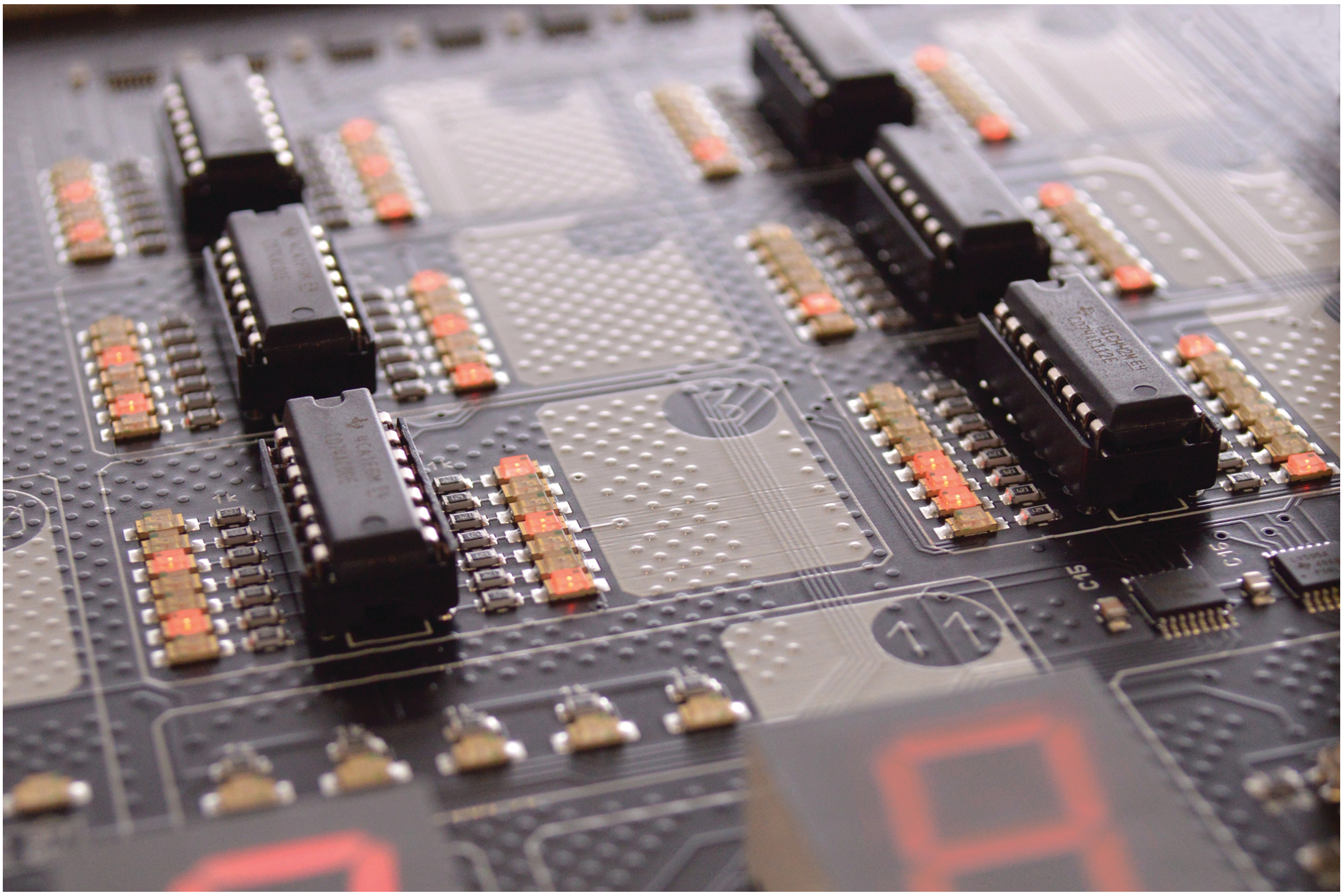
An introduction to electronics



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About this free course

This free course is an adapted extract from the Open University course T212 *Electronics: sensing, logic and actuation*: www.open.ac.uk/courses/modules/t212.

This version of the content may include video, images and interactive content that may not be optimised for your device.

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There you'll also be able to track your progress via your activity record, which you can use to demonstrate your learning.

Contents

Introduction

Electronics is fundamental to modern life. Using a variety of teaching material, including videos, self-assessment questions (SAQs) and interactive activities, this free course will show you how electronic devices and systems pervade everything we do, and explain some of the fundamental ideas underlying their operation.

Note that the interactive activities have been designed to work in the Firefox and Chrome browsers, so you will need to use one of these browsers if you want to access the interactive content.

This OpenLearn course is an adapted extract from the Open University course T212 *Electronics: sensing, logic and actuation*.

Learning Outcomes

After studying this course, you should be able to:

- recognise a variety of exciting high-tech products and systems enabled by electronics
- manipulate voltages, currents and resistances in electronic circuits
- demonstrate familiarity with basic electronic components and use them to design simple electronic circuits
- see how signals can be represented in the time and frequency domains for Fourier analysis
- record, analyse and filter audio signals to improve their fidelity.

1 Electronics everywhere

Electronics is the art of controlling the movement of electrons in order to design components and circuits that are put together to create the technology of the modern world. Increasingly electronics is at the cutting edge of technology, as illustrated in the following video.

Video content is not available in this format.

Electronics at the cutting edge

To get an insight into the central role that electronics plays in society, watch the video below.

Video content is not available in this format.

One day in the life of electronics

This section of the course will introduce you to the sensing–logic–actuation cycle, the three aspects of which form the basis of understanding electronics.

1.1 Autonomous systems

Any autonomous system has three fundamental aspects: sensing the environment using sensors, reasoning through logic and information processing, and then interacting with the environment through actuators. Together, these are known as the *sensing–logic–actuation cycle*, as shown in Figure 1.

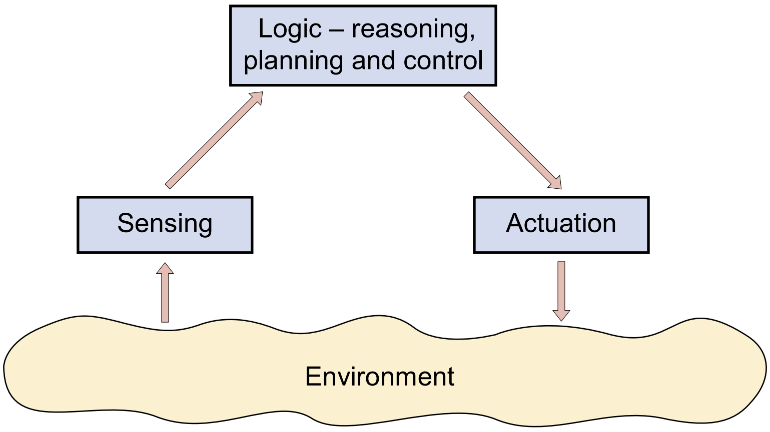
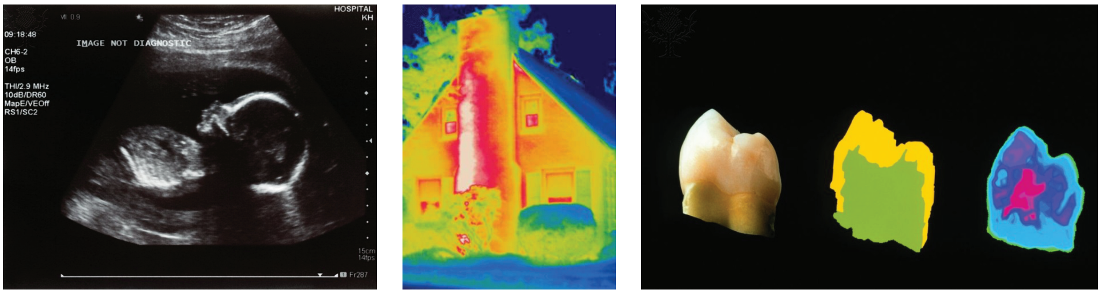


Figure 1 The sensing–logic–actuation control cycle for autonomous systems

Each of the three aspects of the sensing–logic–actuation cycle will be discussed briefly here.

Sensing

Electronic devices can sense the world, converting a wide variety of physical phenomena into electrical signals that communicate useful information. Such devices have capabilities similar to the five human senses: hearing (microphones), seeing (cameras), touch (piezoelectrics), and smell and taste (chemical sensors), although sometimes our human senses are better. However, electronic devices can sense things we cannot. For example, Figure 2 shows how ultrasound allows us to 'see' inside our bodies, infrared images allow us to 'see' patterns of heat and terahertz images allow us to see through opaque coverings.



(a) (b) (c)

Figure 2 Electronics allows us to perceive things beyond the human senses: (a) ultrasound image of an unborn baby; (b) infrared image of a house; (c) terahertz image of a tooth

The electrical signals generated by sensors can be processed in many useful ways. For instance, there are many sensors in modern cars linked to displays and alarms that inform the driver of the engine speed and temperature, whether or not the doors are properly shut, if all the passengers are wearing seatbelts, of the proximity of other vehicles when parking, and so on (Figure 3).

Figure 3 Distance sensors used in a car parking system

Logic

Sometimes the information from sensors is fed directly to a human being to act on, as in the car example. However, in many cases that information is unseen by humans and is used to control systems automatically. To do this requires the functions of reasoning and logic, which are usually carried out by logic circuits or programmable microprocessors (Figure 4). These decide what to do from one moment to the next and control the behaviour of the system.

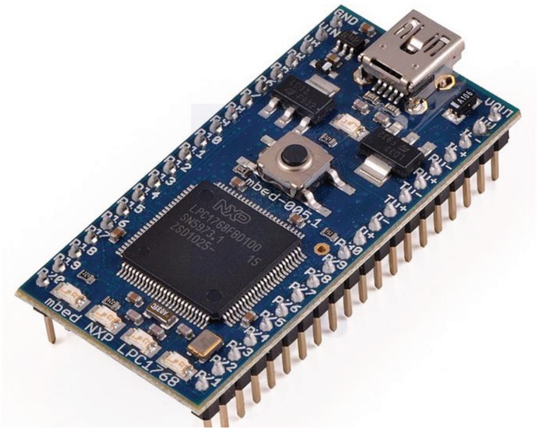


Figure 4 A board with a microprocessor capable of many millions of logical operations per second

Actuation

Actuators are components that control the movement in an autonomous system. In many systems, actuators of various kinds are controlled to give the desired behaviour. These include electric motors of various kinds, and other means of motion such as pistons driven by compressed air.

For example, the Oxboard shown in Figure 5 has two motors. You will learn more about the Oxboard in Section 1.2.

Figure 5 The Oxboard has two motor-wheel actuators

1.2 The sensing–logic–actuation cycle in practice

Watch the video below, which is a promotional video for Oxboard showing a child riding one of their two-wheeled devices. It is remarkable how the board responds to the way the rider moves his feet and body, and how controllable it is.

Video content is not available in this format.
A child riding an Oxboard

Figure 6 gives some of the details of the Oxboard's construction and use.

1. OXBOARD PRODUCT DESCRIPTION

1.1 Oxboard description

The Oxboard is a personal transporter. It is a board with two wheels, one on each side. Oxboard has two built-in motors fed by a battery pack. You can go forwards or backwards with the Oxboard but also take left or right-hand bends. The compact design also ensures that you can use the Oxboard both inside and outside.

The Oxboard is a clever device that reacts to how your weight is distributed. The trick is in particular to relax when standing on the Oxboard; the Oxboard will then ensure the best balance. The Oxboard will react directly if you distribute your weight "unevenly"; lean forward and you will move forwards, lean to the left and the Oxboard veers to the left, etc.

1.2 Oxboard components

1 Crash bumpers
2 Rubber mat with sensors below that sense how you are leaning on the Oxboard
3 Battery indicators
4 Motor, wheels and tyres
5 LED lights (x 2)
6 On button
7 Connector for charger

Figure 6 The Oxboard product description

Think about the sensing–logic–actuation cycle for the Oxboard transporter system. The board has sensors to detect the way the rider moves his feet and body. It uses logic to compute all the complicated forces associated with the motion; based on that information, it controls the two actuators (motor-driven wheels) to transport the rider in his desired direction.

SAQ 1

Draw a sensing–logic–actuation cycle for the Oxboard transporter using Figure 1 as a template.

Answer

A possible answer is shown in Figure 7.

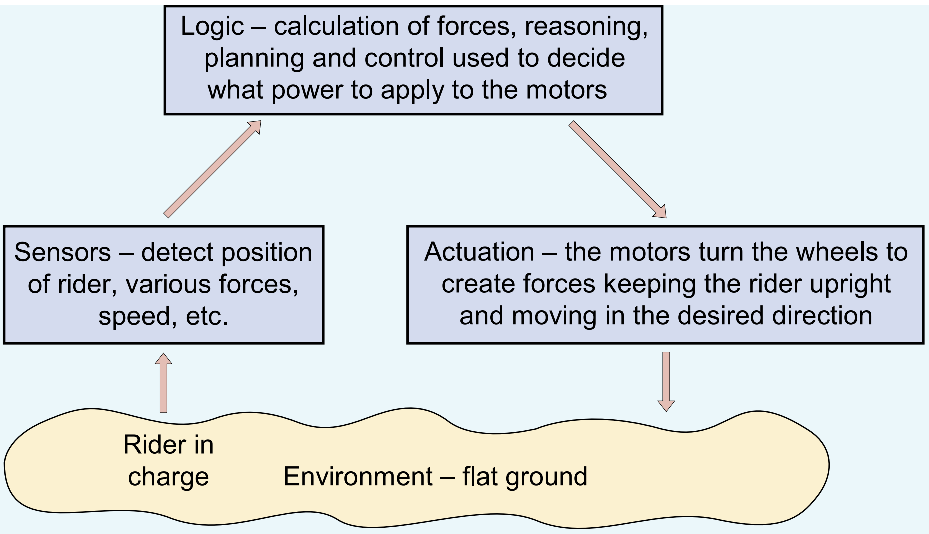


Figure 7 The sensing–logic–actuation control cycle for the Oxboard transporter

2 Basic theory of electrical circuits

Now that you have seen some of the applications of electronics through the sensing–logic–actuation cycle, let's return to fundamentals.

