each column with an appropriately scaled unit:

Length (mm)	Period (ms)
250	6.2
300	8.6
350	11
400	23

Alternatively we could have written 'Length (10^{-3}m)', etc. What we are doing here is to take a common exponent out of all the numbers to get a sensible range of numbers in the table or on the axis of a graph. It is good practice to use the standard multipliers shown in section 1.1, or to try to keep to the third powers: .., 10^6, 10^3, $1, 10^{-3}$, 10^{-6},..

1.6 Exercises

Use these exercises to test your understanding of the chapter.

1. Fill in the blanks:

   a)   The frequency of a periodic event is measured in _____.

   b)   An event that repeats 1000 times per second has a frequency of _____.

   c)   The density of air is about _____.

   d)   An event that repeats 10,000 times per second has a period of _____.

   e)   5cm is _____ m.

2. Express the following in scientific notation to three significant figures:

   a) 61743 6.17×10^4

   b) 20000

   c) 0.02

   d) 1/500

   e) 1/0.05

   f) 2556×10^{-4}

   g) 0.0564×10^5

3. Simplify the following:

   a) $10^4 \times 10^5$

   b) $10^4 \times 10^{-3}$

   c) $10^{-6} \times 10^3 \times 10$

   d) $10^1 \div 10^{-3}$

2. Experiments

UCL's courses in speech and hearing invariably contain a laboratory component. Laboratory work adds to and backs up lecture material, it provides 'hands-on' experience with acoustics equipment and phenomena, and it encourages a discipline of experimental study. In this chapter we look at two aspects of laboratory work for which students need to be prepared: the drawing and analysis of graphs, and logarithmic scales.

2.1 Graphs

We shall be concerned exclusively with **X-Y graphs,** that is graphs that show how one measured parameter varies with the specification of one controlled parameter. Thus in the measurement of the period of a pendulum, we set the length of the pendulum and measure the time taken for it to complete a swing.

The parameter that we set (the length of the pendulum) is called the **independent variable** - it's the one that can have values independent of anything else. By convention we plot this along the **horizontal axis** of the graph: the **X-axis.**

The parameter that we measure (the period of the pendulum swing) is called the **dependent variable** -it's the one that depends on the setting of the independent variable. By convention we plot this along the **vertical axis** of the graph: the Y-axis.
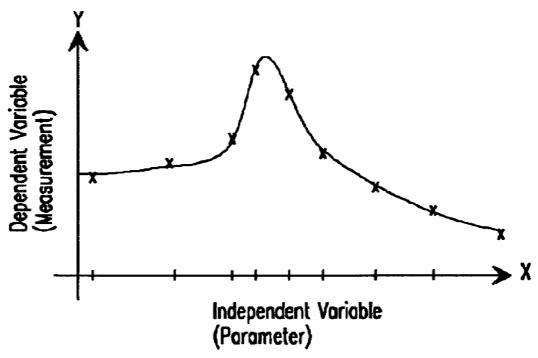

Figure 2. Prototype X-Y graph.

Graph drawing hints

1. Each graph should have a title so that it can stand alone.
2. Each axis should be labelled with the measurement and the units of measurement.
3. Choose values of the independent variable (where possible) so that points are spread evenly **along the line of the graph.** This ensures that you have more points (per X-axis unit) where the graph is changing rapidly, see Fig 2.
4. Mark points on the graph with small crosses. When drawing in a connecting line, draw a smooth continuous line that approximates the position of the points. Use a ruler to draw a straight line fit in circumstances where this is appropriate.
5. When there is more than one line on a graph, draw them in different colours. Remember to provide a key.
6. Preferably use the grid lines on graph paper to represent 1, 2 or 5 basic units, and never to represent 3, 6, 7 or 9 units.

Equation of a straight line graph

Many X-Y graphs produce what looks like a simple linear relationship between the independent and the dependent variable. This means that the value of the dependent variable increases by some constant when the value of the independent variable is increased by a constant - regardless of the value of the independent variable. This is commonly called **a straight-line graph.**

We can express a linear relationship between the dependent and the independent variable with the following equation:

Dependent Variable = Slope × Independent Variable + Constant

Or, using conventional symbols:

y = m × x + c

Here, **y** is the dependent variable, **x** is the independent variable, **m** is the **slope** or **constant of proportionality**, and **c** is a constant known as the **intercept** (for it represents the value of **y** where the line intercepts the y-axis).

To measure the slope and the intercept off a graph, we proceed as follows (refer to Figure 3):

1. Draw in a straight line approximating the measured points.
2. Find a convenient range of **x** on the graph - say about 2/3 of the length of the x-axis. Call this range **Dx**. It will have the measurement units as the x-axis
3. For this range of **x** values, find the corresponding range of **y** values **using the straight line.** Call this range **Dy**. It will have the same measurement units as the y-axis.
4. Calculate the slope of the graph from: slope = Change in **y** / Change in **x**
        m = Dy / Dx
5. Measure the intercept by noting where the straight line crosses the y-axis (i.e. the value of the line when **x** is 0). This can be positive or negative depending on whether the line crosses the y-axis above or below the x-axis.
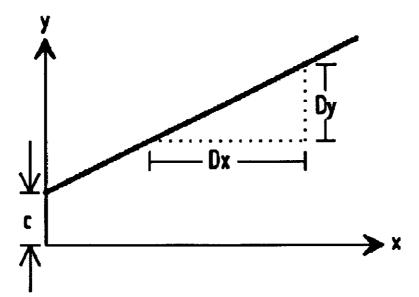   **c** = intercept

Figure 3. Equation of a straight-line graph.

