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GLOSSARY

OF PHYSICAL QUANTITIES

for use with 16- to 19-year-olds

IOP Institute of Physics

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Contents

Foreword

This document is a pre-publication sample. It contains a set of 33 definitions of physical quantities. The definitions have been developed jointly in the UK by the Institute of Physics and the National Physical Laboratory. The purpose of this work has been – and is – to promote greater coherence between the awarding organisations administering A-level physics qualification in the UK.

In November 2017, this version of the document was prepared for a presentation to a seminar at EPS Headquarters in Mulhouse, France, with the intention of assessing interest among physics educators from across Europe in the Glossary Project, and in its adoption, in some form, in their respective countries.

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Activity of a radioactive source

Description

Radioactivity is the random and spontaneous breakdown of unstable atomic nuclei involving the emission of alpha, beta or gamma radiation.

The activity of a radioactive sample is defined as the rate at which radioactive particles are emitted. Activity is usually represented by the symbol A.

Discussion

Radioactivity is a random process; it is impossible to predict exactly when a particular nucleus will decay. However, the probability per unit time that a given nucleus will decay is constant.

For a number of nuclei, N, in a sample of a radioactive nuclide, the activity, A, is related to the decay constant λ, which is the probability of decay per nucleus per unit time. If, during time Δt, N changes by ΔN, where $\Delta N < 0$, then the activity, A, is the rate of decay, i.e:

$$A = -\Delta N / \Delta t = \lambda N$$

as long as Δt is small compared with the half-life of the nuclide.

Activity is measured by detecting the radioactive emissions from decay events and counting the number of such detections in a fixed time interval. For this to provide an accurate measurement, the time interval used must allow a sufficiently large number of decays to be detected, while being sufficiently small for the activity not to drop significantly between its start and end, i.e. it must be much less than the half-life of the sample.

A sample of a radioactive material may contain different nuclides, often resulting from previous decays. Furthermore, most radioactive nuclides decay by more than one process; for example, a nucleus of bismuth-212 may decay via either alpha or beta emission. The different processes will have different decay constants and hence different activities. In both cases, the total activity of the sample is the sum of the activities due to all the different decay processes.

SI unit

becquerel, Bq

Expressed in SI base units

s^{-1}

Other commonly used unit/s

Ci (curie) (1 Ci = 3.7×10^{10} Bq), minutes^{-1}, hours^{-1}, years^{-1}

Mathematical expressions

- The activity A of a source consisting of a particular radioactive nuclide at a particular time is

$$A = -\Delta N / \Delta t = \lambda N$$

where λ is the decay constant of the nuclide and N is the number of radioactive nuclei at that time.

- In calculus notation

$A = -\mathrm{d}N / \mathrm{d}t = \lambda N$

Related entries

- Decay constant, radioactive
- Half-life, radioactive

In context

Radioactive sources used in domestic smoke detectors typically have activities of about 40 kBq.

The radioactive sources supplied for use in school practical work are limited to 370 kBq for each individual source.

Radioactive sources are often used in medicine, for example to track how certain materials are distributed around the body. The activities of such sources are usually of the of order 10 MBq. The activity of sources used for cancer treatment is very much higher, typically up to 370 TBq (370×10^{12} Bq) or 370,000 GBq.

Charge

Description

Electric charge is an intrinsic property of matter carried by some fundamental particles. Charge can take a positive or negative value.

Charge is usually represented by the symbol q or Q.

The magnitude of the charge carried by a single electron or proton is usually considered to be the basic natural unit of charge and is given the symbol e.

Discussion

Often but not always, q is used for the charge of a single particle while Q is used for the overall charge of a larger object.

Both static electricity (an imbalance of charge that does not readily move) and current electricity can be explained, on an atomic scale, in terms of charged particles – usually electrons. When objects are charged by frictional contact, there is always a transfer of electrons. For example, if you charge a balloon by rubbing it against your sweater, electrons move from the sweater (to which they are less strongly bound) to the balloon, giving the balloon an overall negative charge and your sweater an equal amount of positive charge. In a plasma (ionised gas) and in an electrolyte (solution containing ions) electric current involves the motion of both positive and negative ions.

All charged particles experience a force in an electric field; all *moving* charged particles experience a force in a magnetic field. The size of a particle's charge influences the size of force that it experiences in both these fields. The sign of its charge influences the direction of the force.

Charge is always conserved; it can neither be created nor destroyed. The charge carried by an object is the algebraic sum of all of its constituent positive and negative charges. An object with no overall positive or negative charge is said to be electrically neutral. In any closed system, the total amount of charge remains constant. In any chemical or nuclear reaction, and any reaction involving fundamental particles, the algebraic sum of the charges remains constant.

Positive and negative charge

Observations of electric charge date back to the ancient Greeks, who noticed that if amber ('elektron' in Greek) is rubbed it can attract small objects. In the 17th century, objects such as rubbed amber were said to be 'charged' (filled) with 'electricity'; experiments showed that two objects charged in the same way (e.g. amber rubbed with fur) always repel each other, but objects charged in different ways can attract each other (e.g. amber rubbed with fur attracts glass rubbed with silk, but repels ebonite (a type of hard rubber) rubbed with wool. It was found that charged objects can be classified into just two types – amber rubbed with fur and ebonite rubbed with wool, both have the same type of charge, which historically, came to be known as negative, while glass rubbed with silk has what is now known as a positive charge.

When the electron was discovered in the late 19th century, it was found to have negative charge.

SI unit

coulomb, C

Expressed in SI base units

A s

Mathematical expressions

$\boldsymbol{F} = q\boldsymbol{E}$

where $\boldsymbol{F}$ is the force exerted on a particle of charge q in an electric field $\boldsymbol{E}$.

$F = qvB \sin \theta$

where F is the magnitude of the force exerted on a particle of charge q travelling at speed v in a magnetic field of magnitude B and θ is the angle between the magnetic field and the particle's velocity.

$Q = It$

where Q is the total charge that passes a point in a circuit in time t and I is the current.

Related entries

- Current, electric
- Electric field
- Magnetic field
- Magnetic flux
- Potential difference, electrostatic

In context

The charge carried by a proton is $e = 1.60 \times 10^{-19}$ C. An electron carries charge $-e = -1.60 \times 10^{-19}$ C.

An electron is a fundamental particle – it is not composed of anything else. A proton is composed of two up-quarks (u) each with a charge $+2e/3$, and a down-quark (d) with charge $-e/3$. Quarks are fundamental particles. A neutron is composed of two d-quarks and one u-quark, giving it an overall charge of zero.