In what follows, you will look at one of the most important components in electronics: the resistor. This is an example of a *passive component* – a component that does not supply its own electricity. First, however, let's review some basic electrical quantities.

Note that the term DC means direct current such as that in a circuit powered by a battery. In contrast, the term AC means alternating current as provided by electrical mains suppliers.

2.1 Basic electrical quantities

The international standard units, *Système international d'unités* (SI units), that are commonly used for electrical quantities include coulombs, amperes, volts, ohms, watts and joules.

The fundamental unit of electricity is the negative charge of the electron or the positive charge of an ionised atom that has lost a single electron (resulting from the positive charge on the protons in the nucleus outnumbering that of the remaining electrons).

Electrical charge is measured in coulombs (symbol C). The charge on a proton is approximately 1.6×10^{-19} C, while the charge on an electron is the same magnitude but has the opposite sign (approximately -1.6×10^{-19} C). An electrical current is a flow of electric charge, measured in amperes (symbol A), where a current of one ampere is a total charge of one coulomb flowing in one second. Ampere is often abbreviated to amp.

In a circuit, positive and negative electric charges typically flow in the opposite direction to each other, as shown in Figure 8. This course will use conventional current flow, the predominant convention in the electronics industry, which is indicated in the direction taken by positive charges. In metal wires, the current is carried by electrons, which move in the opposite direction. This was not known at the time the convention was established.

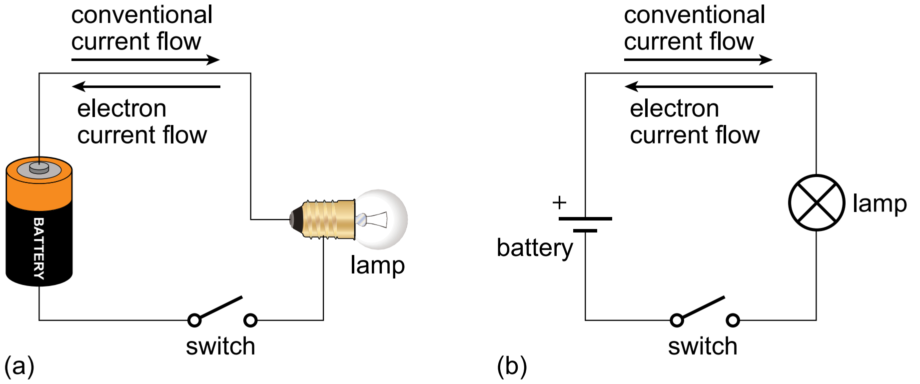


Figure 8 Current flow in an example circuit showing a light bulb (lamp) powered by a battery: (a) schematic using pictures to represent the components; (b) the same circuit using standard circuit schematic symbols. By convention, current flows in the opposite direction to the flow of electrons.

A quantity closely related to current is voltage. Voltage is a measure of the potential difference between two points. A potential difference of one volt (symbol V) will drive a coulomb of charge through a resistance of one ohm every second. Note that we usually refer to current flowing *through* a component such as a resistor, but to the voltage being *across* the component (because two points are required to define the voltage). Voltage can be expressed as the energy per coulomb of charge (J C^{-1}).

2.2 Relationships between quantities

For many materials, current and voltage are directly proportional to each other over a wide range of values, with the resistance as the constant of proportionality, so

voltage = current × resistance

Such materials are said to obey *Ohm's law* and are said to be ohmic. However, not all materials are ohmic in nature.

As current flows through a circuit, it transfers energy. When it flows through a material that has a non-zero resistance, this energy is used (for instance, to light a bulb or run a motor) or dissipated as heat (which is why electronics circuits sometimes feel warm, and why computers need cooling fans). As in every other context, the rate of change of energy is known as power, and can be measured in watts (symbol W).

In the context of an electrical current flowing through a resistor, the power used or dissipated can be calculated by multiplying the current flowing through it by the potential difference across the resistor, giving

power (watts) = current (amps) × potential difference (volts)

Before you move on, Table 1 recaps the electrical quantities mentioned so far, their units and how they relate to each other.

Table 1 Electrical quantities and their units

Quantity	Unit	Equation
energy	joules, J	
voltage (potential difference)	volts, V or energy per charge, joules per coulomb, J C^{-1}	
current	amps, A or charge per second, coulombs per second, C s^{-1}	
power	watts, W or energy per second, joules per second, J s^{-1}	power = voltage × current
resistance	ohms, Ω	resistance = voltage ÷ current

All the quantities listed in Table 1 can be measured in larger or smaller multiples of their standard unit using SI prefixes, which make it easier to read values at a glance. Some of these are listed in Table 2.

Table 2 Common prefixes for SI units

Prefix	Symbol	Multiple of standard unit		Example
micro	μ	one millionth	10^{-6}	microamp, μA
milli	m	one thousandth	10^{-3}	millivolt, mV
kilo	k	one thousand	10^{3}	kilo-ohm, kΩ
mega	M	one million	10^{6}	megawatt, MW

As you gain experience in electronics, try to notice the values of currents, voltages and other quantities for the components you see, and note the associated effects they are having on the circuit. This will help you to choose values when you design, and to troubleshoot when designs or circuits do not work.

2.3 Ohm's law and Kirchhoff's laws

Circuit behaviour follows some fundamental laws that allow you to calculate the expected values of voltage, current and resistance at any point in a circuit. These laws will now be explored mathematically.

Ohm's law

Ohm's law states that $\text{voltage} = \text{current} \times \text{resistance}$. This can also be written as

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

or, in symbols,

$$I = \frac{V}{R}$$

The algebraic symbol for current, I, comes from the French word *intensité*.

Kirchhoff's laws

Kirchhoff's first law (the current law)

At any junction, or node, in an electrical circuit, the sum of the currents flowing into the node is equal to the sum of the currents flowing out of the node.

This is the same as saying that charge can neither be stored at, nor dispensed from, these nodes. This is a useful rule of thumb – it helps when thinking about problems to be able to distinguish between places where energy can and cannot be stored.

This law is illustrated in Figure 9, where the sum of the currents in the inputs to the node equals the current out.

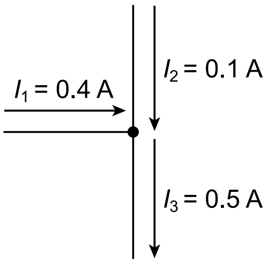


Figure 9 Kirchhoff's first law

Kirchhoff's second law (the loop or mesh law)

When direction is taken into account, the sum of the potential differences around any closed circuit or network is zero. This is illustrated in Figure 10, which is a screenshot taken from an online circuit simulation package called Multisim Live. Here, starting with the battery, the voltages around the circuit are 6.0 V − 1.0 V − 3.0 V − 2.0 V = 0 V.

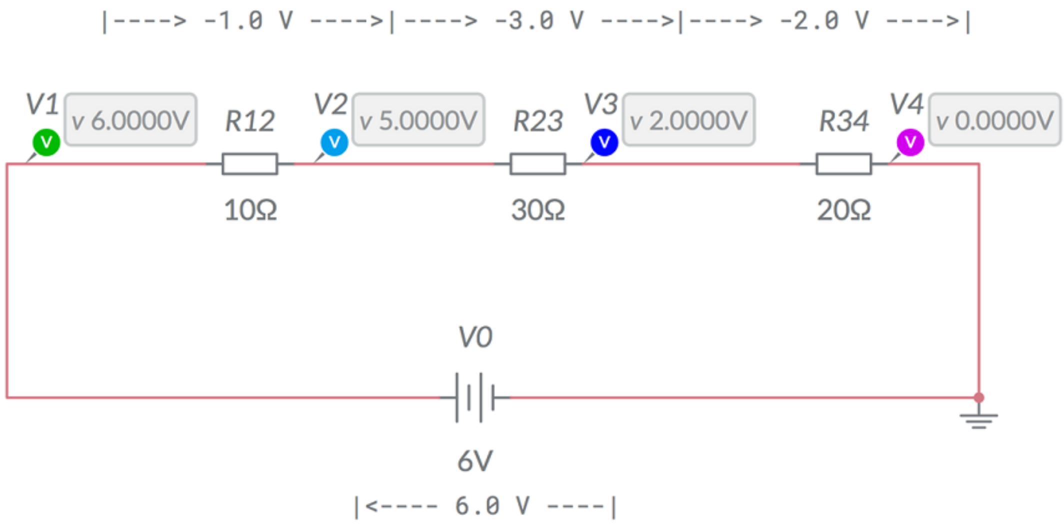


Figure 10 Illustration of Kirchhoff's second law (screenshot from Multisim Live)

Series and parallel networks (combining the laws)

The ordering of the components, and how they are connected, is important in a circuit. For example, two components (here resistors) can be arranged in two different ways, as shown in Figure 11. A circuit in which the current must take a single path, going through first one component and then the other in *series*, is shown in Figure 11(a); a circuit in which the current splits and takes two *parallel* paths at the same time is shown in Figure 11(b).

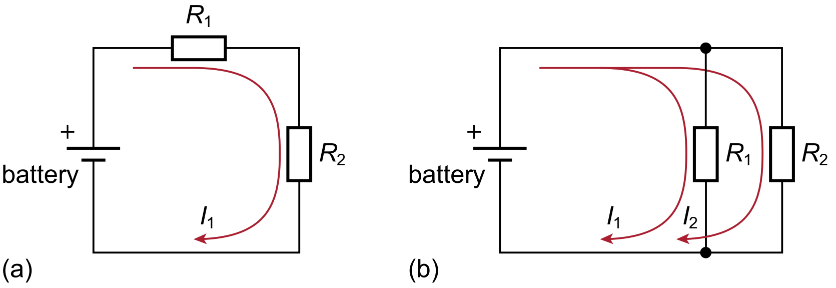


Figure 11 Circuit schematics showing two resistors arranged in (a) series and (b) parallel

By combining Ohm's and Kirchhoff's laws, it can be shown that:

- the total resistance R of n resistors in series is given by

  $$R = R_1 + R_2 + \cdots + R_n$$

- the total resistance R of n resistors in parallel is given by

  $$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

SAQ 2

In Figure 11, let $R_1 = 470\,\Omega$ and $R_2 = 1.3\,\mathrm{k}\Omega$. To three significant figures:

a. What is their resistance in series?
b. What is their resistance in parallel?

Answer

a. In series, the combined resistance is$R_1 + R_2 = (470 + 1300)\ \Omega = 1770\,\Omega$.

b. In parallel, the combined resistance is

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{470\,\Omega} + \frac{1}{1300\,\Omega}}$$

$$= \frac{1}{0.00212\ldots + 0.000769\ldots}\,\Omega$$

$$= \frac{1}{0.00289\ldots}\,\Omega = 345\,\Omega$$

to three significant figures.

Alternatively, note that for two resistors in parallel,

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{R_2+R_1}{R_1R_2}} = \frac{R_1R_2}{R_1 + R_2}$$

so the resistance in parallel can be written simply as

$$\frac{470 \times 1300}{470 + 1300}\,\Omega = \frac{611\,000}{1770}\,\Omega = 345\,\Omega \text{ (to 3 s.f.)}$$

2.4 Colour coding and standard resistor values

Conventional fixed resistors have coloured bands showing their value. These can be decoded using Table 3. For example, a resistor with four bands where the coding is yellow (4), violet (7), red (× 100) and brown (1%) has a resistance of

(47 Ω × 100) ± 1% = 4700 Ω ± 47 Ω

There is a similar five-band scheme where there are three instead of two digits in the resistance value, and a six-band scheme that also gives temperature information. Sometimes it can be hard to see these colour values on the resistors and a multimeter is used to check them.

Table 3 The four-band colour-coding scheme for resistors

Colour	Band 1 First digit	Band 2 Second digit	Band 3 Multiplier	Band 4 Tolerance
Black	0	0	x 1 (x 1)	-
Brown	1	1	x 10 (x 10)	1%
Red	2	2	x 100 (x 100)	2%
Orange	3	3	x 1 000 (x 1k)	not used
Yellow	4	4	x 10 000 (x 10k)	not used
Green	5	5	x 100 000 (x 100k)	not used
Blue	6	6	x 1 000 000 (x 1M)	not used
Violet	7	7	-	not used
Grey	8	8	-	not used
White	9	9	-	not used
Gold	-	-	-	5%
Silver	-	-	-	10%

Resistors are required across a range of millions of ohms. To keep costs low, manufacturers have defined ‘standard’ sets of resistor values such as those shown in Table 4 for resistors with a tolerance of ±5%.