When the slope and intercept have been calculated, new values of y can be predicted from values of x and vice-versa, using:

$$\mathbf{y} = \mathbf{m} \times \mathbf{x} + \mathbf{c}$$

or

$$\mathbf{x} = (\mathbf{y} - \mathbf{c}) / \mathbf{m}$$

2.2 Logarithmic Scales

There are occasions where the independent and the dependent variable have a different kind of relationship with one another - one that is not simply linear.

Consider the circumstances when a constant added to an x-value changes the y-value by a constant multiple. For example: adding 2 to **x** might make **y** increase by 50% of its current value.

A relationship like the following is one of these:

$$\mathbf{y} = \mathbf{a} \times \mathbf{b}^{\mathbf{x}}$$

Where **a** and **b** are constants. Thus if **a**=1 and **b**=2, then y would be equal to 2 to the power of x and we would get the following table of results:

x	y
1	2
2	4
3	8
4	16

Here **y** doubles for every increase in **x** by 1.

It turns out that we find many such relationships in acoustics. People's judgements of intensity or pitch appear to be based on proportional changes in the physical parameter, rather than on incremental changes. Musical notation is based on the concept of **octaves,** where one octave spans a doubling in the fundamental frequency of the note. So for every octave we go up a musical scale, the frequency of the note doubles.

How are we to work with such relationships, and to graph them? The first problem we have is that the line on our graph of **y** against **x** is not a straight line. The second is that the **y** values increase at an alarming rate. In the example above, when **x** reaches 20, **y** reaches 1 million!

If you are familiar with logarithms, you will know that we can transform the equation

$$\mathbf{y} = \mathbf{a} \times \mathbf{b^x}$$

to

$$\log(\mathbf{y}) = \log(\mathbf{a}) + \log(\mathbf{b}) \times \mathbf{x}$$

by taking logarithms of both sides of the equation. We now have an equation which looks like the formula for a straight line graph (slope=log(b), intercept=log(a)).

If you are not familiar with logarithms, read the next section.

Introduction to Logarithms

If you have read this booklet this far, and have understood chapter 1, you have already understood the basics of logarithms. How? Because in section 1.5 we introduced the following formulae:

$$10^a \times 10^b = 10^{a+b}$$
$$10^a / 10^b = 10^{a-b}$$
$$1 / 10^a = 10^{-a}$$

These, you remember, were the formulae for manipulating the exponents of numbers in scientific notation. We use them to find out that:

$$10^4 \times 10^2 = 10^6 \qquad \text{i.e.} \qquad 10000 \times 100 = 1000000$$
$$10^{-3} / 10^{-5} = 10^2 \qquad \text{i.e.} \qquad 0.001 / 0.00001 = 100$$

The whole basis of logarithms is that these formulae hold even when the values a and b are not whole numbers. Thus the following are also correct:

$$10^{1.3} \times 10^{2.6} = 10^{3.9}$$
$$10^{0.8} / 10^{-1.5} = 10^{2.3}$$

It only remains to ask what the number $10^{1.3}$ actually represents. Refer to Figure 4:
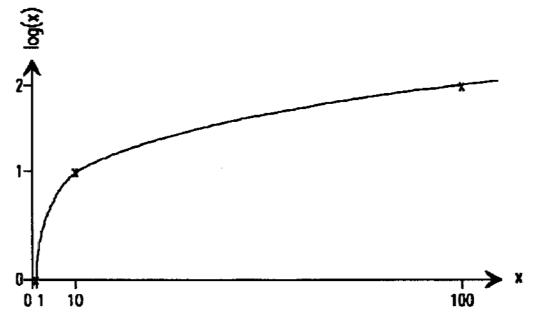
Figure 4. Logarithm of x, plotted against x, showing how fractional logarithms might be assigned values.

Thinking of the y-axis in Figure 4 as representing 'powers of ten' for a minute, you can see that 10^0 is 1, 10^1 is 10 and 10^2 is 100. But you can also see that we could define values for fractional powers of ten, for example that $10^{1.3}$ would be about 20. Any number can then be expressed as a power of 10; just that this might require a fractional power of 10. You can use the following approximate conversions to verify the calculations above:

$$10^{1.3} = 20 \qquad 10^{2.6} = 400 \qquad 10^{3.9} = 8000$$
$$10^{0.8} = 6.3 \qquad 10^{-1.5} = 0.0315 \qquad 10^{2.3} = 200$$

(You can check these on your calculator if it has a 10^x button or a y^x button - in the first case type the exponent and then the 10^x button; in the second, type in 10, then the y^x button, then the exponent. You will get values that are close to those above).