A coulomb of positive (or negative) charge is equivalent to the charge carried by 6.25×10^{18} protons (or electrons). The charge on the dome of a van de Graff generator used in bench-top demonstrations is of the order 10^{-6} C. In a single cloud-to-ground lightning strike, the charge transferred is typically 15–350 C.

Conductance, electrical

Description

The electrical conductance of a component in an electric circuit is a property of a component that describes how the electric current in the component is related to the electrical potential difference (voltage) across it. The greater the electrical conductance, the larger the current for a given potential difference, and the smaller the potential difference, for a given current.

Electrical conductance is usually represented by the symbol *G*.

Electrical conductance is defined, for some component, by the equation

$G = I / V$

where *V* is the electrical potential difference across the component and *I* the corresponding electric current.

Discussion

Conductance is simply the reciprocal of resistance.

SI unit

siemens, S

Expressed in base units

$kg^{-1}\ m^{-2}\ s^{3}\ A^{2}$

Other commonly used Unit(s)

mho (1 mho = 1 ohm^{-1} = 1 S)

Mathematical expressions

Conductance is related simply to resistance, as

$G = 1 / R$

- The conductance of a component is related to the electrical conductivity, σ, of the material from which the component is made, by

$G = \sigma A / L$

where *A* is the component's cross-sectional area and *L* is its length.

Related entries

- Conductivity, electrical
- Resistance, electrical
- Resistivity, electrical

In context

See Resistance, electrical.

Conductivity, electrical

Description

The electrical conductivity of a material is an intrinsic, bulk property that, together with the spatial dimensions and shape of a sample of the material, determines the electrical conductance (and therefore electrical resistance) of that sample.

Electrical conductivity is usually represented by the symbol σ.

Electrical conductivity is defined by the equation

$$\sigma = L / RA$$

where R is the electrical resistance of a sample of material of length L and uniform cross-sectional area A.

Conductivity is the reciprocal of resistivity:

$$\sigma = 1 / \rho$$

where ρ is the electrical resistivity of the material.

Discussion:

A model to explain conductivity

A model of electrical conduction in solids, known as band theory, can account for the huge range of conductivities seen in different materials. In this model, electrons in a solid can only have certain ranges of energy, called energy bands.

An electric current in a solid involves electrons that are free to move through the solid and are not associated with any particular atomic nucleus. These electrons are known as conduction electrons and they have energies in the so-called conduction band.

In the presence of an electric field, the conduction electrons acquire a drift velocity along the field direction and this motion constitutes an electric current. The greater the number density of conduction electrons, the greater the current for a given electric field, and hence the greater is the conductivity.

Electrons that remain bound to particular atoms and are not free to move through the material are known as valence electrons. Valence electrons have lower energies than conduction electrons; their energies lie in the valence band. Between the conduction band and the valence band there is a range of energies that are 'forbidden' – electrons in the solid cannot have energies in that range. The energy difference between the valence and conduction bands is called the band gap. A valence electron may be promoted to the conduction band if it acquires additional energy that is at least as great as the band gap.

In metals, the conduction and valence bands overlap, each atom contributes one or more electrons to the conduction band, and the conductivity is high. Transferring energy to a metal (e.g. by heating) does not result in any significant increase in the number of conduction electrons.

In a semiconductor, there is a smaller number density of conduction electrons than in a metal – on average much less than one per atom. So the conductivity is lower. However, semiconductors are characterised by having a small band gap. It is relatively easy to promote valence electrons to the conduction band (e.g. by heating or illuminating the material), which increases the conductivity. It is also possible to alter the energy band structure by combining two or more semiconducting elements

(e.g. GaAs) and/or by 'doping' a semiconductor with small amounts of impurities – and thus to make 'designer' semiconductor materials with particular properties.

Insulators have very few conduction electrons as their band gaps are very large. They have very low conductivity.

SI unit(s)

$S\ m^{-1}$

Expressed in SI base units

$m^{-3}\ kg^{-1}\ s^{3}\ A^{2}$

Other commonly used units

$\Omega^{-1} m^{-1}$

Mathematical expressions

- $\sigma = L / RA$

where R is the electrical resistance of a sample of material of length L and cross-sectional area A.

- $\sigma = 1 / \rho$

where ρ is the electrical resistivity of the material.

Related entries

- Resistance, electrical
- Resistivity, electrical

In context

Solid materials with conductivities greater than about 10^5 S m^{-1} are classed as conductors, those with conductivities between about 10^5 and 10^{-6} S m^{-1} are semiconductors, and those with lower conductivities are classed as insulators. Silver has the highest conductivity of any metal element. **Table 1** below lists electrical conductivities of various materials at 20 °C, illustrating the enormous range of values.

Material	Conductivity σ/S m^{-1}
Silver	6.30×10^7
Copper	5.96×10^7
Titanium	2.38×10^6
Constantan	2.04×10^6
Nichrome	9.09×10^5
GaAs	5×10^{-8} to 10^3
Amorphous carbon	1.25 to 2×10^3
Sea water	4.8
Silicon	1.56×10^{-3}
Glass	10^{-11} to 10^{-15}
Sulphur	10^{-16}
Paraffin wax	10^{-18}
Teflon	10^{-23} to 10^{-25}

Current, electric

Description

The electric current at a point in a circuit is defined as the rate of flow of charge past that point.

Electric current is usually represented by the symbol I.

The current does not have to be constant in time. For a time-varying current, the current at any instant, t, is

$I = \mathrm{d}Q / \mathrm{d}t$

where $\mathrm{d}Q$ is the charge passing the point between times t and $t + \mathrm{d}t$.

Discussion

In any electrical circuit with a single current path, the current at one point in the circuit is the same as at any other point. Where a circuit branches at a junction, the total current that enters the junction is equal to the total current that leaves it (**figure 1**).

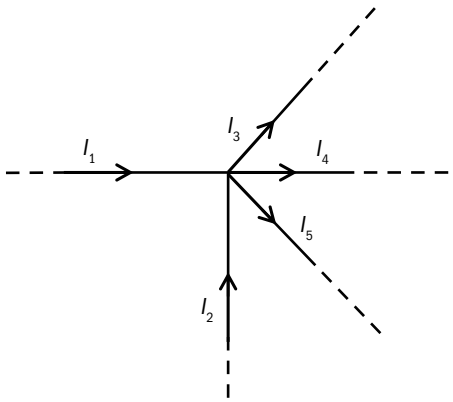


Figure 1
If currents I_1 and I_2 enter a circuit junction and currents I_3, I_4 and I_5 leave it then $I_1 + I_2 = I_3 + I_4 + I_5$.