Table 4 Standard resistor values in ohms (±5%)

1.0	10	100	1.0 k	10 k	100 k	1.0 M
1.1	11	110	1.1 k	11 k	110 k	1.1 M
1.2	12	120	1.2 k	12 k	120 k	1.2 M
1.3	13	130	1.3 k	13 k	130 k	1.3 M
1.5	15	150	1.5 k	15 k	150 k	1.5 M
1.6	16	160	1.6 k	16 k	160 k	1.6 M
1.8	18	180	1.8 k	18 k	180 k	1.8 M
2.0	20	200	2.0 k	20 k	200 k	2.0 M
2.2	22	220	2.2 k	22 k	220 k	2.2 M
2.4	24	240	2.4 k	24 k	240 k	2.4 M
2.7	27	270	2.7 k	27 k	270 k	2.7 M
3.0	30	300	3.0 k	30 k	300 k	3.0 M
3.3	33	330	3.3 k	33 k	330 k	3.3 M
3.6	36	360	3.6 k	36 k	360 k	3.6 M
3.9	39	390	3.9 k	39 k	390 k	3.9 M
4.3	43	430	4.3 k	43 k	430 k	4.3 M
4.7	47	470	4.7 k	47 k	470 k	4.7 M
5.1	51	510	5.1 k	51 k	510 k	5.1 M
5.6	56	560	5.6 k	56 k	560 k	5.6 M
6.2	62	620	6.2 k	62 k	620 k	6.2 M
6.8	68	680	6.8 k	68 k	680 k	6.8 M
7.5	75	750	7.5 k	75 k	750 k	7.5 M
8.2	82	820	8.2 k	82 k	820 k	8.2 M
9.1	91	910	9.1 k	91 k	910 k	9.1 M

The standard or *preferred* values shown in Table 4 are chosen such that whatever value resistance is required, there is one within 5% of the specified value. Fixed resistors’ costs are usually very low.

3 Some fundamental circuits

By combining resistors in different ways, some circuits can be created that are very important in electronics. This section will look at two of these, the voltage divider and the Wheatstone bridge, before introducing a new component in the form of an operational amplifier (op-amp).

3.1 Voltage dividers

Voltage dividers are widely used in electronic circuits to create a reference voltage, or to reduce the amplitude of a signal. Figure 12 shows a voltage divider. The value of V_{out} can be calculated from the values of V_{S}, R_1 and R_2.

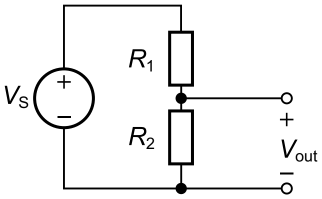


Figure 12 A voltage divider circuit

In the first instance, let's assume that V_{out} is not connected to anything (for voltage dividers it is always assumed that negligible current flows through V_{out}). This means that, according to Kirchhoff's first law, the current flowing through R_1 is the same as the current flowing through R_2. Ohm's law allows you to calculate the current through R_1. It is the potential difference across that resistor, divided by its resistance. Since the voltage V_{S} is distributed over two resistors, the potential drop over R_1 is $V_{R1} = V_{\mathrm{S}} - V_{\mathrm{out}}$.

The current through R_1 (I_{R1}) is given by

$$I_{R1} = \frac{(V_{\mathrm{S}} - V_{\mathrm{out}})}{R_1}$$

Similarly, the current through R_2 is given by

$$I_{R2} = \frac{V_{\mathrm{out}}}{R_2}$$

Kirchoff's first law tells you that $I_{R1} = I_{R2}$, and therefore

$$\frac{V_{\mathrm{out}}}{R_2} = \frac{(V_{\mathrm{S}} - V_{\mathrm{out}})}{R_1}$$

Multiplying both sides by R_1 and by R_2 gives

$$R_1 V_{\mathrm{out}} = R_2 \left(V_{\mathrm{S}} - V_{\mathrm{out}}\right)$$

Then multiplying out the brackets on the right-hand side gives

$$R_1 V_{\text{out}} = R_2 V_{\text{S}} - R_2 V_{\text{out}}$$

This can be rearranged to

$$R_1 V_{\text{out}} + R_2 V_{\text{out}} = R_2 V_{\text{S}}$$

giving

$$(R_1 + R_2) V_{\text{out}} = R_2 V_{\text{S}}$$

and therefore the fundamental result is obtained:

$$V_{\text{out}} = \frac{R_2 V_{\text{S}}}{(R_1 + R_2)}$$

SAQ 3

Suppose V_{S} = 24 V and R_2 = 100 Ω. You want V_{out} = 6 V. What value of R_1 do you need?

Answer

Rearranging the equation for V_{out} gives

$$V_{\text{out}} (R_1 + R_2) = R_2 V_{\text{S}}$$

and therefore

$$R_1 + R_2 = \frac{R_2 V_{\text{S}}}{V_{\text{out}}}$$

which means the equation for R_1 is

$$R_1 = \frac{R_2 V_{\text{S}}}{V_{\text{out}}} - R_2$$

Substituting in the values given,

$$R_1 = \frac{100\,\Omega \times 24\,\text{V}}{6\,\text{V}} - 100\,\Omega = 400\,\Omega - 100\,\Omega = 300\,\Omega$$

3.2 The Wheatstone bridge

Originally developed in the nineteenth century, a Wheatstone bridge provided an accurate way of measuring resistances without being able to measure current or voltage values, but only being able to detect the presence or absence of a current. A simple galvanometer, as illustrated in Figure 13, could show the absence of a current through the Wheatstone bridge in either direction. The long needle visible in the centre of the galvanometer would deflect to one side or the other if any current was detected, but show no deflection in the absence of a current.

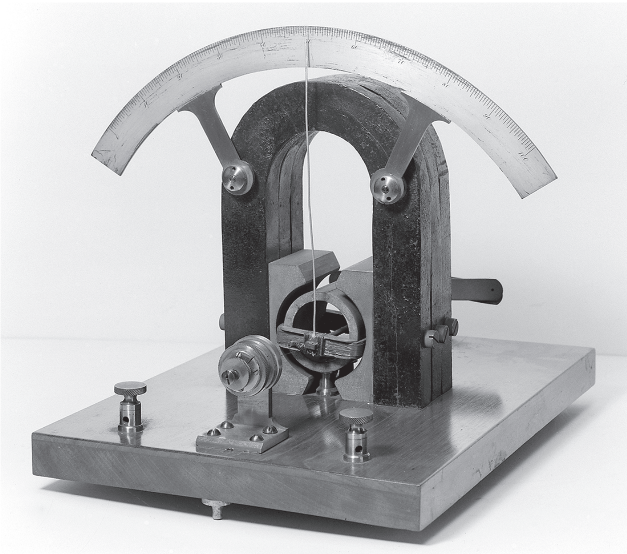


Figure 13 An early galvanometer showing magnet and rotating coil

Figure 14(a) shows a circuit made of four resistors forming a Wheatstone bridge. Its purpose here is to show whether there is any current flowing between V_{left} and V_{right}.

Figure 14(b) shows an equivalent way of drawing the circuit.

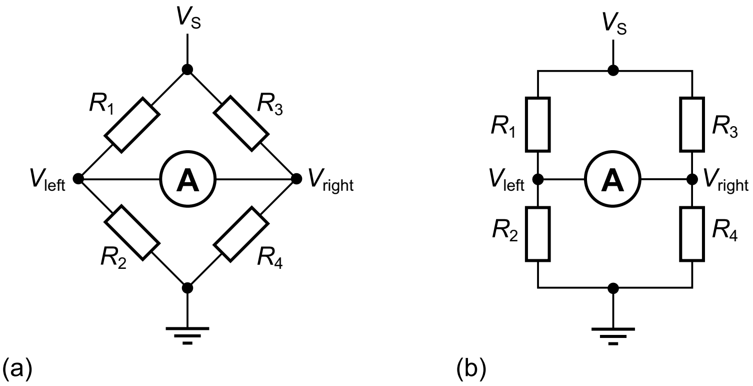


Figure 14 Equivalent examples of a Wheatstone bridge

The bridge is said to be *balanced* (that is, no current flows through the bridge and the needle of the galvanometer shows no deflection) if the voltages V_{left} and V_{right} are equal.

It can be shown that the bridge is balanced if, and only if, $\dfrac{R_1}{R_2} = \dfrac{R_3}{R_4}$, as follows.

When $V_{\mathrm{left}} - V_{\mathrm{right}} = 0$ then $V_{\mathrm{left}} = V_{\mathrm{right}}$. Then the Wheatstone bridge can be viewed as two voltage dividers, R_1 and R_2 on the left and R_3 and R_4 on the right. Applying the voltage divider equation gives $V_{\mathrm{left}} = \dfrac{R_2}{(R_1 + R_2)} V_{\mathrm{S}}$ and $V_{\mathrm{right}} = \dfrac{R_4}{(R_3 + R_4)} V_{\mathrm{S}}$.

So

$$\frac{R_2}{(R_1 + R_2)} = \frac{R_4}{(R_3 + R_4)}$$

and

$$R_2\,(R_3 + R_4) = R_4\,(R_1 + R_2)$$

Multiplying out the brackets gives

$$R_2 R_3 + R_2 R_4 = R_4 R_1 + R_4 R_2$$

which simplifies to

$$R_2 R_3 = R_4 R_1$$

and

$$\frac{R_3}{R_4} = \frac{R_1}{R_2}$$

So, if R_4 were unknown, R_1, R_2 and R_3 could be chosen so that the needle of a galvanometer showed no deflection due to the current. Then

$$R_4 = \frac{R_2 \times R_3}{R_1}$$

SAQ 4

Assume the Wheatstone bridge shown in Figure 14 is balanced. If $R_1 = 1000\,\Omega$, $R_2 = 10\,\mathrm{k}\Omega$ and $R_3 = 50\,\Omega$, what is the resistance of R_4?

Answer

By the formula given in the text,

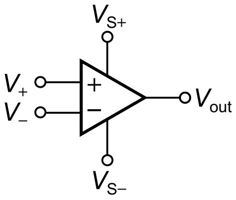
$$R_4 = \frac{R_2 \times R_3}{R_1} = \frac{10\,000 \times 50}{1000}\,\Omega = 500\,\Omega$$

3.3 Operational amplifier circuits

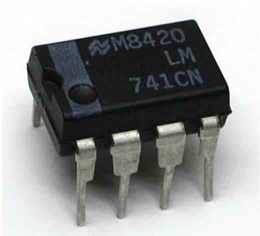
Operational amplifiers are a fundamental component in electronics. This section focuses on a classic amplifying device, the 741 op-amp.

As shown in Figure 15(a), the op-amp symbol has five terminals. The terminals V_+ and V_- are used for the input and they control the output, usually as an amplified signal on V_{out}. The op-amp is built using several resistors and other components called transistors. All these transistors and resistors are packed inside the very small package you can see in

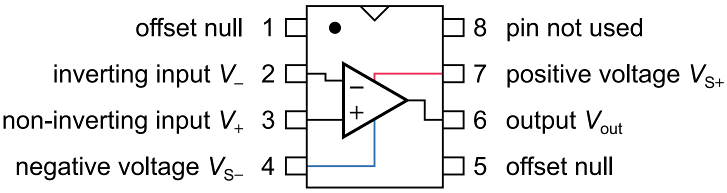
Figure 15(b). A dot and a dent on top of the package are generally used to identify the orientation of the package and therefore the pin number. You can also see these marked on the configuration diagram shown in Figure 15(c).



(a)



(b)



(c)

Figure 15 (a) Symbol for an op-amp; (b) the 741 op-amp package; (c) top view of an LM741 dual inline package (DIL), showing internal configuration and pin connections

Dual power supplies

On the op-amp symbol, the vertical lines marked V_{S+} and V_{S-} are very important, since, as already mentioned, they are the op-amp's connection to a power supply. However, when there is no room for confusion, the two vertical lines leading to the power source (V_{S+} and V_{S-}) are sometimes omitted from the symbol.

Often a mains dual power supply provides the positive and negative voltages required for an op-amp. Alternatively, you could decide to use batteries to power the op-amp. Since batteries always give a positive voltage, how can they deliver a negative voltage? Figure 16 shows how two batteries can be connected to an op-amp to deliver positive and negative voltages.

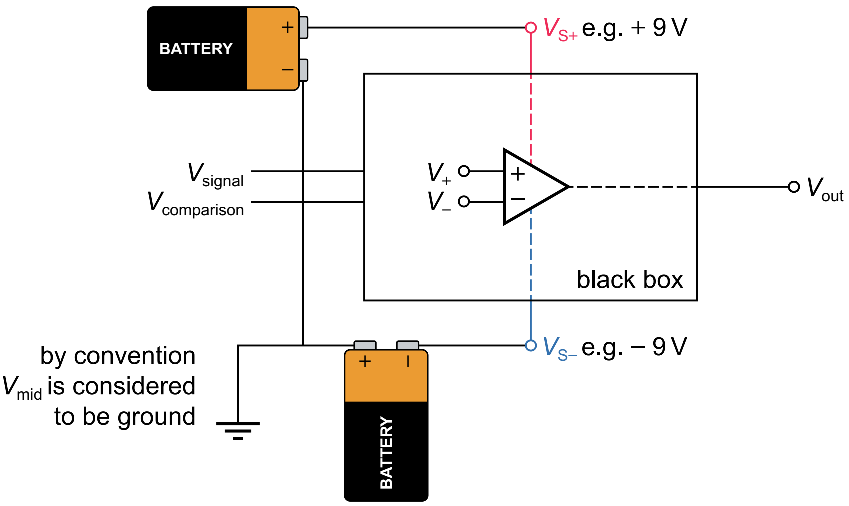


Figure 16 Black box representation of the 741 op-amp, showing the power supplies

3.4 Designing a sensor circuit

Figure 17 is a screenshot taken from Multisim Live, showing a circuit with four parts. On the right is a light-emitting diode (LED) and a 470 Ω resistor, $R5$. On the left there is a device called a light-dependent resistor (LDR). This is labelled $R2$ and forms a voltage divider with a fixed resistor $R1$. The resistance of the LDR has been measured as 380 Ω in full ambient light and 1.5 kΩ in the dark. We want the LED to switch on when the environment begins to darken and the resistance of $R2$ is 680 Ω or more. (Note that $U1$ is the label that Multisim Live gives to the op-amp.)