These fractional exponents are the **logarithms** of the numbers we have calculated here. 1.3 is the logarithm of 20, since $10^{1.3}$ is 20. Likewise 2.6 is the logarithm of 400, because $10^{2.6}$ is 400.

Since 10 is not a magic number, and we could have gone through the whole explanation with some other number just as well, we sometimes make this explicit in the words: 1.3 is the logarithm of 20 in the base 10, or $\log_{10}(20)$ is 1.3.

To find the **logarithm** of a number, you really have to use a calculator or a set of tables. Electronic calculators usually have a button marked log which calculates the logarithm (the exponent of 10) corresponding to the number you have typed in. So:

$$\log_{10}(20) \qquad = 1.3$$
$$\log_{10}(6.3) \qquad = 0.8$$
$$\log_{10}(0.0315) \qquad = -1.5$$

And the reason this is important? The explanation is in those formulae for manipulating exponents: multiplying two numbers together is the same as adding their logarithms, dividing two numbers is the same as subtracting their logarithms. And importantly when one number is raised to the power of another, this is the same as multiplying the logarithm of the first by the power. In summary:

$$Y = A \times B \quad => \quad \log(Y) = \log(A) + \log(B)$$

$$Y = A / B \quad => \quad \log(Y) = \log(A) - \log(B)$$

$$Y = A^B \quad => \quad \log(Y) = \log(A) \times B$$

Thus to multiply A by B using logarithms, we add together the log of A and the log of B to obtain the log of the answer (Y). We then change log(Y) back to a real number by calculating $10^{\log(y)}$ with your calculator's 10^x button or with its inverse-log function.

Powers of ten

Since logarithms are based on powers of 10, the correlation between scientific notation and logarithms is fairly simple:

Number	Power of 10	Logarithm
10,000,000	10^7	7
1,000,000	10^6	6
100,000	10^5	5
10,000	10^4	4
1,000	10^3	3
100	10^2	2
10	10^1	1
1	10^0	0
0.1	10^{-1}	-1
0.01	10^{-2}	-2
0.001	10^{-3}	-3
0.0001	10^{-4}	-4
0.00001	10^{-5}	-5
0.000001	10^{-6}	-6
0.0000001	10^{-7}	-7

Logarithmic Graph Paper

This is just graph paper where the divisions are spaced in such a way that equal proportional change becomes equal distance along the page. Thus on logarithmic graph paper, the distance between 1 and 10 is the same as that between 10 and 100 or between 25 and 250. See Figure 5.
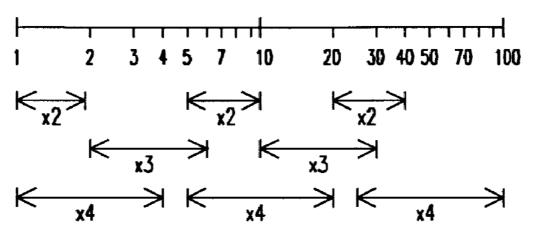
Figure 5. A logarithmic scale, showing equal multiples as equal distances

When you plot a set of points xl, x2, x3, x4, etc on logarithmic graph paper, the spacing between points is the same as if you plotted log(x1), log(x2), log(x3), log(x4), etc on normal graph paper.
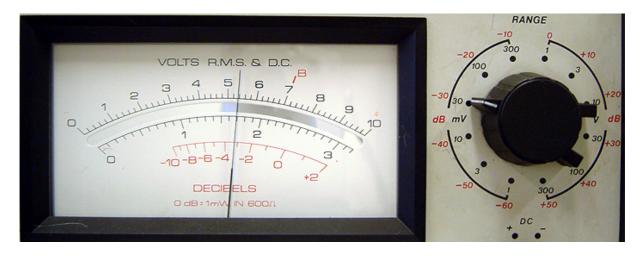
2.3 Laboratory Equipment

How to read an analogue voltmeter

The voltmeters that we use in the lab experiments consist primarily of a meter and a range switch. The meter has two main scales that we are interested in: 0 – 10 above the mirrored area and 0 – 3 below. On the range switch we are interested in the black values from 1mV – 300V.
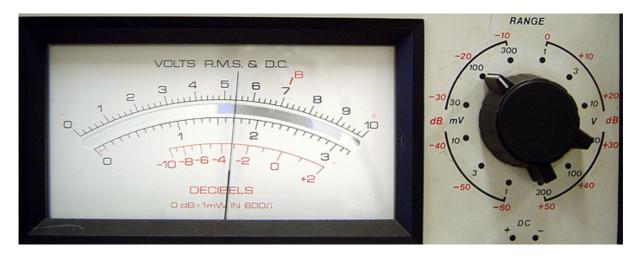
To read the meter you first need to look at the range switch. This tells you what the meter will read when the needle is at Full Scale Deflection (FSD) i.e. at the end of its range. If the number on the range switch begins with a 1, i.e. 1mV, 10mV… you use the top scale on the meter (0-10). If it begins with a 3, i.e. 3mV, 30mV … you use the bottom scale (0-3) then using this information read the appropriate value off the meter. The values on the left-hand side of the range knob are in milliVolts and the right-hand side are in Volts.