Although portable devices, such as mobile phones, may use direct current provided by batteries, large items such as washing machines run off the mains supply, which provides an alternating current.

SI unit(s)

ampere, Amp, A

Expressed in SI base units

A

Mathematical expressions

- $I = \mathrm{d}Q / \mathrm{d}t$

where Q is the charge passing a point in the circuit.

- $V = I R$

where V is the voltage across one or more resistive components, of total resistance R

- $P = V I = I^2 R$

where P is the power dissipated in one or more resistive components, of total resistance R, with a voltage V across them.

Related entries

- Potential difference, electrical
- Power
- Resistance, electrical
- Voltage

In context

The current in a typical torch bulb is around 0.5 A. In a high power device, such as a kettle, which runs off the alternating mains supply, the current is around 10 A.

De Broglie wavelength

Description

All particles can show wave-like properties. The de Broglie wavelength of a particle indicates the length scale at which wave-like properties are important for that particle.

de Broglie wavelength is usually represented by the symbol λ or λ_{dB}.

For a particle with momentum p, the de Broglie wavelength is defined as:

$\lambda_{dB} = h / p$

where h is the Planck constant.

Discussion

If a particle is significantly larger than its own de Broglie wavelength, or if it is interacting with other objects on a scale significantly larger than its de Broglie wavelength, then its wave-like properties are not noticeable. For everyday objects at normal speeds, λ_{dB} is far too small for us to see any observable quantum effects. A car of 1,000 kg travelling at 30 m s^{-1}, has a de Broglie wavelength $\lambda_{dB} = 2 \times 10^{-38}$ m, many orders of magnitude smaller than the sizes of atomic nuclei.

A typical electron in a metal has a de Broglie wavelength is of order 10 nm. Therefore, we see quantum-mechanical effects in the properties of a metal when the width of the sample is around that value.

SI unit(s)

metre, m

Expressed in SI base units

m

Other commonly used unit/s

nm

Mathematical expressions

- $\lambda_{dB} = h / p$

where h is the Planck constant and p is the momentum of the particle.

Related entries

- Wavelength

In context

We can infer the wave-like nature of matter by observing the diffraction pattern produced when electrons pass through a crystalline material. The pattern occurs when the de Broglie wavelength of the electrons is comparable with the spacing between the atoms of the crystals. For a material such as graphite, where the interatomic spacing is 0.1–0.2 nm, electrons need to be travelling at speeds of the order of 10^6 m s^{-1} for this to be the case.

Decay constant, radioactive

Description

Radioactivity is a random process; it is impossible to predict exactly when a particular nucleus will decay.

However, it is possible to determine the probability that a nucleus will decay in a given time.

For a particular decay mechanism, the radioactive decay constant for a nuclide is defined as the probability per unit time that a given nucleus of that nuclide will decay by that mechanism. The radioactive decay constant is usually represented by the symbol λ. The definition may be expressed by the equation

$$P = \lambda \Delta t$$

where P is the probability of a given unstable nucleus decaying in the time interval Δt which must be much smaller than the half-life of the nuclide.

If there are initially N nuclei in a sample, the average change in that number, ΔN, resulting from decays after time Δt is

$$\Delta N = -\lambda N \Delta t$$

Discussion

Any sample of a radioactive nuclide whose activity is practically measurable will contain a number of nuclei, N, in excess of around 10^{20}. The proportion of these nuclei that decay in time Δt will get closer and closer to the expected proportion, $\lambda \Delta t$, the larger the value of N, so this proportion can usually be considered exact in practice.

The decay constant depends only on the particular radioactive nuclide and decay mechanism involved – it does not depend on the number of nuclei present or on any external conditions (such as temperature).

In most radioactive samples, there will be more than one way of decaying, either due to different processes within one nuclide or due to there being a mixture of nuclides. In these circumstances, each type of decay process must be considered independently. It is not possible to combine decay constants in a simple way.

SI unit(s)

inverse seconds, s^{-1}

Expressed in SI base units

s^{-1}

Other commonly used unit/s

minutes^{-1}, hours^{-1}, years^{-1}

Mathematical expressions

- $P = \lambda \Delta t$

where P is the probability of a given unstable nucleus decaying in the time interval Δt, which is much smaller than the half-life of the nuclide.

- In calculus notation, the instantaneous rate of decay of a nuclide, i.e. its activity, A, is given by

$$A = \mathrm{d}N / \mathrm{d}t = -\lambda N$$

where N is the number of radioactive nuclei at that instant.

- $t_{1/2} = \ln 2 / \lambda$

where $t_{1/2}$ is the half-life of the radioactive nuclide.

Related entries

- Activity of a radioactive source
- Half life, radioactive

In context

Decay constants have a huge range of values, particularly for nuclei that emit α-particles. For example, the most common isotope of uranium, ^{238}U, has a decay constant of 1.54×10^{-10} yr^{-1} corresponding to a half-life of 4.5 billion years, whereas ^{212}Po has $\lambda = 2.28 \times 10^{6}$ s^{-1}, corresponding to a half-life of 304 ns.

Displacement

Description

Displacement is a vector quantity; it describes the difference in position between two points, measured from one to the other. Referring to **figure 1**, the displacement from A to B is defined by a vector in the direction of the straight line from A to B, with magnitude equal to the distance between A and B measured along that line.

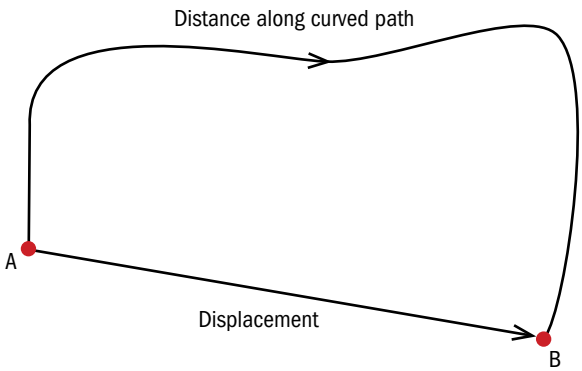


Figure 1
The distance travelled and displacement in moving from point A to point B along a curved path.