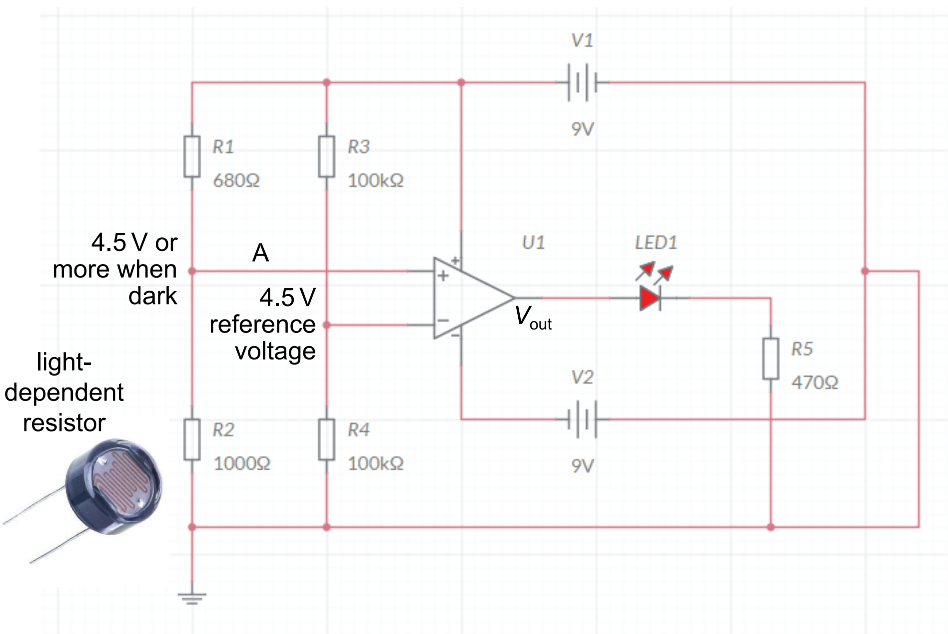


Figure 17 Circuit diagram for an open-loop op-amp switching an LED (screenshot from Multisim Live)

The resistors $R3$ and $R4$ form another voltage divider, which will provide a ‘reference’ signal. Both $R3$ and $R4$ have resistance 100 kΩ. Battery $V1$ provides 9 V, so the reference voltage is

$$9\,\mathrm{V} \times \frac{R4}{(R3 + R4)} = 9\,\mathrm{V} \times \frac{100\,000\,\Omega}{(100\,000 + 100\,000)\ \Omega} = 4.5\,\mathrm{V}$$

If $R1$ is set to 680 Ω and variable resistor $R2$ is also 680 Ω, the voltage at A will be the same as the reference voltage, because

$$9\,\mathrm{V} \times \frac{R2}{(R1 + R2)} = 9\,\mathrm{V} \times \frac{680\,\Omega}{(680 + 680)\ \Omega} = 4.5\,\mathrm{V}$$

As it gets darker, this voltage will increase.
This circuit is shown implemented as a breadboard in Figure 18. When it gets dark and the sensor receives less light, the LED illuminates as required.

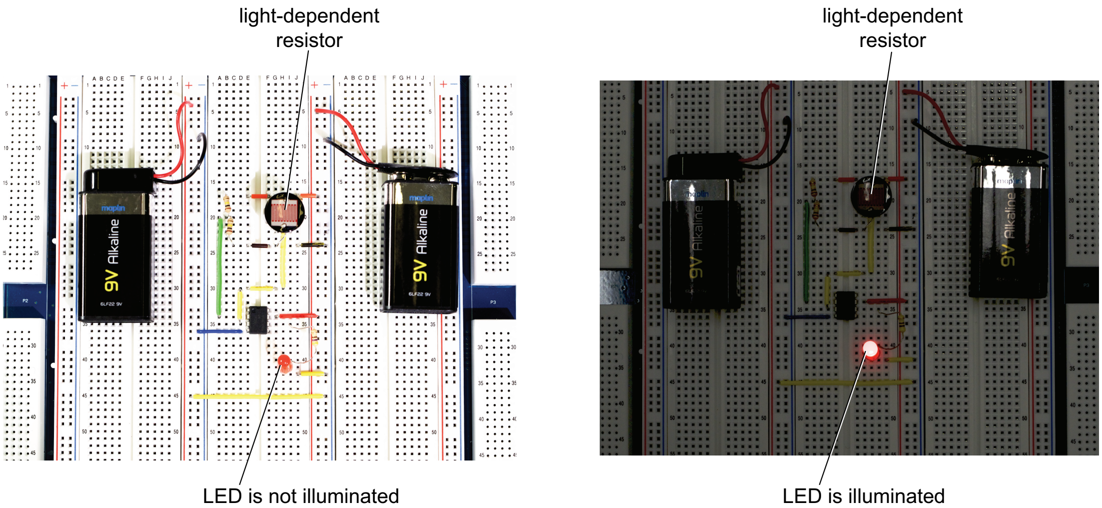


Figure 18 Breadboard circuit for the open-loop op-amp: (a) in light conditions, the LED is not illuminated; (b) when it gets dark, the LED is illuminated

4 Signals and signal processing

The last section in this course focuses on signals, in particular sound signals. You will investigate how sounds can be recorded, analysed and reproduced. By the end of the section, you will return to the op-amp and see how it can be used to amplify a sound or other signal.

4.1 High-fidelity sound reproduction and electronics

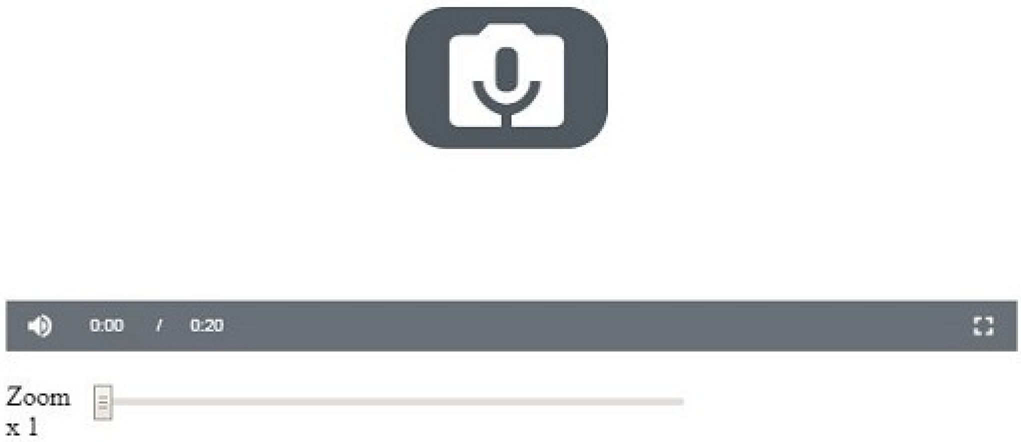
Recording and reproducing sound has been one of the great drivers for innovation in electronics. What we perceive to be sound is vibrating air causing our eardrums to vibrate. For example, consider a guitar string vibrating 440 times per second, causing 440 high–low pressure waves to be transmitted through the air. This wave causes your eardrum to vibrate 440 times per second, which your brain interprets as the note A.

A device such as a microphone converts the highs and lows of the air pressure wave into a high and low voltage wave that represents the sound wave as an electrical analogue, oscillating between high and low voltages 440 times per second. When that electrical wave becomes the input to a loudspeaker, the speaker's cone vibrates back and forth 440 times per second, creating a sound wave that you would hear as the note A.

In a perfect world, the sound made by a loudspeaker would be exactly the same as the original sound, with perfect fidelity. In practice, converting the sound to voltages and back to sound is an imperfect process, and some distortion or extraneous noise is inevitable. This is particularly notable with telephones, which usually have relatively low fidelity and distort the sound of our voices. For reproducing music, engineers try to make the fidelity as high as possible – and some people are prepared to pay a lot of money for high-fidelity equipment, or hi-fi systems as they are called. This aesthetic demand has driven much electronics research for nearly a century. Miniaturisation, low power consumption and computational load are also drivers of innovation, as can be seen with increasingly powerful and smaller mobile phones that last longer and longer between charges.

4.2 Recording sounds

Interactive 1 will allow you to see what 'real' sounds that you make yourself look like as waves. To get started, right-click on the link below the image to open the interactive in a new tab, then click on the large microphone symbol at the centre of the interactive. The first time you do this, you may see a pop-up window asking for permission to use your microphone – click on the appropriate button to allow this. Then try making some sounds. You will see a pink line moving.



Interactive 1 Recording and viewing a sound (Ctrl+right-click to open this link in a new window).

To record a sound, click on the record button (the circle) at the bottom left of the interactive. As an example, Figure 19 shows the wave produced by humming a low note.

Figure 19 Voltage wave produced by humming a low note

To make the picture, the microphone on the computer 'sampled' the sound 44 100 times per second and drew a pink line from 0 V to the value sampled. Because there are so many samples and the screen has limited resolution, some of the lines get overdrawn by others and merge to form solid blocks of colour.

It is quite hard to see the details of the wave at this resolution, but the interactive allows you to click on the wave and move the 'zoom' slider from left to right. Figure 20 shows the result of doing this to the wave in Figure 19. Notice that at the bottom of the wave, there are 24 long downward spikes with a shorter downward spike in between each pair. The long spike represents what is called the *fundamental frequency* of the recorded voice, and the shorter spike is what is called a *harmonic*.

Figure 20 Zooming in to the wave from Figure 19

The interactive can also be used to measure the time between the spikes and therefore calculate the frequencies. To do this, click your mouse on the tip of the leftmost spike and note the numbers at the bottom of the interactive to the right of the loudspeaker icon. The first of these numbers is the time that the spike was recorded. Then click on the tip of the rightmost spike and note this number again. The difference between the two times divided by the number of gaps between the spikes gives you the time period between any pair of spikes, from which you can calculate the frequency.

For example, you can see from Figure 20 that clicking on the leftmost spike shows the numbers 0:00:877 / 0:02:519 at the bottom of the interactive. Therefore that spike was recorded at 0:00:877. Clicking on a spike at the right of the interactive, as shown in Figure 21, shows that it was recorded at 0:01:099. There are 22 gaps between the long spikes in this example, so the time period between any pair of spikes is (0:01:099 − 0:00:877)/22 = (1.099 − 0.877)/22 = 0.01 seconds. Thus, since the period for one oscillation of the long spikes is 0.01, there are 1/0.01 = 100 spikes per second and the frequency is 100 vibrations per second. Engineers use the term hertz (Hz) for ‘times per second’, so the fundamental frequency of this recorded hum is 100 Hz.

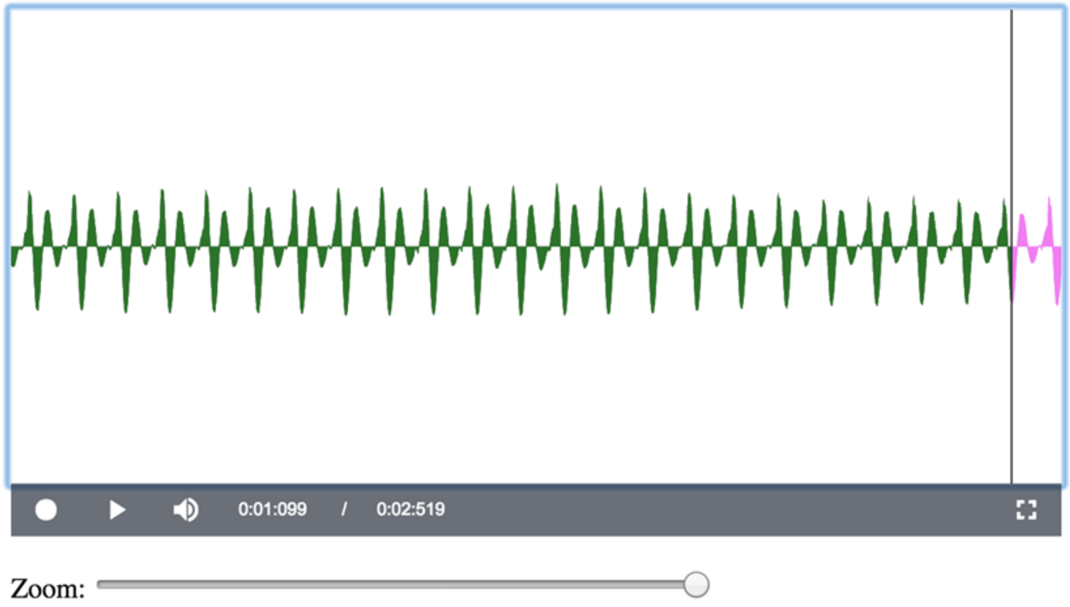


Figure 21 Calculating the fundamental frequency

SAQ 5

A recording of an electric toothbrush shows the time at the top of a peak on the left as 0.219 seconds (Figure 22(a)) and the time at the top of a peak on the right as 0.452 seconds (Figure 22(b)). How many gaps between peaks occur between these two times? What is the period of this wave (that is, the length of time between any two consecutive peaks)? What is the frequency of vibration of this electric toothbrush?