Look at the example above. As the range knob is set to 30mV, we use the bottom scale (which will read 30mV full scale). Therefore the 1 corresponds to 10mV and the 2 to 20mV. Each of the smaller divisions correspond to 1mV (note that there are 10 divisions between 1 & 2) therefore the reading is 10mV + 7mV = 17mV

Look at the example above. As the range knob is set to 100mV, we use the top scale (which will read 100mV full scale). Therefore the 1 corresponds to 10mV the 2 to 20mV … and the 9 to 90mV. Each of the smaller divisions correspond to 2mV (note that there are only 5 divisions between 5 & 6) therefore the reading is 50mV + 4mV = 54mV

How to use a Sinewave Generator

The oscillators that we use in the lab can be divided into two parts, each with a set of buttons and a knob. The buttons provide the coarse control and the knobs the fine control. The left-hand buttons and large knob are for setting the frequency (which we hear as changes in pitch) and the right-hand ones and the small knob below for setting the amplitude (which we hear as change in loudness).

To set the frequency first select the appropriate range using the buttons and then use the large knob to set the exact frequency (note that the scale on this varies as you go round the dial).

In this example the x 1k button is depressed denoting that all the values on the dial should be multiplied by 1000. The dial is reading 1.85 which means the frequency is set to 1850Hz or 1.85kHz

Use the 4 buttons between **Square** and **Mains** to set the course amplitude and the small knob below for fine adjustment. The **Square** button changes the waveform shape and should normally be left in the out position. The **Mains** button turns the oscillator on and off.

In this example the x100mV button is depressed denoting that all the values on the dial should be multiplied by 100mV. The dial is halfway between the 5 & 6 so an output voltage of about 550mV has been set. Because it is difficult to set a voltage accurately using only this dial, all output levels should be checked using a voltmeter
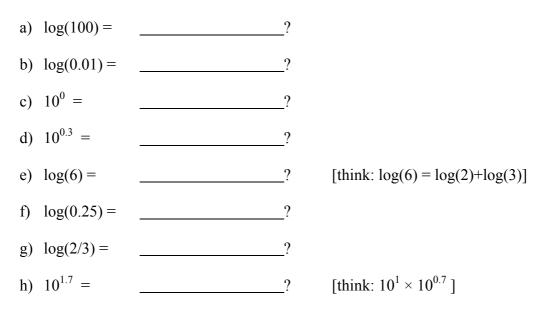
2.4 Exercises

Use these exercises to test your understanding of the chapter.

1. Given the following (approximate) logarithms to base 10:

$\log(2) = 0.3 \quad \log(3) = 0.48 \quad \log(4) = 0.6 \quad \log(5)\ 0.7$

Find approximate solutions to the following sums *without using a calculator*:

a) $\log(100) =$ _____?

b) $\log(0.01) =$ _____?

c) $10^0 =$ _____?

d) $10^{0.3} =$ _____?

e) $\log(6) =$ _____?   [think: $\log(6) = \log(2) + \log(3)$]

f) $\log(0.25) =$ _____?

g) $\log(2/3) =$ _____?

h) $10^{1.7} =$ _____?   [think: $10^1 \times 10^{0.7}$]

2. The following measurements were made from a straight line graph:

When X is 0, Y = 12
Change in Y for 4 units along the X axis = 3.2

a) What is the equation of the line?

b) What is the value of Y when X is 20?

c) What is the value of X when Y is 20?

3. Mechanics

The reason you can perceive sources of noise outside your body is that vibrating objects cause changes in the pressure of the air and these pressure changes propagate through the air away from the source to your ear. If these pressure changes are large enough and within a certain range of frequencies, you perceive these as sound. To get an understanding of what constitutes sound we first need to consider some basic principles of mechanics, specifically the notions of **force** and of **energy.**

3.1 Force

Force

Left alone, objects do not change their velocity. Here the technical term 'velocity' includes both speed and direction. Thus if no external forces are operating objects are either at rest or travelling at constant speed in a single direction.

To change the velocity of an object (its speed or its direction or both) requires an applied force. If we throw a ball, then the ball starts at zero velocity in our hand; its velocity increases as our hand moves forward, until it leaves our hand at which point it has reached maximum velocity (the velocity of our hand). If it weren't for air or gravity it would fly at constant velocity in a straight line from then on.

To make the ball travel faster we need to move our hand more quickly - we need to increase the acceleration of both ball and hand - we have to **push** harder. Thus we can see that the acceleration we can obtain is related to the size of the applied force. The relationship is a direct one, so we can write:

Acceleration obtained is proportional to the applied force.

We also know that the acceleration we can obtain will also depend on the mass of the ball - the greater the mass, the smaller the acceleration:

Acceleration obtained is inversely proportional to object mass.