When dealing with motion in one dimension along a straight line, displacement is usually represented by the symbol s. When considering coordinate systems in two or three dimensions, displacement is usually represented by the symbol $\Delta \boldsymbol{r}$. In **figure 2**, $\Delta \boldsymbol{r} = \boldsymbol{r}_2 - \boldsymbol{r}_1$ where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the position vectors of an object before and after the displacement, respectively. The components of the displacement vector $\Delta \boldsymbol{r}$ are usually written Δx, Δy (and Δz, if in three dimensions).

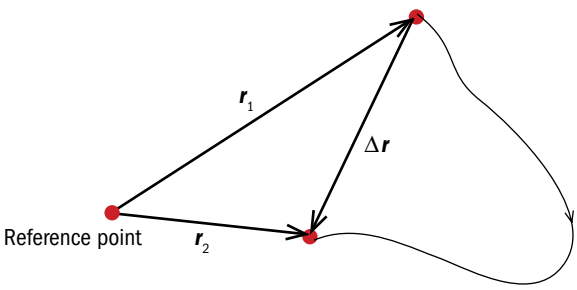


Figure 2
The change of displacement in moving from point 1 to point 2.

Discussion

If the motion between the start and the new position is not along a straight line, the displacement is less than the overall distance travelled. See **figure 1**. In the special case that the motion returns to its original position, the displacement is zero although the distance travelled is not.

For one-dimensional motion along a straight line, direction may be described, e.g. as 'to the left/right' or 'up/down'. If one direction is defined as positive, then displacement in the opposite direction is negative. For example, if 'right' is positive, then a displacement of +4 m means 4 m to the right, and −6 m means 6 m to the left of the starting point.

Displacement

SI unit(s)
metre, m

Expressed in SI base units
m

Other commonly used unit/s
kilometre, km; mile, mi

Mathematical expressions
- $\Delta \boldsymbol{r} = \boldsymbol{r}_2 - \boldsymbol{r}_1$

where Δr is the displacement between two points defined by the position vectors $\boldsymbol{r}_2$ and $\boldsymbol{r}_1$.

Related entries
- Distance
- Velocity

In context
Starting and ending at the same point, an athlete may run a distance of 400 m along the inside lane of a running track, but the displacement of the finishing position with respect to the starting position will be zero.

Electric field

Description

An electric field exists in any region where a charged particle is subject to a force that depends only on the particle's charge and position.

The electric field at a point is a vector quantity usually represented by the symbol ***E***.

The electric field at a point is defined as the force per unit charge that would act on a small positively charged particle located at that point.

If a small test charge of size q is subject to a force ***F*** at some point, and ***F*** depends only on the particle's charge and position, then the electric field at that point is defined as

$$\boldsymbol{E} = \boldsymbol{F} / q$$

Discussion

Electric field is sometimes referred to as electric field strength; this glossary avoids that term because it might be confused with the magnitude of the electric field.

Representing electric fields

Electric fields can be represented graphically by electric field lines and/or by equipotentials.

Electric field lines represent the direction and magnitude of an electric field throughout some region of three-dimensional space. The field lines are continuous unless the region contains charges on which the field lines can begin or end. The orientation of the field lines indicates the direction of the electric field. A strong field is represented by field lines drawn close together; the more closely spaced, the stronger the field.

Equipotentials join points that are all at the same potential. In three-dimensional space, the equipotentials are surfaces, but they are often represented by lines in a two-dimensional 'slice' through the region. Equipotentials are usually drawn so that there is a constant electrostatic potential difference between each one and its neighbours. The spacing between equipotentials indicates the magnitude of the field; the closer the equipotentials, the greater the potential gradient – in other words, the stronger the field.

The field line at any point is always normal to the equipotential drawn through that point. The field direction is from high to low electrostatic potential.

Figure 1 shows field lines and equipotentials for a uniform electric field between two parallel plates.

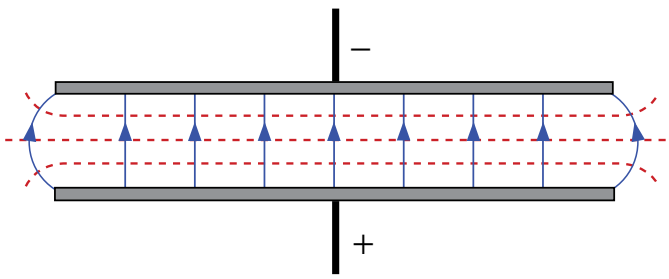


Figure 1
Field lines (solid arrows) and equipotentials (dotted lines) for an electric field between two parallel oppositely charged conducting plates.

Figure 2 shows the radial field of an isolated point charge, or a spherical distribution of charge. If the charge is positive the field is directed radially outwards; if it is negative the field is directed radially inwards.

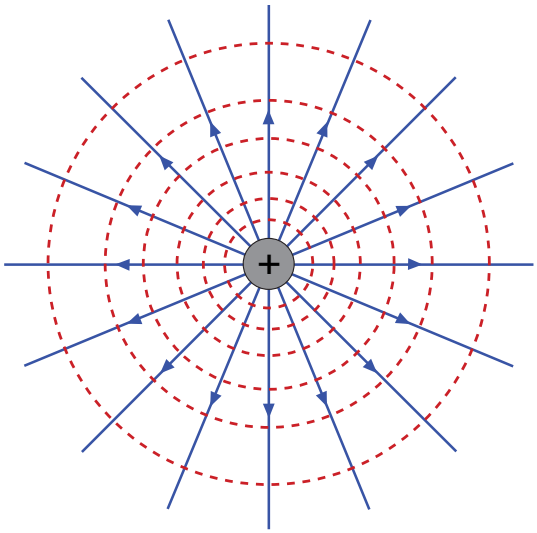


Figure 2
The electric field due to a positive charged spherical object

SI unit(s)

newton per coulomb, N C^{-1}; volt per metre, V m^{-1}

Expressed in SI base units

kg m s^{-3} A^{-1}

Mathematical expressions

- If a test charge q is subject to an electrostatic force $\boldsymbol{F}$ at some point, then the electric field at that point is defined by

$$\boldsymbol{E} = \boldsymbol{F} / q$$

- At any point located a distance r from a point charge Q in free space (a vacuum) the magnitude of the electric field due to the point charge is

$$E = Q / (4\pi\varepsilon_0 r^2)$$

where ε_0 is the permittivity of free space and the field acts in a radial direction as shown in **figure 2**.

- If there is an electrostatic potential difference ΔV between two infinite parallel conducting plates separated by a distance d then there is a uniform electric field between the plates and its magnitude is

$$E = \Delta V / d$$

- More generally, the x component of an electric field is

$$E_x = -\mathrm{d}V / \mathrm{d}x$$

and similarly for the y and z.