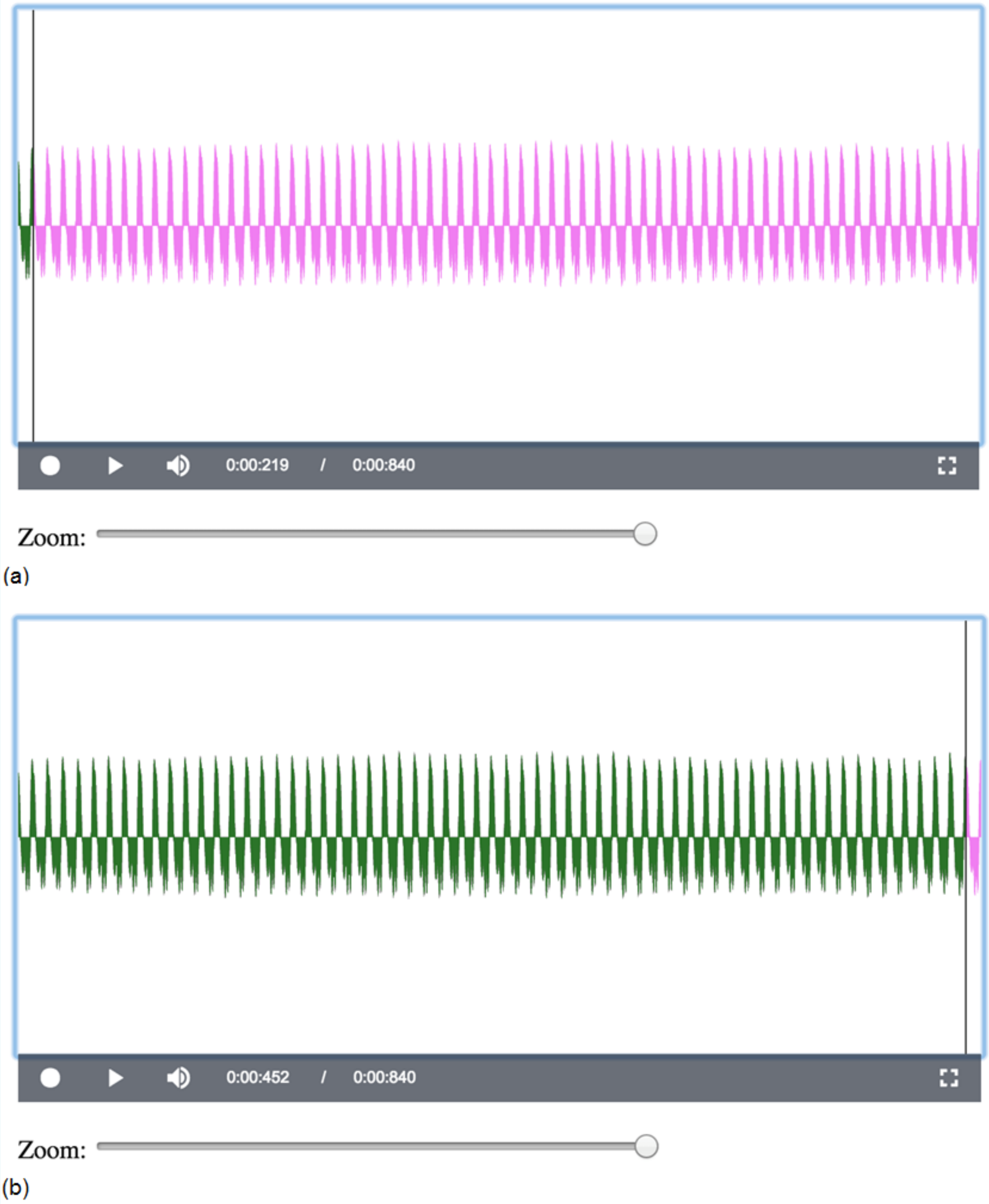


Figure 22 Recording of an electric toothbrush: time at the top of a peak on (a) the left and (b) the right

Answer

There are 61 inter-peak gaps between the two measured times, so the period for one vibration of the electric toothbrush is (0.452 − 0.219)/61 = 0.003820 seconds. The frequency is the reciprocal of this, 1/0.003820 = 262 Hz. So the toothbrush vibrates 262 times per second.

Keep the interactive open, because you will need it in the next section.

4.3 Recording and analysing speech

Generally, sound waves are much more complicated than a wave made by humming a single note or the sound made by an electric toothbrush. For example, Figure 23 shows the waveforms generated by someone saying ‘yes’ followed by ‘no’. Let this be called *Recording A*.

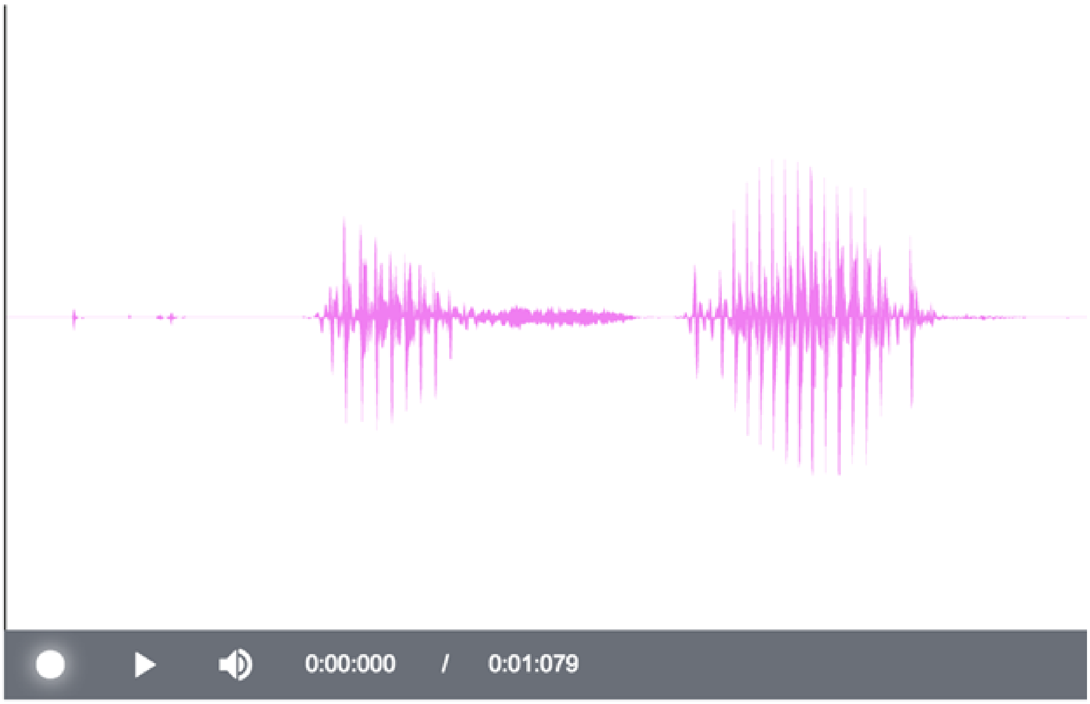


Figure 23 Recording A: ‘yes’ followed by ‘no’

SAQ 6

Each of the bursts of sound shown in Figure 24 is another recording of a person saying either ‘yes’ or ‘no’. Let this be called *Recording B*. Comparing Recording B with Recording A, which of the bursts of sound in Recording B is ‘yes’ and which is ‘no’?

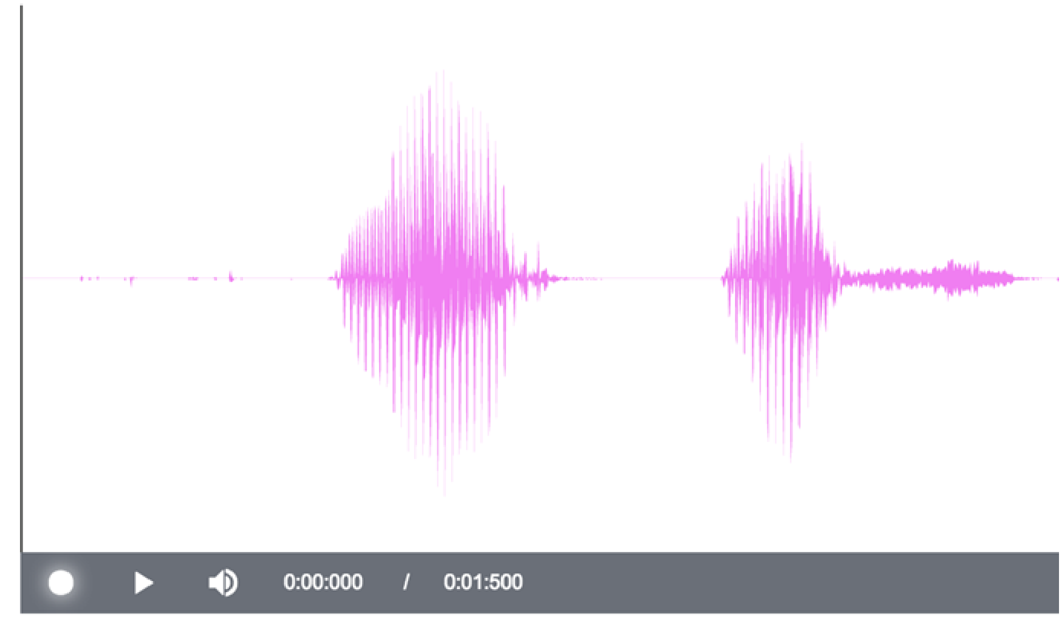


Figure 24 Recording B

Answer

The left sound burst in Recording A has a long tail, presumably caused by the long ‘s’ sound at the end of ‘yes’. The right sound burst does not have this tail. In Recording B, the right sound burst has a tail but the left sound burst does not. From this, it can be guessed (correctly) that the left sound burst in Recording B is ‘no’ and the right sound burst is ‘yes’.

The fact that different words result in different wave patterns underlies the technology of speech recognition. This technology has evolved to a high performance level over the last half century, but it has overcome some formidable problems. For example, are one person’s speech patterns the same as another’s?

Return to Interactive 1 (which you should still have open in a separate tab) and spend five or ten minutes experimenting by making your own sounds. If you hum a low note, are you able to calculate its frequency? Can you distinguish the patterns when you say ‘yes’ and ‘no’? Are your ‘yes’ and ‘no’ wave patterns similar to those shown in Figure 23?

When you have finished, close the interactive.

4.4 Signals and sine waves

Interactive 2 shows a signal based on a sine wave, $\sin(2\pi ft)$, where f is the frequency of the wave and t is time. Here the frequency of the wave is $f = 200$ Hz. The *period* of the wave, T, is the time between successive peaks; in this case, $T = 5$ ms (milliseconds). As would be expected, $T = 1/f = 1/200 = 0.005$ s. Similarly, $f = 1/T = 1/0.005 = 200$ Hz.

The signal is written as

$$s(t) = A\sin(2\pi ft + \phi)$$

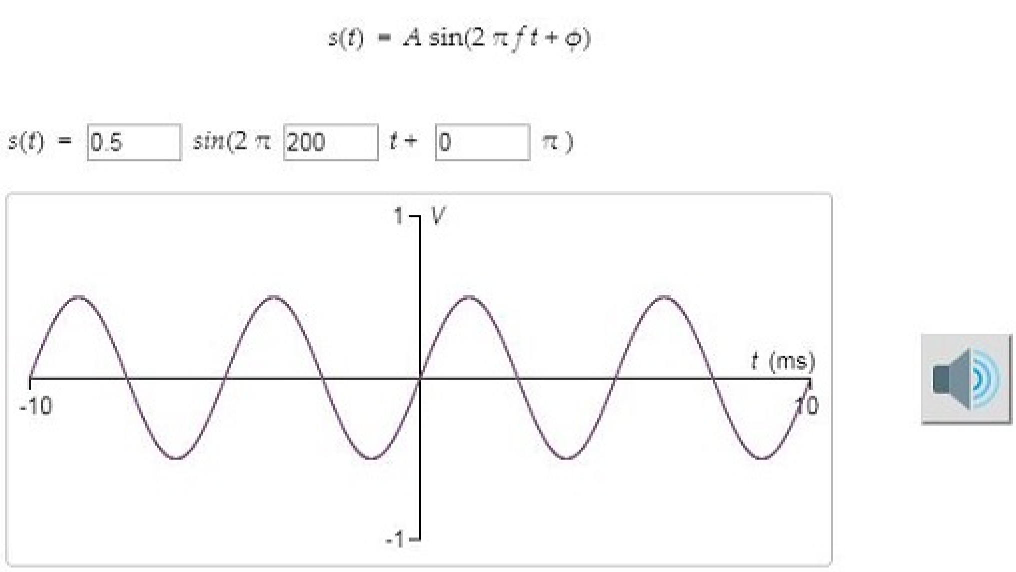
where A is called the *amplitude* of the wave, i.e. the largest value of the wave above or below the horizontal axis. Here it is set to $A = 0.5$.

ϕ is the *phase* of the wave, which means how far the wave is shifted to the left or the right. Here it is set to 0, since the wave goes through the origin and is not shifted either left or right.

Right-click on the image below to open the interactive in a new tab, then press the loudspeaker button to hear what the signal sounds like.

Interactive content is not available in this format.

Interactive 2 Investigating a sine wave



SAQ 7

a. Change A to 1.0 and play the sound. What do you observe?

b. Change f to 400 and play the sound. What do you observe?

c. Change ϕ to $\pi/2$ and play the sound. (You can enter a phase of $\pi/2$ into the interactive as 90 degrees.) What do you observe?

Answer

a. The wave is displayed with twice the height and the sound is louder.

b. The wave is displayed with the lines much closer vertically, and the sound is at a higher pitch (it is an octave higher than before).

c. The wave is moved along by a quarter of its period. Now it has the highest value at $t = 0$, where previously it was 0 at $t = 0$. However, it sounds the same.