Using standard units, the relationship between force, mass and acceleration can be written as simply:

Force ($kgms^{-2}$) = Mass (kg) . Acceleration (ms^{-2})

The units for force: **$kgms^{-2}$** are so commonly used they are given a special name: the **newton,** written N.

Going back to the car that accelerated at $2.45ms^{-2}$ in section 1.3, what was the force applied by the engine on the road? We need to know the mass of the car: well a Mini weighs about 650kg, so let's use that:
Force (N) = 650. 2.45 = 1590N

Dynamics and Statics

Thus far we have viewed force as something that accelerates masses. However forces can exist in circumstances where no mass is being accelerated - those circumstances are when more than one force are in balance with each other. Thus when you carry a bag of shopping, the force caused by gravity on the shopping - its weight - pulls on your arm. The muscles in your arm pull back upward with exactly the same force, so the shopping doesn't move. However those muscles are now pulling on your shoulder blade which is pushing your skeleton down towards the ground - ultimately all of the force required to hold up the bag of shopping is relayed to the force applied by your feet on the ground (totalling your weight and the weight of the shopping). If the ground where you are standing is solid, it conveniently supports your weight that is it presses back on your feet the same force that they apply to the ground. Thus all forces are in balance and nothing is moving or accelerating.

The tricky concept is that the forces still exist and they have measurable quantity even though nothing is moving. It is only when the shopping bag splits and the tins fall out that the forces are dynamically manifested. The mixing of forces and movement has other consequences as we shall see in section 3.2.

Pressure

In many circumstances when we measure force, we are interested in the total amount of force being applied: the force on the ball while it being thrown, the weight of an object pushing down on a table. There are forces however, where the simple quantity of force is not very useful: the weight of the atmosphere for example, or the force caused by a single molecule bouncing off the inside wall of a bicycle tyre.

In these circumstances we are more interested in the amount of force **per unit area.** This is called **pressure** and is measured in **newtons per square metre** or **Nm^{-2}.** This unit too, has a special name of its own: the **pascal,** written Pa.

Thus a definition of pressure is:

Pressure (Pa) = Force (N) / Area (m^2)

The pressure inside a gas is of special interest in acoustics, since we know that sound waves in air are manifested as small fluctuations in air pressure. The pressure in a gas is due to the movement of its constituent molecules which continually bump into each other and the walls of the containing vessel. Inside a gas, the pressure is independent of the direction of measurement.

The range of fluctuations of air pressure that our ears perceive as sound are very small: from about 0.00002Pa (20μPa) to about 200Pa. These are between 1/500 and 1/5000000000 of atmospheric pressure. Note both the size and the range of these numbers!

In the case of air, gravity keeps the atmosphere close to the surface of the Earth. At the top of the atmosphere the pressure is zero, at the surface of the earth the pressure is approximately 100kPa (100,000Nm^{-2}). This is equal to the weight of 10,000kg of air spread over 1 square metre. If the air had a constant density of 1kgm^{-3} then this pressure could be said to be the consequence of a column of air 10km high. Since the atmosphere actually reduces in density with height it is actually over 30km thick. The reason such an enormous pressure doesn't crush us into the ground is that the pressure is exerted in every direction both inside and outside our bodies - the forces are in balance.

Instruments for measuring air-pressure are called **barometers.** Barometers are often calibrated in milliBars, 1 milliBar is 100Pa. Car tyre pressures are still measured in Imperial units: pounds per square inch (psi); 1 pound per square inch is approximately 7000Pa.

3.2 Energy

The concept of energy allows us to unify our ideas about a number of physical and chemical processes. Whether we are talking about **heat-flow** (changes in temperature), **work** (forces in movement), or **potential** (internal energy), the concept of energy as a unit of currency helps us describe and quantify change. In all processes that involve these phenomena, the units of energy may change form but the total number of units is constant.

Different forms of energy

What is energy? Well it is something you need if you are going to do some work. What is work? You do work when you exert a force in circumstances that you move something. So to lift something from the floor requires you to exert a force on it equal to its weight. In the lifting from the floor you are doing work, and this requires energy from you.

Where does this energy come from? When you lift something there are changes in chemicals in the muscles of your body: energy that is stored in the bonds that tie the components of a molecule together is released when the bonds are broken. Where does the energy go to? Most of it goes into the object you've lifted off the floor, it is now further from the centre of the earth and has more potential to damage something if it falls. In lifting an object, you are transferring energy from you to the object.

An object has energy if it has potential to do work. We shall call this the **internal energy** of the object. This energy can be stored in many forms: potential energy (if the object is subject to a force - such as gravity), kinetic energy (if the object is moving), electrical energy (if there is an imbalance in positive and negatively charged particles), chemical energy (molecular bonds), heat energy (molecular vibration), and others.

Now the internal energy of an object can change for only two reasons: (i) it does some work on another object (in which case the internal energy of that other object increases) or (ii) it loses energy as heat (in which case the temperature of the surroundings increases).