Related entries

- Charge
- Electrostatic potential
- Force
- Potential difference, electrostatic

In context

In liquid crystal displays (LCDs) electric fields are used to control the orientation of long molecules that have a small positive charge at one end and a small negative charge at the other. The magnitude of the field used in LCDs is typically 1.00×10^6 N C^{-1}. An electron has charge $q = -1.60 \times 10^{-19}$ C, so when located in a field of this magnitude an electron experiences a force that acts in the opposite direction to that of the field and has magnitude $F = 1.60 \times 10^{-13}$ N.

Close to the Earth's surface, there is a naturally occurring electric field of about 150 N C^{-1}, which becomes weaker with increasing altitude. The field direction is vertically downwards – the Earth is negatively charged whereas the atmosphere has a net positive charge. The field is produced and maintained by various processes including the interactions of cosmic rays and the solar wind (a stream of charged particles) with the atmosphere, and radioactivity within the Earth.

Electrostatic potential

Description

The electrostatic potential at a point is $V = W / q$, where W is the work done in bringing a positive test charge q to that point from a defined position of zero potential.

Given a point, P in an electric field and a reference point A of 'zero potential', the electrostatic potential at P is equivalent to the electrostatic potential difference between A and P.

If the field is due to an isolated charged object then one convention is to define the potential to be zero at an infinite distance from the object. If the charge of the object is positive, then the potential is positive everywhere in the field; if the charge is negative, the potential is negative everywhere in the field.

Electrostatic potential is usually represented by the symbol V.

Discussion

The electrostatic potential at a point is often defined as the ratio between the work done in bringing a test charge from infinity to that point, and the charge itself. While this definition is not incorrect, there are two observations worth making. First, strictly speaking, only *differences* in electrostatic potential are meaningful, which means that, to define electrostatic potential, it is necessary to choose some point that acts as the zero of potential. By choosing 'infinity' as that point, we really mean a point that is a very long way from the source of the field we are considering, where no force is exerted by the field. This is only a convenience, however, and in some situations it is more convenient to choose a different point, such as one on the Earth's surface.

The second observation is the use of 'test charge' in this definition (and in this glossary entry). It is assumed that the test charge is sufficiently small to have a negligible effect on the field through which it is moving. For the purposes of the definition we use

$$V = W / q$$

where W is the work done externally, i.e. by a force acting against the field, in bringing the test charge q to the specified point at a constant velocity.

Electrostatic potential is closely related to electrostatic potential energy. If a charge q is at a point that has electrostatic potential V, then the potential energy associated with the charge and whatever is giving rise to the potential is simply qV.

SI unit(s)

volt, Vm^{-1}

Expressed in SI base units

$A^{-1}\,kg\,m^2\,s^{-3}$

Other commonly used unit/s

JC^{-1}

Mathematical expressions

- $V = Q / 4\pi\varepsilon_0 r$

is the electrostatic potential a distance r from a point charge of magnitude Q, where ε_0 is the permittivity of free space (8.85×10^{-12} F m^{-1}).

- $V = W / q$

is the electrostatic potential at a point, where W is the work done in bringing a test charge q to that point from a defined position of zero potential.

Related entries

- Charge
- Electric field
- Potential difference, electrostatic
- Work

In context

In a hydrogen atom, the electron is on average at a distance 5.3×10^{-11} m from the proton. If we want to ionise the atom, that is remove a single electron, the work we have to do is equal to the electrostatic potential due to the proton, at this distance, multiplied by the electron's charge. Expressed in terms of volts, the electrostatic potential is 13.6 V.

Energy of a system

Description

The energy of a system that is completely isolated is a quantity that is conserved: it cannot change and is therefore useful in making numerical calculations.

When using the conservation of energy in calculations, it is important to identify an appropriate starting state and an end state for the process to be analysed.

In most circumstances, systems are not isolated and energy can be transferred into or out of them. There are two ways this can happen. One is if the system does some work, or has some work done on it. As an example, we can change the energy of a spring by stretching it. The other way in which the energy of a system can change is if its temperature is different from that of its surroundings. In that case, energy will be transferred from the hotter entity (the system or its surroundings) to the cooler one. This process is referred to as heating.

The energy of a closed system can be split into a kinetic energy, due to its bulk motion, and an internal energy, due to the motion of its constituent parts and the interactions between them. Those interactions – and the relative positions of the constituents – give rise to a term for potential energy that is part of the internal energy of the system.

Energy is usually represented by the symbol E.

Discussion

The conservation of energy is a very powerful tool for doing calculations. However, it is very important to define carefully what the system is. Consider a ball falling towards the floor; there is a force acting on the ball due to the Earth, and an equal force acting on the Earth due to the ball. The interaction between the ball and the Earth has an associated energy, so it makes sense to define the system in this case as the combination of the Earth and the ball. Within that system, energy is conserved. This condition means that as the ball gets closer to the floor, that is, the separation between the ball and the Earth decreases, the potential energy of the system decreases so its kinetic energy must increase. In this case, because the Earth's mass is so much greater than the ball's, the Earth's acceleration is effectively zero, and almost all the additional kinetic energy is with the ball, which therefore speeds up as it falls.

SI unit(s)

joule, J

Expressed in SI base units

kg m^2 s^{-2}

Mathematical expressions

- $\Delta E = W + Q$

ΔE is the change in the internal energy of the system due to W, the work done on it and to Q, the energy transferred to the system by heating.

Related entries

- Force
- Heat
- Internal energy
- Kinetic energyy
- Potential energy
- Power
- Specific heat capacity
- Work

In context

We often use electrical heaters to raise the temperature of a room. The way we do this is for the power station, via the electricity transmission network, to do some electrical work on the element of the heater, which raises its temperature well above room temperature. As a result, the element transfers energy, by heating, to the surrounding air to raise its temperature. To raise the temperature of a small room by 5 °C requires about 100 kJ of energy, or about 2 minutes of a 1 kW electric heater, although in practice, the air in the room will also heat other objects in contact with it, so that this time will be longer. In this scenario it may be useful to consider either the electrical heater element alone, or the electrical heater together with the air in the room, to be the system under discussion.

Force

Description

Forces arise from interactions between objects, or between an object and a field. There are just four distinct ways in which particles can interact, giving rise to four distinct types of force. The four fundamental interactions and forces are:

- gravitational (which acts between all matter)
- electromagnetic (includes electrostatic and magnetic forces)
- strong (very short range, acts between subatomic particles)
- weak (very short range, acts between subatomic particles)

Generally, two objects can interact with more than one of these forces. Only the gravitational and electromagnetic forces are readily perceived in normal life although the strong and weak forces are important for the stability of nuclei.