4.5 Making signals from combinations of sine waves

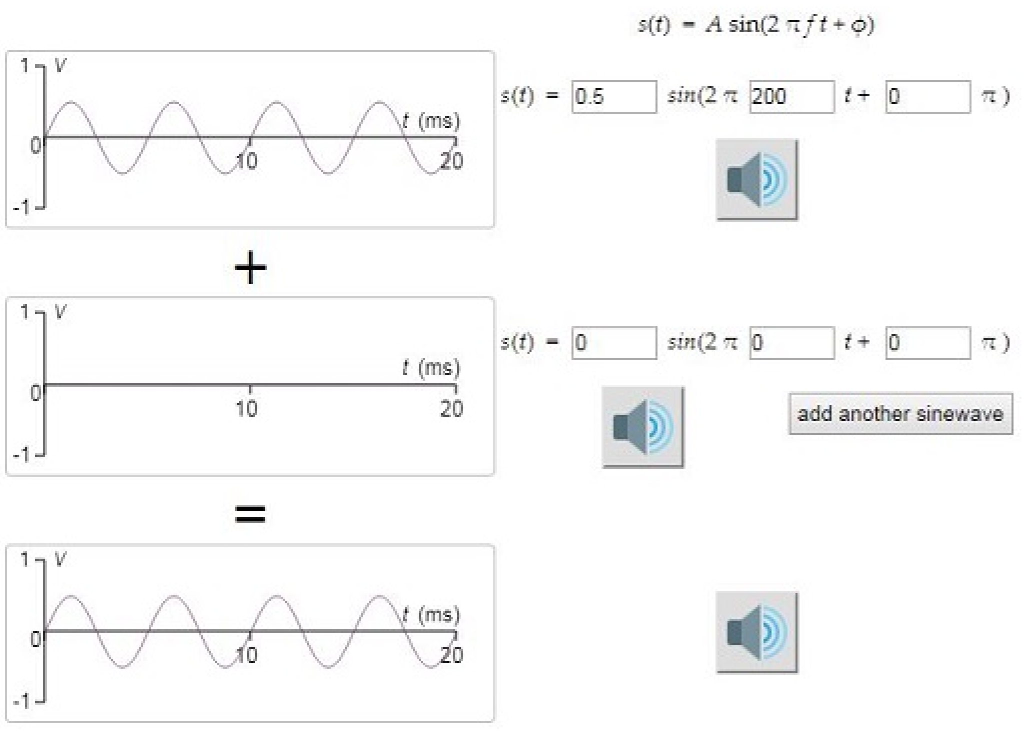
Right-click on the image below to open Interactive 3 in a new tab, then change the values for the top two waves so that the frequency of the first is 440 Hz and the frequency of the second is 660 Hz. Make the amplitude of both 0.5.

The wave at the bottom is formed by combining these two waves, by adding their values for each value of *t*.

Click on the loudspeaker button for each of the top two waves and listen to the resulting sounds. Then click on the loudspeaker button for the bottom wave and listen to its sound.

Interactive content is not available in this format.

Interactive 3 Combining sine waves



SAQ 8

a. Is the composite signal at the bottom a sine wave?

b. What is the ratio of the frequencies of the sine waves at the top?

c. Does the combined signal sound pleasant with the single sine waves in harmony?

d. Do you think there is any relationship between the ratio of the frequencies and the notes harmonising?

Answer

a. No, the combined signal is not a sine wave. It has a more complicated shape.

b. The ratio of the frequencies is 440:660 or 2:3.

c. This is a subjective question, but you may agree that it sounds as if the individual waves do combine to make a harmonised sound.
d. Generally, in music, notes with frequencies in simple proportions harmonise with each other.

SAQ 9

Keep the frequency of the first wave at 440 Hz and its amplitude at 0.5. Change the frequency of the second wave to 880 Hz and change its amplitude to −0.17 (don't overlook the minus). What is the shape of the resulting wave?

Answer

The resulting wave has a triangular shape, as shown in Figure 25. This could be called a 'sawtooth' wave.

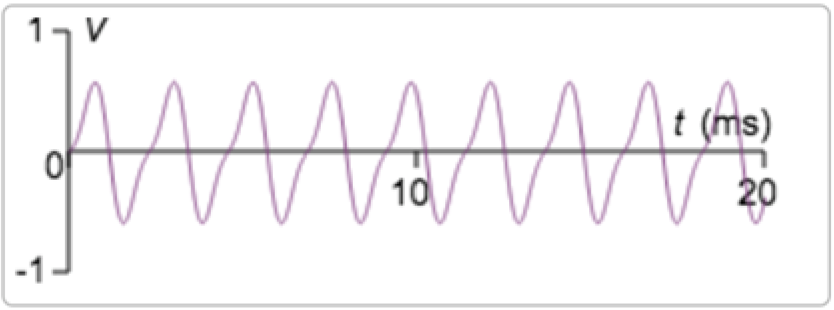


Figure 25 Sawtooth wave

Keep the interactive open, because you will need it in the next section.

The square wave challenge

The wave shown in Figure 26 approximates what is called a 'square' or 'rectangular' wave. The challenge is to design this wave using sine waves as components.

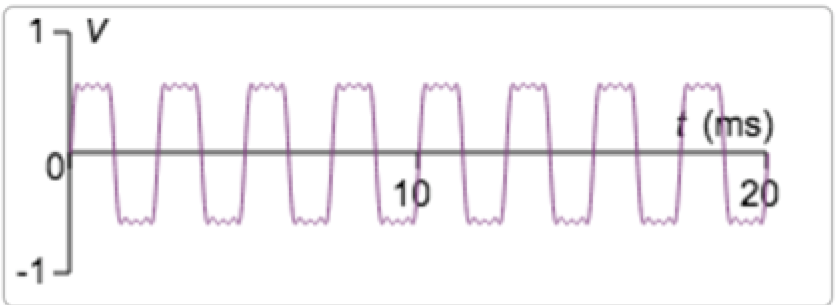


Figure 26 Approximation to a square wave

To make this wave using Interactive 3 (which you should still have open in a separate tab), start with two sine waves, the first having A = 0.7 and f = 400 Hz, and the second having A = 0.2 and f = 1200 Hz. This will give something similar to the wave shown in Figure 27, which is a good start.

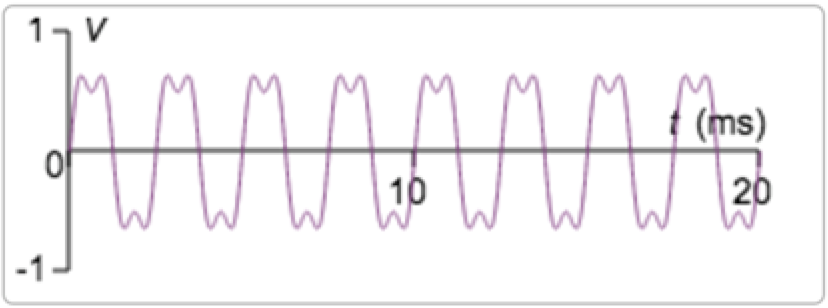


Figure 27 Combination of two sine waves

To make the top and bottom smoother requires sine waves with other frequencies. To get another sine wave, click on the ‘add another sine wave’ button below the second sine wave. Set the frequency of this to f = 2000 Hz.

SAQ 10

Suggest an appropriate value of A for the wave with frequency f = 2000 Hz.

Answer

Setting A = 0.1 gives the wave shown in Figure 28. This is closer to what is desired.

Figure 28 Combination of three sine waves

To finish this challenge requires one more sine wave. Click again on the ‘add another sine wave’ button to get a fourth sine wave. Set its frequency to f = 2800 Hz.

SAQ 11

Suggest an appropriate value of A for the wave with frequency f = 2800 Hz.

Answer

Setting *A* = 0.05 gives the wave shown in Figure 29. This is even closer to the desired square wave.

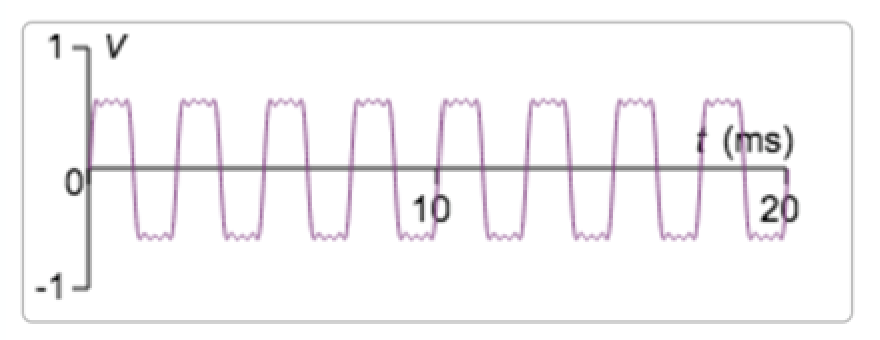


Figure 29 Combination of four sine waves

You can now close the interactive.

In the square wave challenge, the shape of the wave was made closer to that required by adding higher frequencies with decreasing amplitudes. This is a general principle behind a very powerful theory for representing and processing signals.

4.6 From the time domain to the frequency domain

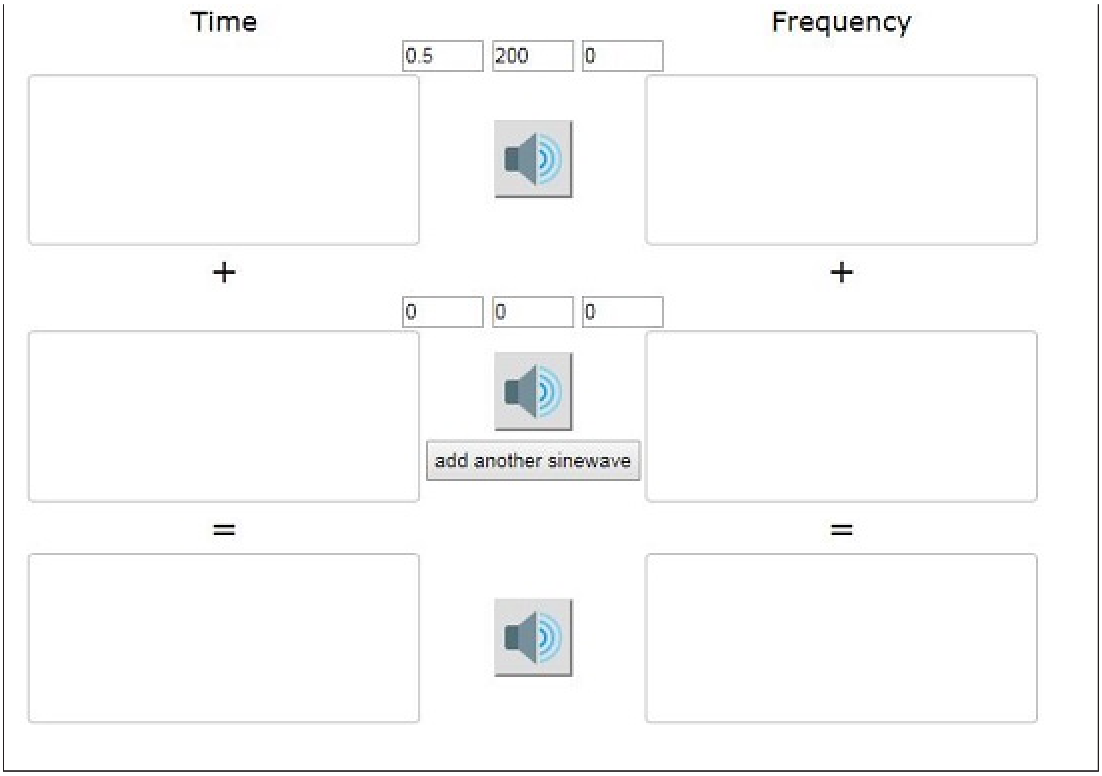
In the previous sections, you saw that complicated waveforms can be created by combining simple sine waves in a systematic way. Remarkably, *any* waveform can be represented as a combination of sine waves of appropriately chosen amplitude (loudness), frequency (pitch) and phase. This result, demonstrated by the French mathematician and physicist Joseph Fourier (1768–1830), lies at the heart of the design of electronic systems to reproduce high-fidelity sound.

The most familiar representation of waves is in what is called the *time domain*, i.e. the changing value of the signal through time. As you have seen, complicated waves can be formed from combinations of sine waves of given frequency and amplitude. This allows another representation in what is called the *frequency domain*. To see this, enter the following waves into Interactive 4:

- Wave 1: A = 0.7, f = 110 Hz
- Wave 2: A = 0.2, f = 330 Hz
- Wave 3: A = 0.1, f = 550 Hz
- Wave 4: A = 0.05, f = 770 Hz.

Interactive content is not available in this format.

Interactive 4 Waves represented in the time domain and the frequency domain



SAQ 12

a. What is the shape of the combined waveform?
b. What do you see to the right of the combined waves, in the 'frequency domain'?

Answer

a. The shape approximates a square wave, as shown in the previous section.
b. Read the following.

Figure 30 shows the composite wave formed from the four sine waves listed above. On the right of this is a graph showing amplitude against frequency. There is a vertical line of height *A* = 0.7 corresponding to frequency *f* = 110 Hz, a vertical line of height *A* = 0.2 corresponding to *f* = 330 Hz, a vertical line of height *A* = 0.1 corresponding to *f* = 550 Hz and a vertical line of length *A* = 0.05 corresponding to *f* = 770 Hz. This set of lines is called the *frequency spectrum* of the signal on the left.