We are ready to make two important observations:

1. Energy is energy regardless of what form it takes. Thus we only need one unit to measure energy.
2. Energy can neither be created nor destroyed, it can only be converted from one form to another.

We can combine these two ideas together in a single formula:

Decrease in internal energy of an object =
    Increase in heat energy of surroundings +
        Any work done by the object (on another object)

This is called the 'first law of thermodynamics' or the law of conservation of energy.

And the units of energy? Well they must be the units of work:

Work done (Nm) = Force (N) × Distance (m)

Thus the units of energy are **newton-metres** or **Nm.** This derived unit has a special name: **joules,** written J.

If you climb a set of stairs 15m high, and you weigh 66kg, then you have exerted a force of about 650N (66kg × 9.81ms^{-2}) and spent about 10kJ of energy (650N × 15m). This is about as much energy as you benefit from eating a spoonful of plain yoghurt. However you also get hot and move a lot more than is absolutely necessary: so your actual energy expenditure is greater than this.

> A typical person will take in food with a total useful energy of about 10,000kJ (10MJ) per day, about the same as a washing machine uses to wash a load of clothes. A dry cell battery contains about 4kJ of energy that it can provide as electrical current. A 2-litre pan of boiling water has about 650kJ more energy than a pan of cold water.

> Units of food energy are still commonly measured in **calories** (more correctly **kilocalories),** 1 kilo-calorie is about 4.2kJ. So a spoonful of sugar of 50 kilocalories contains about 210kJ.

Power

There are occasions when it is appropriate to ask 'how fast is the energy being used?' The rate of energy consumption or production is a useful measure of a continuous process. Thus although we might measure the total amount of energy generated by an exploding stick of dynamite, we are more likely to be interested in the amount of energy per unit time generated by a power station.

The concept of energy rate is called **power:**

Power (Js^{-1}) = Energy spent (J) / Time taken (s)

The units of power are **joules per second** or **Js^{-1}** which has the special name **watts,** written W.

A bar on an electric fire takes in energy from the mains supply at the rate of 1000W (or 1kW = 1000Js^{-1}). Thus every hour a one bar electric fire uses 3600s × 1000Js^{-1} = 3.6MJ of energy. You will see this unit of energy (3.6MJ) referred to as a 'kilowatt-hour' and it is the basic unit in which we buy energy from the electricity company. 3.6MJ of electricity costs about 10p.

Intensity

There are other circumstances when direct measurement of energy or energy rate are impossible or irrelevant. Consider the measurement of the energy provided by the sun. We can't measure how much energy is in the sun. We can't measure the total amount of energy radiated per second from the sun. What we can measure is how much energy falls onto the surface of the earth over a given area. Here we are interested not only in energy rate, but energy rate per unit area - it's like saying how much energy per second is coming through my window from the sun.

Energy rate (power) per unit area is called **intensity:**

Intensity (Js^{-1}m^{-2}) = Energy rate (Js^{-1}) / Received Area (m^2)

Intensity is measured in Joules per second per square metre, or **watts per square metre,** written **Wm^{-2}.**

The intensity of the sun at the surface of the earth on a clear day is about 1000Wm^{-2} - a one bar electric fire on every square metre of earth.

We use intensity to measure sound energy, since in general we cannot capture all the energy radiated by a sound source - we only measure that which happens to enter the front of our microphone. Knowing the rate of energy hitting our microphone and its surface area we can calculate the intensity of the sound at the microphone.

3.3 Exercises

Use these exercises to test your understanding of the chapter.

1. How much chocolate would I need to spread over a 1m^2 surface to generate a pressure underneath of 1Pa? (assume g=10ms^{-2}). If I spread that amount of chocolate over 1/20 of the area, how does the pressure change?

2. Winding a grandfather clock involves lifting a weight of 250g up a distance of 0.8m. Taking the acceleration due to gravity (g) to be 10ms^{-2}, how much more energy does the fully wound clock have over the fully unwound one?

3. If the intensity of a sound at 2m from the source is 10Wm^{-2} , what would be the intensity at 6m from the source if the energy was radiated equally in all directions? (Hint: the total power at 2m is distributed over the surface of a sphere of radius 2m, but the total power at 6m is distributed over the surface of a sphere of radius 6m).

4. Acoustics Glossary

This glossary defines those terms that we use a lot in our teaching that have not been described earlier in this booklet. Descriptions of more acoustic terms can be found in a hyper-linked acoustics glossary at: http://www.sfu.ca/sonic-studio/handbook/index.html

amplitude

Amplitude is used to indicate the size of the variation in a signal, or the amount of a *sinewave* component present in a signal. For sound pressure signals, amplitude is usually measured in Pascals. For electrical signals, amplitude is usually measured in Volts. When describing the amplitude of a sinewave component of a sound, typically a *decibel* scale is used, with respect to some reference amplitude.

aperiodic

An aperiodic signal has a *waveform* that does not repeat in time. *Noise* signals are aperiodic by definition.