Force is a vector quantity. Both the magnitude and direction of a force are important when determining its effects. A force is often represented by the symbol $\boldsymbol{F}$.

When two objects interact, each exerts a force on the other; the forces are equal in size but opposite in direction.

Forces can do work by changing an object's motion and/or deforming the object. For example, a single force acting on an object, $\boldsymbol{F}$, changes the magnitude and/or direction of its momentum, $\boldsymbol{p}$. This change in momentum is in the direction of the force. Force can be defined as rate of change of momentum:

$$\boldsymbol{F} = \mathrm{d}\boldsymbol{p} / \mathrm{d}t$$

In situations where mass does not change, this is equivalent to the equation

$$\boldsymbol{F} = m\,\boldsymbol{a}$$

where $\boldsymbol{a}$ is the acceleration produced by the force and m is the mass of the object.

Discussion

Forces may be attractive or repulsive. The force of gravity is always attractive. The electromagnetic force can be either attractive or repulsive: the force between two electric charges is attractive if the charges have opposite signs but repulsive if they have the same sign. The strong force is considered to be either always attractive, or to be attractive or repulsive, depending on which fundamental theory is used to describe it and on the separation between the particles concerned. The weak force may be attractive or repulsive, or neither, depending on certain properties of the particles concerned.

Our understanding of forces and their effects is summarised in Newton's three laws of motion. They are classical laws, which means that they apply to situations where speeds are significantly less than the speed of light.

Newton's first law of motion states that an object continues to move at constant velocity, or remains at rest, unless acted on by an unbalanced or 'resultant' force.

Newton's second law of motion relates an object's rate of change of momentum to the resultant force acting on it.

Newton's third law of motion states that all forces are the result of interactions. When two objects interact, each exerts a force on the other. The forces are equal in magnitude and opposite in direction, and act along the same line; they are both the same type of force (e.g. both gravitational).

Contact forces and friction are actually electromagnetic in origin. When a hand pushes on a door, there is an electromagnetic interaction between the electrons in the molecules at the surfaces of the hand and the door. However, in determining the motion of interacting objects, the nature of the forces(s) exerted on them is irrelevant; the only things that matter are the magnitude and direction of any forces and their lines of action.

SI unit(s)

newton, N

Expressed in SI base units

kg m s^{-2}

Mathematical expressions

- $\boldsymbol{F} = \mathrm{d}\boldsymbol{p} / \mathrm{d}t$

where $\boldsymbol{p}$ is the momentum of an object acted upon by a resultant force $\boldsymbol{F}$.

- $\boldsymbol{F} = m\,\boldsymbol{a}$

where $\boldsymbol{a}$ is the acceleration of an object of mass m that is acted upon by a resultant force $\boldsymbol{F}$.

Related entries

- Potential energy
- Work

In context

The expanding gases in a Rolls-Royce Griffon engine exert a force of magnitude up to around 11,000 N upon each piston head.

Two protons separated by 0.10 nm (10^{-10} m, a typical interatomic distance) repel each other with an electrostatic force of magnitude 2.3×10^{-8} N and attract one another with a gravitational force of magnitude 1.9×10^{-44} N.

The Earth and Sun attract each other with a gravitational force of magnitude 3.6×10^{22} N.

Reference

- www.spitfireperformance.com/RR-Griffon.pdf

Frequency

Description

Frequency describes the rate of repetition of a periodic event. Frequency is defined as the number of cycles (number of repeats) per unit time (the number does not have to be an integer).

Frequency is usually represented by the symbol f, or sometimes by the symbol ν (the Greek letter "nu"). For a periodic event with period T, the frequency f is related to the period by

$$f = 1 / T$$

Discussion

Frequency and period are very closely related. In terms of measurement, it is usually easier to measure the period if the frequency is very low. The rotation of the Earth on its axis has a period of approximately 24 hours and we measure its period. But the vibration of a loudspeaker cone is of the order 10^3 Hz and we measure the number of times it vibrates in a given time.

SI unit(s)

hertz, Hz

Expressed in SI base units

s^{-1}

Mathematical expressions

- $f = 1 / T$

where T is the period.

- The frequency of a wave is related to its wavelength, λ:

$$f = v / \lambda$$

where v is the speed of the wave.

- For electromagnetic radiation with frequency f, the energy, E, of a photon is given by

$$E = h f$$

where h is the Planck constant.

Related entries

- Period
- Wavelength

In context

Electromagnetic radiation is often given a name according to its frequency and, sometimes, its application. Radio waves have frequencies between MHz and GHz. Visible light has frequencies between about 4.3×10^{14} Hz and 7.5×10^{14} Hz. Gamma rays have frequencies in excess of 10^{20} Hz.

Gravitational field

Description

A gravitational field exists in any region where a particle is subject to a force that depends only on the particle's mass and position.

The gravitational field at a point is a vector quantity usually represented by the symbol $\boldsymbol{g}$.

The gravitational field at a point is defined as the force per unit mass that would act on a particle located at that point.

If a test mass m is subject to a force $\boldsymbol{F}$ at some point, and $\boldsymbol{F}$ depends only on the particle's mass and position, then the gravitational field at that point is defined as

$$\boldsymbol{g} = \boldsymbol{F} / m$$

Discussion

Gravitational field is sometimes referred to as gravitational field strength; this glossary avoids that term because it might be confused with the magnitude of the gravitational field.

The force in the description is known as a gravitational force and is often called weight, but the latter term is to be avoided as it is ambiguous.

Historically, g was sometimes referred to as the 'acceleration due to gravity' as it is numerically equal to the acceleration experienced by a free-falling object in a gravitational field.

SI unit(s)

newton per kilogram, N kg^{-1}

Expressed in SI base units

m s^{-2}

Other commonly used unit/s

gal (1 Gal = 10^{-2} N kg^{-1})

Mathematical expressions

- If a mass m experiences a gravitational force F, then the gravitational field at that point is

$$\boldsymbol{g} = \boldsymbol{F} / m$$

- The magnitude of the gravitational field g on the Earth's surface is related to the universal gravitational constant G

$$g = GM / R_E^2$$

where M is the Earth's mass and R_E its radius.

Related entries

- Electrostatic field
- Gravitational potential
- Weight

In context

The magnitude of the gravitational field at the surface of the earth is around 9.8 N kg^{-1}.