Figure 30 Transforming a signal in the time domain into the frequency domain

One of the many problems with reproducing sound is that the desired sound may be contaminated by noise. For example, if you record a video and commentary on your phone in a crowded place, you will record what you want (you speaking) but also what you may not want (the hubbub surrounding you). Engineers talk about the part of the recording that is wanted as the *signal* and the part that is not wanted as *noise.*

For example, suppose you are recording yourself playing the piano and an emergency vehicle goes past with its high-pitched siren blaring. By using electronics, it may be possible to *filter out* that unwanted noise, or at least make it a lot less intrusive.

To represent noise, add a fifth sine wave to your signal with A = 0.3 and f = 935 Hz. This distorts the signal, as shown in Figure 31. Click on the loudspeaker button and you will hear that the sound is now quite discordant. It is not very clear what the noise is doing in the time-domain representation on the left, but the rogue frequency of 935 Hz can be seen clearly as a vertical bar of length 0.3 in the frequency-domain representation on the right. Now it is easy to imagine that one could take a pair of scissors and snip out that unwanted part of the composite signal in the frequency domain, before reassembling everything as the 'cleaned' signal in the time domain.

Figure 31 Noise with frequency f = 935 Hz shows clearly in the frequency domain

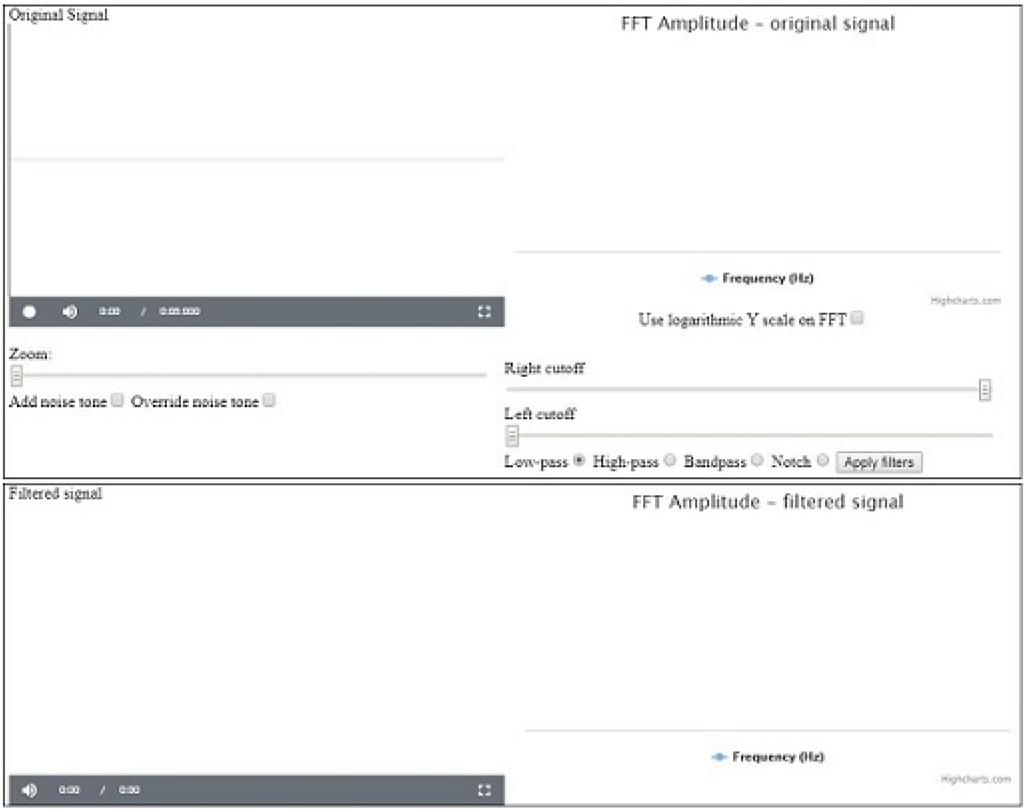
Apart from removing unwanted noise, Fourier's theory can also be used to manipulate signals in the frequency domain to give interesting new aesthetic results when the signals in the time domain are played through a loudspeaker. This has stimulated research and technology that has been widely used in the music industry for more than half a century, since the invention of the electric guitar.

4.7 Signals and noise

In this section, you will see some remarkable applications of the ideas in the preceding sections. To get going, right-click on the link below the image to open Interactive 5 in a new tab, then – if necessary – click on the microphone icon to enable the interactive to use your computer's microphone.

If there is a tick in the 'Use logarithmic Y scale on FFT' box, click on it to remove it.

If there is a tick in the 'Add noise tone' box beneath the 'zoom' slider, click on the box to remove it.



Interactive 5 Recording sounds and adding noise (Ctrl+right-click to open this link in a new window).

When you are ready, press the record button (the circle), say the word 'yes', then click on the square button to stop recording. Your screen should now be similar to Figure 32.

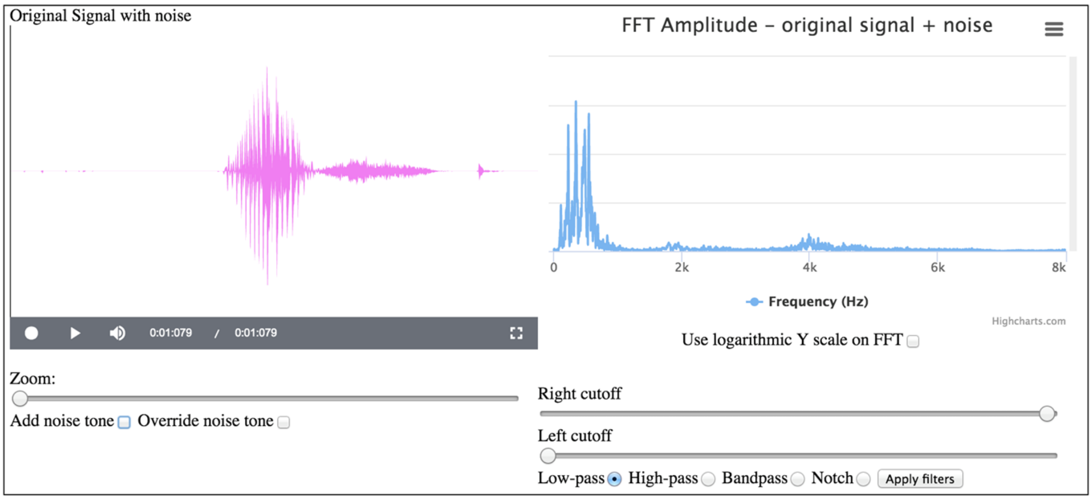


Figure 32 A recording of 'yes' in the time domain, transformed into the frequency domain

Tick the 'Add noise tone' box by clicking on it. Also tick the 'Override noise tone' by clicking on it. This will give a 'Noise frequency' slider. Move this to the right until the figure in the box is about 1200 Hz. This will add a sine wave with this frequency as noise to your sound. Look at the frequency spectrum on the right and you will see a peak close to 1200 Hz. Note that as you move the slider, the position of this peak will change, but for the moment make sure it is set at around 1200 Hz.

Now click on the play button (the triangle) and you will hear your ‘yes’ played back with a whistling noise in the background. Your screen should be similar to that shown in Figure 33.

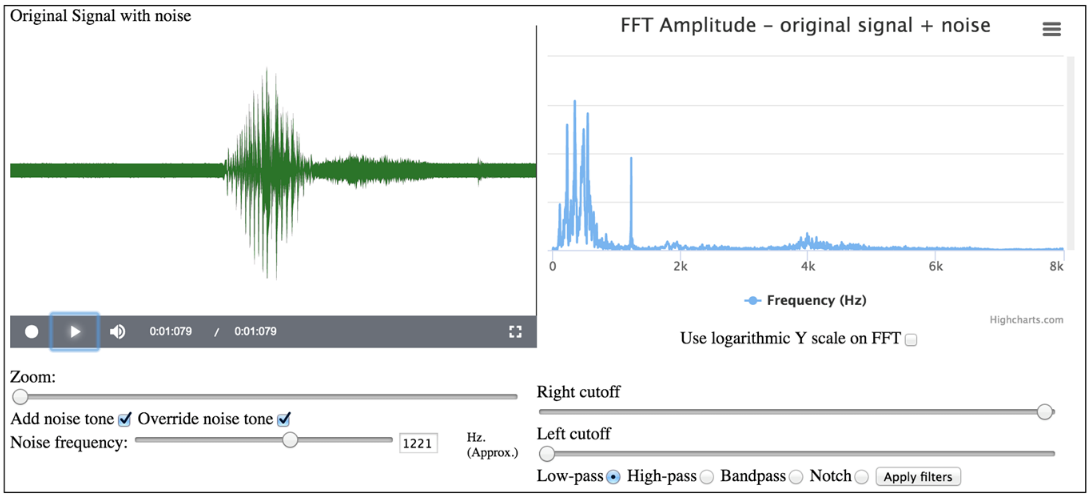


Figure 33 ‘Yes’ with a rogue component at 1221 Hz acting as noise

Keep the interactive open with your ‘yes’ recording in it. In the next section, you will see how the noise you added can be ‘clinically’ removed, restoring the signal to almost exactly what it was without the noise.

4.8 Filtering

Filtering is the art of removing parts of a signal that are not required and retaining those parts that are required. The four main kinds of filter are shown in Figure 34. For example, a notch filter will remove the noise at the 1200 Hz peak.

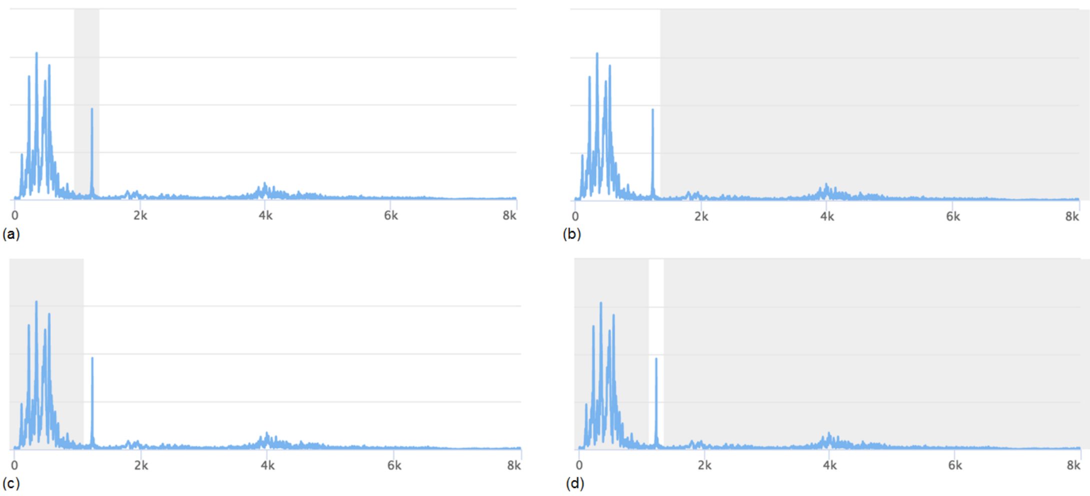


Figure 34 Types of filter: (a) notch filter – the frequencies in the shaded area are removed; (b) low-pass filter – high frequencies (in the shaded area) are removed, low frequencies are ‘passed’; (c) high-pass filter – low frequencies (in the shaded area) are removed, high frequencies are ‘passed’; (d) band-pass filter – low and high frequencies (in the shaded area) are removed, those in the remaining band are ‘passed’

You should still have Interactive 5 open in a separate tab, containing your recording of the word ‘Yes’ with an added noise tone of 1200 Hz. Select the ‘Notch’ button and use the ‘Right cutoff’ and ‘Left cutoff’ sliders to create a notch filter, as shown in Figure 34(a). Then click on the ‘Apply filters’ button next to the ‘Notch’ button.

Your result should be similar to that shown in Figure 35. As you can see, the noise has been removed without doing too much damage to the original signal.

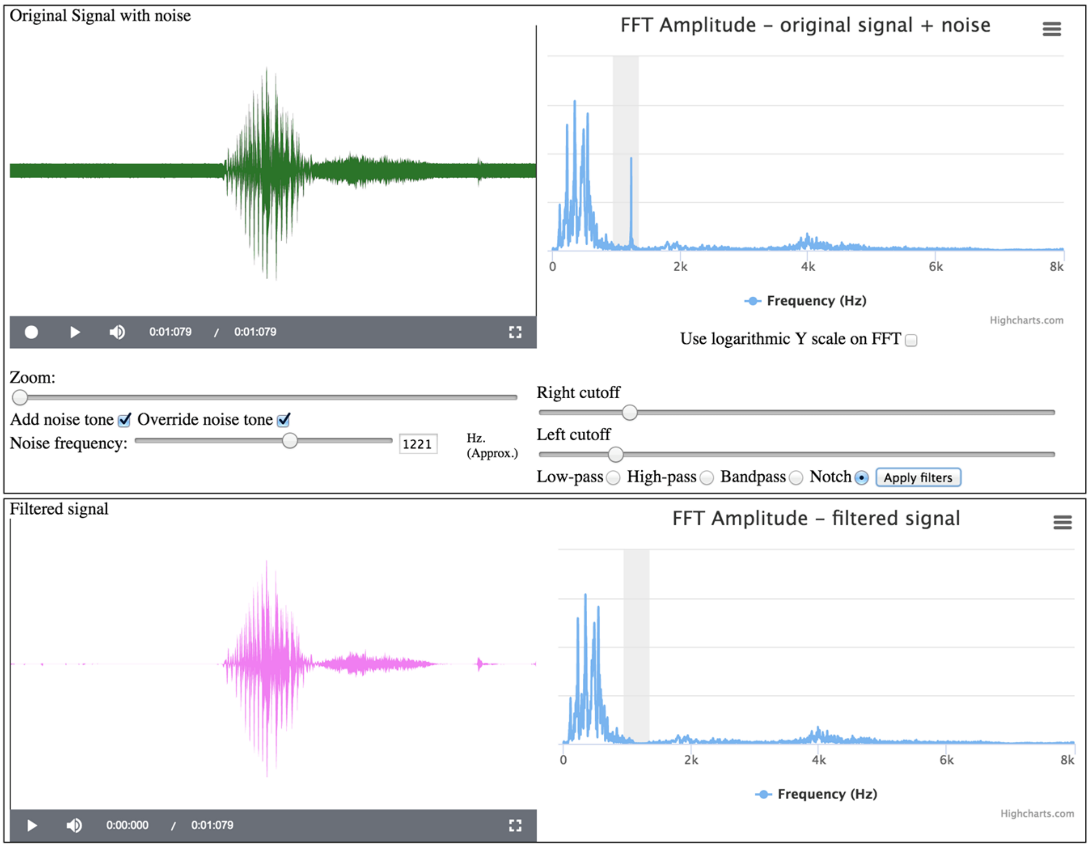


Figure 35 ‘Yes’ plus rogue 1221 Hz component, with notch filter applied

SAQ 13

Click on the play button (the triangle) at the bottom left of the interactive to play the filtered signal.

a. Was the noise removed as you listened to your signal?
b. Was the signal damaged, giving low-fidelity reproduction?