bandwidth

Bandwidth is a characteristic of systems most commonly applied to simple *resonators*. The bandwidth of a simple resonator is the range of frequencies about the resonant frequency within which the response is within 3 *decibel*s of the peak response. Sometimes the term is applied to complex systems, in which case it usually refers to the width of a frequency region within which the response does not vary by more than 3 decibels. Bandwidth is the frequency domain measure of *damping*: heavily-damped systems have a wide bandwidth, lightly-damped systems have a narrow bandwidth.

damping

Damping is a characteristic of systems most commonly applied to simple *resonators*. The damping in a system refers to how rapidly vibrations in the system die away after excitation with an input *pulse*. In heavily damped systems, vibrations die away quickly; in lightly damped systems, vibrations can continue for some time after the pulse has passed through. Don't confuse damping with attenuation: a heavily damped system can still amplify a sound.

decibel (dB)

The decibel scale is a logarithmic amplitude scale, in which the size of a vibration is expressed in terms of its relative size to some reference vibration. To convert a relative amplitude to decibels, it is satisfactory to take the logarithm of the ratio (to base 10) and to multiply by 20. Decibels are convenient to use in acoustics because many systems operate in

a multiplicative manner rather than in an additive manner. For example an amplifier might change the amplitude of a signal by a factor of 10 rather than by 10V. A doubling of amplitude is equivalent to a change of 6dB; an increase by a factor of 10 is equivalent to a change of 20dB. In the dBSPL scale of sound pressure, the reference amplitude is taken to be 20μPa.

filter

A filter is a system that has been designed to change the *spectral* content of a signal for a particular purpose. For example, a **low-pass filter** is a system which strongly attenuates frequency components in a signal above a given cut-off frequency. A **high-pass filter** is a system that strongly attenuates frequency components in a signal below a given cut-off frequency. A **band-pass filter** is a system that strongly attenuates frequency components outside a given range of frequencies. The vocal tract is sometimes called a filter when it is being used to shape the larynx excitation signal.

forced oscillation

The *frequency response* of a system can be explored by passing *sinewave* signals through the system, and by measuring the relative size of the output amplitude with respect to the input. The forcing of a system to vibrate at a single sinewave frequency is called forced oscillation.

formant

A formant is another name for a *resonance* in the vocal tract that leads to a peak in the *frequency response* of the vocal tract system. The name formant comes from the shaping effect these resonances have on larynx excitation – they give form to the output *spectrum*.

frequency

The frequency of a *sinewave* refers to the number of complete cycles of vibration completed in one second. The frequency of sinewave vibrations is measure in hertz (Hz). Do not use frequency to describe the repetition frequency of waveforms other than sinewaves; use *fundamental frequency* instead.

frequency response

The frequency response of a system is a graph of how the system responds to *sinewaves* of different frequency. A frequency response graph plots response (the ratio of the output amplitude to the input amplitude) for sinewave signals as a function of the frequency of those sinewaves.

Fourier analysis

Fourier analysis refers to the decomposition of a section of signal into a sum of *sinewave* components. The shape of the input waveform is analysed in terms of the *frequency*, *amplitude* and *phase* of a number of constituent sinewaves. The sinewave amplitude and frequency information is commonly plotted on a *spectrum*. Information is neither created nor destroyed by Fourier analysis, since the addition of the component sinewaves perfectly recreates the original signal. There are many similarities between Fourier analysis and the kind of frequency selective processing that takes place in the ear.

fundamental frequency

Fundamental frequency is a measure of the repetition rate of complex periodic signals; that is the number of repetitions of the basic *waveform* shape that occur in one second. Fundamental frequency is measured in hertz (Hz). You usually do not use the term fundamental frequency with *sinewave* signals, and it has no meaning for *aperiodic* signals.

harmonic

A harmonic is one of the constituent *sinewave* components found from Fourier analysis of a complex *periodic* waveform. Complex periodic signals have constituent sinewaves that occur only at whole-number multiples of the *fundamental frequency*. The first harmonic occurs at the fundamental frequency (and hence is sometimes called "the fundamental"), the second harmonic occurs at twice the fundamental frequency, the third at three times, and so on.

loudness

Loudness is one of three perceptual attributes of sound attested by human listeners. Loudness relates to the quantity of sound, and seems to be strongly affected by the *amplitude* of the pressure vibrations. However loudness is not linearly related to pressure change, and is more closely related the logarithm of the amplitude. This is why a *decibel* scale is commonly used for instrumental analysis of sounds.

noise

A noise signal is another name for an *aperiodic* signal. Do not use the term noise when you just mean "sound" or "interfering signal". Sometimes it is convenient to use the term "background noise" to refer to environmental sounds present when a recording is being made; and "system noise" to refer to unwanted signals added by systems as part of their operation.

periodic

A periodic signal has a repetitive *waveform* shape. Such signals are commonly produced by oscillating or cyclic sound generation systems. A distinction is sometimes drawn between

simple and complex periodic waveforms. Simple periodic waveforms are sinewaves; complex periodic waveforms are repetitive but not sinusoidal.