The value of *g* varies from place to place on the Earth's surface. One reason for this is that *g* depends on distance from the Earth's centre, and Earth is not a perfect sphere – Earth's radius is smaller at the poles than at the equator. Also, the Earth's density is not uniform so Earth's mass is not equally distributed.

Gravimetry, involving measurements of surface gravitational field, can provide information about the nature of the materials in the Earth's interior, e.g. oil deposits. Variations in *g* of the order of 10^{-8} N kg^{-1} can be detected using sensitive instruments.

The acceleration of free fall on Earth, as measured for example in a simple pendulum experiment or by timing a falling object, is affected by the Earth's rotation as well as by the local gravitational field. The effects of rotation are greatest at low latitudes (close to the equator), but even at the equator rotational effects reduce the acceleration of free fall by only about 3×10^{-2} m s^{-1} so such effects can often be ignored.

Gravitational potential

Description

The gravitational potential at a point in a gravitational field is the work done per unit mass that would have to be done by some externally applied force to bring a massive object to that point from some defined position of zero potential, usually 'infinity'. It is the gravitational potential difference between the chosen point and the position of zero potential.

Gravitational potential is often represented by the symbol V.

If the field is due to an isolated massive point object (or any object of finite size), then it is conventional to define the potential to be zero at an infinite distance from the object; the potential is negative everywhere else because the gravitational force is always attractive.

Gravitational potential is also defined as the gravitational potential energy per unit mass relative to a defined position of zero potential energy. The two definitions are equivalent.

Discussion

There is a strong similarity between gravitational potential and electrostatic potential. In both cases, the underlying forces depend on the separation, r, of interacting objects as $1 / r^2$ and, in both cases, the change in the potential is defined via the work done in changing the separation between the interacting objects. The difference lies in the nature of the force: charges may be positive or negative, so the electrostatic interaction may be attractive or repulsive. The force of gravity is always attractive.

SI unit(s)

$\mathrm{J\,kg^{-1}}$

Expressed in SI base units

$\mathrm{m^2\,s^{-2}}$

Mathematical expressions

- Raising an object through a height Δh at the surface of the Earth leads to a change of gravitational potential

$$\Delta V = g\,\Delta h$$

where g is the gravitational field at the surface of the Earth and Δh is much less than the radius of the Earth.

- More generally

$$\Delta V = \frac{GM}{R} - \frac{GM}{R + \Delta h} = \left(\frac{GM}{R}\right)\left(\frac{\Delta h}{R + \Delta h}\right)$$

where M and R are, respectively, the mass and radius of the Earth and G is the universal gravitational constant.

Gravitational potential

Related entries

- Gravitational field
- Potential energy

In context

The difference in gravitational potential between sea level and the summit of Mount Everest is about 8.7×10^4 J kg^{-1}. If a mountaineer of mass 100 kg travels from sea level to the Everest summit, the gravitational potential energy of the Earth-mountaineer system increases by about 8.7×10^6 J.

Half-life, radioactive

Description

Radioactivity is a random process; it is impossible to predict exactly when a particular atomic nucleus will decay. However, the time for a given fraction of nuclei in a sample to decay can be determined.

The half-life of a sample of a radioactive nuclide is defined as the time interval during which half the nuclei in a sample undergo radioactive decay (see **figure 1**). The length of this interval does not depend on its starting point, i.e. on the number of nuclei present initially. If the nuclide decays to non-radioactive products, the half-life is also the time interval during which the activity of the sample halves. The activity is usually easier to measure than the number of nuclei.

Half-life is usually represented by the symbol $t_{1/2}$.

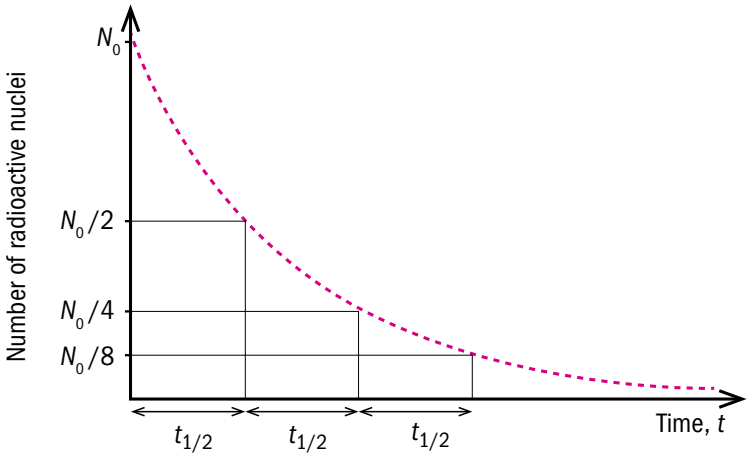


Figure 1
The number of radioactive nuclei remaining in a sample over time.

Discussion

Although the concept of half-life is well defined for a particular decay process in a particular radioactive nuclide, many nuclides decay through different mechanisms and each will have its own half-life. In addition, the products of the decay, the daughter nuclei, are often radioactive themselves and will have a different half-life. Therefore, even in what starts out as a pure sample of a single nuclide, there can be numerous decay processes, each with a different half-life. In such cases, the decay in activity of the sample is not a simple exponential process and cannot be described by a simple half-life.

SI unit(s)

seconds, s

Expressed in SI base units

s

Other commonly used unit/s

hours, minutes, days, years

Mathematical expressions

- The half-life of a given nuclide is related to λ, its radioactive decay constant, by

$$t_{1/2} = \ln 2 / \lambda$$

- The number of radioactive nuclei present depends upon time according to

$N = N_0 \exp(-\lambda t)$

where N_0 is the number present when $t = 0$.

Related entries

- Activity of a radioactive source
- Decay constant, radioactive

In context

The range of half-lives is very large, from fractions of a second to millions of years. Long half-lives are a particular problem in dealing with radioactive waste, which must be made secure for many thousands of years due to its toxicity.

Some medical diagnostic procedures involve injecting a radioactive nuclide into the patient's bloodstream to image various parts of the body. The half-life of the chosen nuclide must be long enough for there to be time for the nuclide to enter the body and reach the area of interest but short enough for the activity to be within recommended safety levels in a few hours. The gamma-emitting nuclide ^{99m}Tc, widely used in such procedures, has a half-life of 6.01 hours.

In other applications, a long half-life is desirable. For example, most domestic smoke detectors use the nuclide americium-241, which is a source of alpha radiation. This nuclide has a half-life of 432 years, so its activity does not change noticeably over the many years for which a detector may be in use.