Answer

a. You should have found that the noise added to the signal was removed completely.
b. The filtered version of your signal should sound exactly the same as the original, or very close to it.

If this experiment did not work well for you, please try it again. It should work robustly and the results can be remarkable.

SAQ 14

Click on the ‘Bandpass’ button and then click on the ‘Apply filters’ button. What do you see and hear now?

Answer

In the time-domain representation of the filtered sound, you are likely to see only a solid band of noise. When you click on the play button, you should hear only the noise – your ‘yes’ should have been completely filtered out.

SAQ 15

Click on the ‘Low-pass’ button and then click on the ‘Apply filters’ button. What do you see and hear now?

Answer

In the time-domain representation of the filtered sound, you should see everything below the right cutoff filtered in, including the noise. This time the ‘yes’ will be muffled because the higher frequencies were lost.

SAQ 16

Click on the ‘High-pass’ button and then click on the ‘Apply filters’ button. What do you see and hear now?

Answer

In the time-domain representation of the filtered sound, you should see everything above the left cutoff filtered in, including the noise. This time the ‘yes’ will be muffled because the lower frequencies were lost.

SAQ 17

Select ‘High-pass’ and change the left cutoff to about 3 kHz. Click on ‘Apply filters’. Does this filter in or out any discernible part of the ‘yes’ sound?

Answer

The high-pass filter should remove the noise and most of the ‘yes’ sound, but you may find that the ‘s’ part can still be heard clearly. This supports the earlier conjecture that the tail of the ‘yes’ sound is the relatively high-frequency ‘sss’ as the word ends.

When you first looked at the recordings of 'yes' and 'no' on this course, it was noted that they have different shapes in the time domain and that this might be useful for speech recognition. As can be seen in Figure 36, 'yes' and 'no' also have different patterns in the frequency domain and this too is useful for speech recognition.

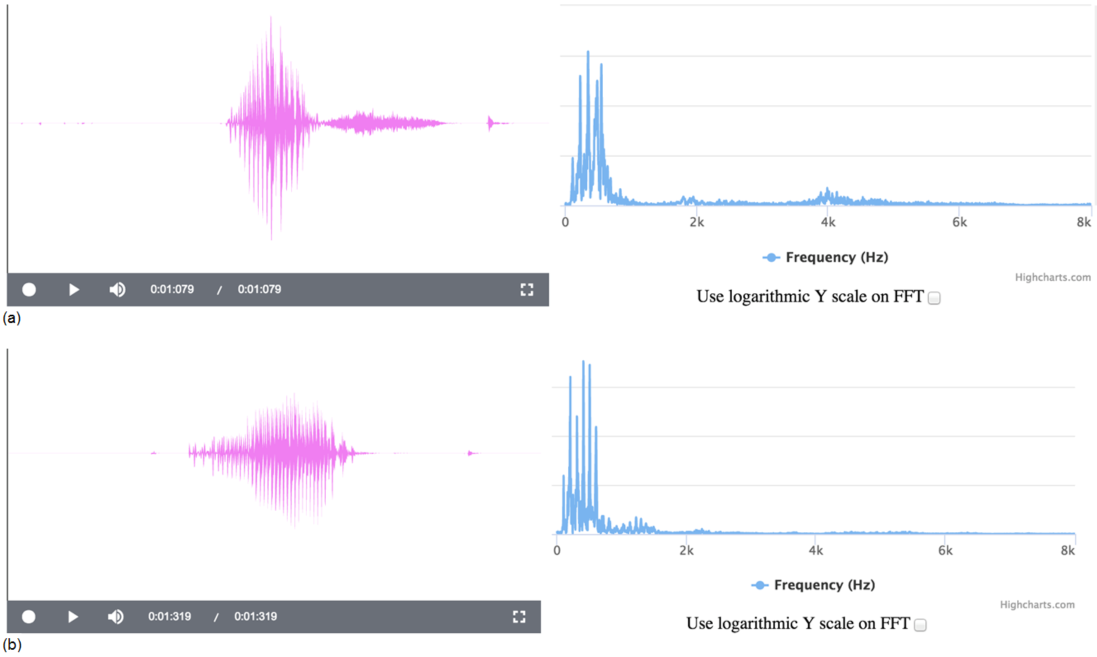


Figure 36 'Yes' and 'no' in the frequency domain: (a) 'yes' has a pattern with many high-frequency components; (b) 'no' has a pattern with few high-frequency components

You can now close the interactive.

4.9 Amplifying signals

Most of the electrical signals that record sounds are very weak. For example, a guitar pickup generates electricity as the metal string vibrates in a magnetic field. The amount of electricity that can be generated in this way is limited and typical voltages are in the order of 100 mV. To become useful, this signal needs to be *amplified*. This means, literally, that the amplitude of the signal has to be increased.

One way to amplify a signal is to use an operational amplifier (op-amp) with two resistors connected to form an amplifying feedback circuit, as shown in Figure 37.

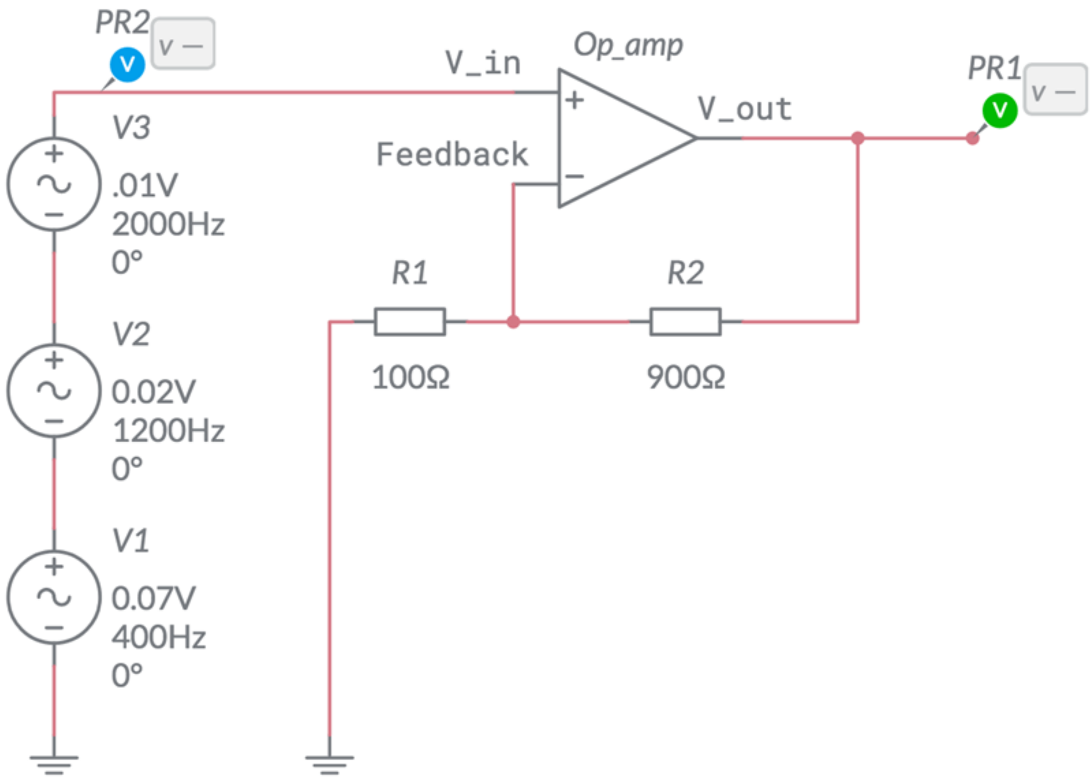


Figure 37 Circuit to generate and amplify a weak signal (screenshot from Multisim Live)

The *gain* of the amplifier is defined to be

$$G = \frac{V_{\text{out}}}{V_{\text{in}}}$$

where V_{in} is the input voltage and V_{out} is the output voltage. For this kind of circuit, the gain is given by the formula

$$G = \frac{R_1 + R_2}{R_1}$$

The circuit in Figure 37 is made using the Multisim Live simulation package. The three circular objects on the left are here used to generate a signal. *V1* generates a voltage sine wave with amplitude 0.07 V and frequency 400 Hz. *V2* generates a voltage sine wave with amplitude 0.02 V and frequency 1200 Hz. *V3* generates a voltage sine wave with amplitude 0.01 V and frequency 2000 Hz. Together, they generate the very weak signal shown in Figure 38.

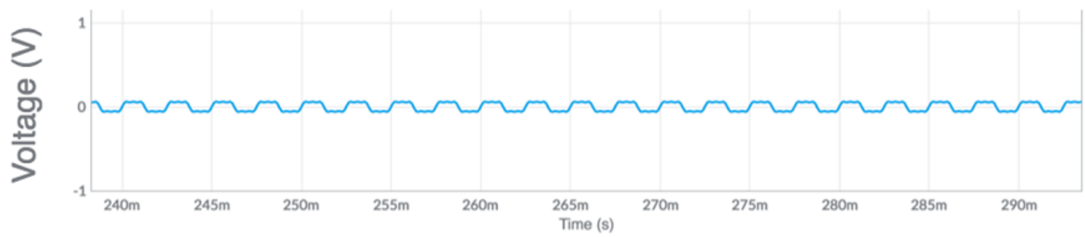


Figure 38 The waveform to be amplified (screenshot from Multisim Live)

SAQ 18

a. What is the gain for the circuit shown in Figure 37?

b. What would the resistor R_2 have to be to make the gain 100?

Answer

a.

$$G = \frac{(100 + 900)\,\Omega}{100\,\Omega} = 10$$

b. Rearranging the equation for G in terms of R_2 gives

$$R_2 = GR_1 - R_1 = R_1\,(G - 1)$$

So for a gain of 100, with R_1 = 100 Ω,

$$R_2 = 100\,\Omega \times (100 - 1) = 9900\,\Omega$$

The original circuit shown in Figure 37 gives the result shown in Figure 39.

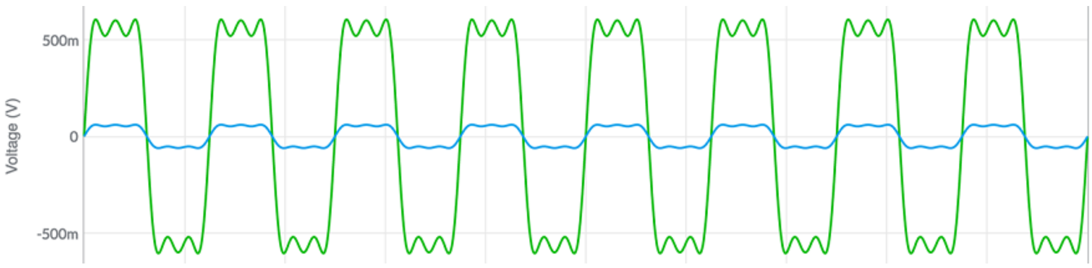


Figure 39 The signal (blue) and the amplified signal (green) (screenshot from Multisim Live)

Op-amps are able to amplify signals many thousands of times. Here the amplification is by a gain factor of 10 so that the signal and the amplified signal can both be seen on the same scale. Typically a signal of 100 mV would be amplified by a factor of 50 or more to bring the result to the order of magnitude ±5 V. Some signals from sensors are much weaker and may require a gain in the order of hundreds or even thousands.

This concludes your lightning visit to the world of electronic signals and filtering. You have seen how effectively noise can be removed from a signal, and how different sounds (such as 'yes' and 'no') appear in both the time and the frequency domain. As well as investigating the theoretical properties of signals, you have seen how they can be amplified using op-amps. If you are interested in going further, a version of the Multisim Live simulator can be used online at no cost – see www.multisim.com.

Conclusion

In this free course, ‘An introduction to electronics’, you have been introduced to some of the fundamental ideas underlying electronics. You have considered the many ways in which electronics impinges on our lives, and looked into some of the technicalities. These included the basics of electrical and electronic circuits, including the use of voltage dividers and Wheatstone bridges to make sensor circuits. You also made a brief journey into the world of signals and signal processing, where electronics plays such a dominant role. Inevitably this course has only scratched the surface, but hopefully you have been inspired to continue your studies and learn more about this fascinating subject.

This OpenLearn course is an adapted extract from the Open University course T212 *Electronics: sensing, logic and actuation*.

Acknowledgements

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