phase

The phase of a sinewave signal refers to the position in the sinewave cycle attained by the signal at a given time. Since a sinewave waveform shape can be simply related to the height of a point on a rotating disk, the phase of a sinewave is often measured as the angle a line drawn from the axis to the point makes with the horizontal. Thus phase is commonly measured in units of angle, for example degrees (0-360°) or in radians (0-2π).

pitch

Pitch is one of three perceptual attributes of sound attested by human listeners. Pitch relates to the "musical quality" of complex *periodic* sounds, and seems to be related to the *fundamental frequency* of the sound. Although pitch changes smoothly with increasing fundamental frequency, it appears that pitch is not linearly related to fundamental frequency, and there is strong evidence for a more logarithmic relationship.

pulse

A pulse is a short transient signal. A narrow pulse is often used to explore the *frequency response* of systems, since its *spectrum* has approximately the same amplitude at every *sinewave frequency*.

pulse train

A pulse train is a complex periodic signal made up of a regular sequence of *pulses*.

resonance

Resonance occurs when a system responds strongly to certain input signals. This happens when a frequency component in the input signal matches a preferred frequency of vibration of the system. The output of the system at resonance is larger than at other frequencies. Resonance can be measured by looking at the relative change in the amplitude of frequency components in the signal close to the resonant frequency.

resonator

A resonator is a system designed to exhibit strong *resonance* at one or more resonant frequencies. When a resonator is excited by an input sinewave signal at one of its resonant frequencies, a large response occurs. A simple resonator has exactly one resonant frequency.

sinewave

The term sinewave is short for sinusoidal *waveform*, and refers to a particular periodic waveform shape that follows a trigonometric sine function. This shape of signal is found in the simplest oscillating systems, for example a pendulum, a tuning fork, or a mass on a spring. Mathematically the sinewave signal y(t) has the form $a.\sin(2\pi ft+\varphi)$ where a=amplitude, f=frequency, t=time, and φ=phase.

source-filter model

The source-filter model of speech production provides a powerful explanation of the form of the *spectra* of speech sounds. In the source-filter model it is assumed that we can describe the generation of sounds in the vocal tract separately and independently from their subsequent shaping by their passage through the vocal tract. This is largely true for vowels, roughly true for fricatives and untrue for sounds like whistles. Thus for a vowel spectrum explained by the source filter model, we would say that the source is larynx excitation which has a particular spectrum independent of the vocal tract shape; and the filter is the vocal tract tube from larynx to lips that shapes the sound independently of the settings of the larynx.

spectrogram

A spectrogram is a graphical representation of how the *spectral* composition of a sound changes with time. The horizontal axis is time, the vertical axis is frequency (of sinewave components) and the amplitude of the sinewaves components of the signal at any given time and frequency is displayed on a grey scale. Conventionally, white is chosen for least amplitude, and black is chosen for most amplitude. For speech sounds, the frequency axis usually extends to 8kHz, and the amplitude scale covers the top 50dB of the amplitude of sinewave components.

spectrum (spectra, spectral)

A spectrum is a graphical representation of the amplitude of the *sinewave* components present in a signal within a given time window. A spectrum is calculated from a section of signal using *Fourier analysis*. A spectrum graph plots the amplitude of each sinewave component against the frequency of the component. The amplitude scale of a spectrum is commonly expressed in *decibels*. The *phases* of component sinewaves are not displayed on a conventional spectrum.

timbre

Timbre is one of three perceptual attributes of sound attested by human listeners. Timbre relates to the general quality of sounds other than that explained by pitch or loudness, and seems to be related to the overall *spectral* shape of the sound. The perceived timbre of complex sounds is well explained by a bandpass filter analysis matching the spectral analysis performed by human ears.
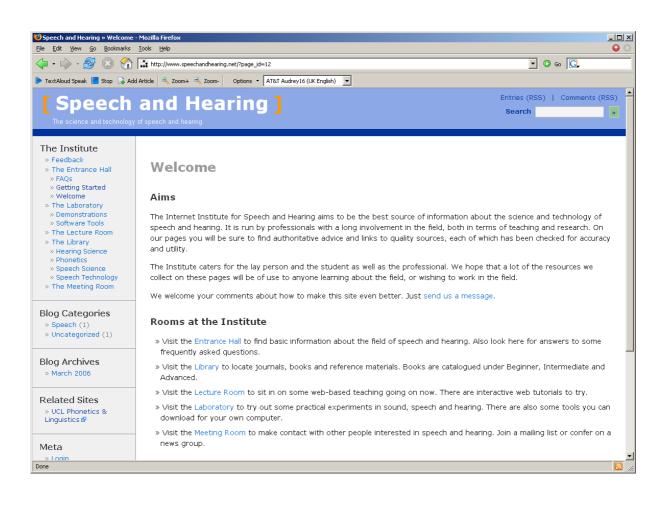
waveform

A waveform is a graph of how the *amplitude* of a signal changes with time.

white noise

White noise is a particular kind of *noise* signal that has approximately equivalent average amplitude of all its *sinewave* components.

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