Kits supplied to schools for practical work involving radioactivity typically use either ^{137}Cs or ^{60}Co as a source of beta radiation. Caesium-137 has a half-life of 30.1 years but the half-life of ^{60}Co is only 5.3 years. Over a period of 30 years, the activity of a caesium source will halve, but that of a cobalt source will decrease to about 1/50th of its original value; the caesium source will still be useful after 30 years, but the cobalt would need to be replaced long before 30 years elapse.

Kinetic energy

Description

Kinetic energy is energy associated with motion.

Kinetic energy is usually represented by the symbol E_k or the abbreviation KE.

In Newtonian physics, the kinetic energy of an object of mass m, travelling at speed v, is defined by the equation:

$$E_k = \tfrac{1}{2} m v^2$$

Discussion

Kinetic energy is not an absolute quantity because to measure the speed of an object, there must be an observer with respect to whom the object is (or is not) moving. The expression for an object's kinetic energy, $\tfrac{1}{2} mv^2$, is accurate in classical, Newtonian physics for speeds much less than the speed of light. At very high speeds, the expression for the kinetic energy is modified to become

$$E_k = (\gamma - 1)\, m_0\, c^2$$

where m_0 is the mass of the particle measured when it is at rest, c is the speed of light and

$$\gamma = (1 - v^2 / c^2)^{-1/2}$$

In the limit $v \ll c$, this expression for E_K reduces to the classical $\tfrac{1}{2} m v^2$.

SI unit(s)

joule, J

Expressed in SI base units

$\mathrm{kg\,m^2\,s^{-2}}$

Mathematical expressions

- $E_k = \tfrac{1}{2} m v^2$

is the kinetic energy of an object with mass m moving at speed v.

Related entries

- Energy of a system
- Internal energy
- Potential energy

In context

The typical kinetic energies of the following objects are of the orders of magnitude indicated:

A runner of mass 70 kg running at about 5 m s^{-1}: 10^3 J.

A car of mass 2000 kg travelling at 70 mph (about 31 m s^{-1}) on a motorway: 10^6 J.

An electron moving randomly in a metal at room temperature: 10^{-19} J.

Magnetic field

Description

A magnetic field exists in any region where a charged particle is subject to a force that depends only on the particle's charge, velocity and position. The force acts at right angles to both the magnetic field and the particle's velocity.

The magnetic field at a point is a vector quantity, usually represented by the symbol ***B***.

The magnitude of the magnetic force, ***F***, acting on a positive charge q moving at velocity v in a magnetic field ***B*** is

$$F = qvB \sin\theta$$

where θ is the angle between the direction of travel of the particle and the direction of the magnetic field (i.e. the angle between ***v*** and ***B***), and v and B are, respectively, the magnitudes of ***v*** and ***B***. The force is therefore zero if the particle is moving parallel to the field direction ($\theta = 0$, $\sin\theta = 0$) and greatest when motion is at right angles to the field ($\sin\theta = 1$, $F = Bqv$).

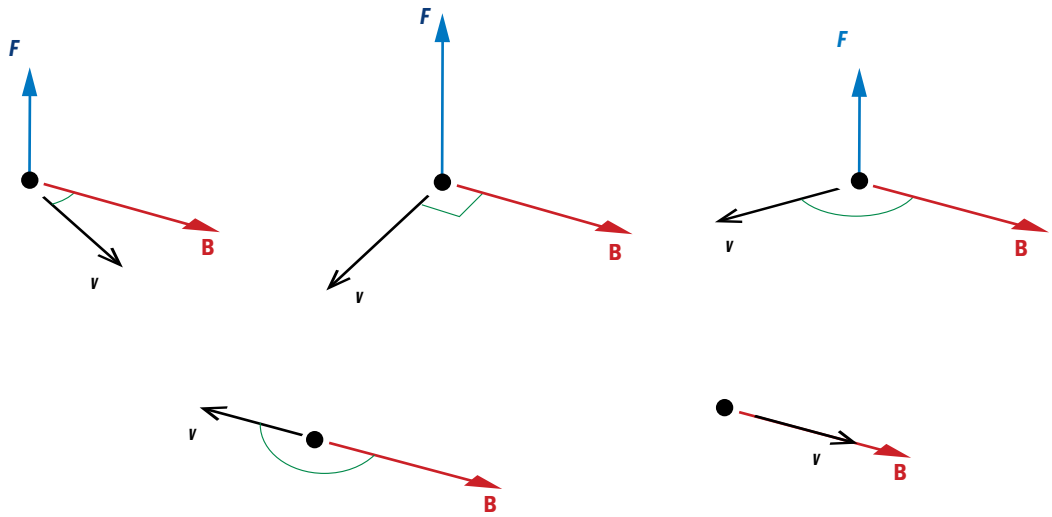


Figure 1
The magnitude of the force exerted by a magnetic field upon a moving positively charged particle depends upon the angle, θ, between the particle's velocity, ***v***, and the magnetic field ***B***. This magnitude is shown by the length of the blue arrow in each diagram.

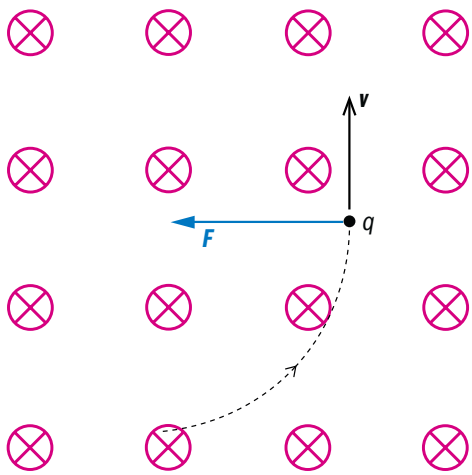


Figure 2
A particle of positive charge q moving with velocity ***v*** in a magnetic field which is directed into the page.

When a current exists in a wire within a magnetic field, a force acts on the wire that is the total of all the individual forces on each of the charged particles. When the magnetic field is uniform over a straight section of wire with length L, then that section of the wire is subjected to a force whose magnitude is given by

$$F = I\,L\,B\sin\theta$$

where I is the current and θ is the angle between the directions of the wire and the magnetic field.

Discussion

Representing magnetic fields

Magnetic fields can be represented graphically by magnetic field lines, also called lines of flux. The direction of a field line at any point indicates the field direction at that point. A small dipole test magnet (e.g. a compass needle) placed at a point in the field would align along the field line passing through that point.

A strong field is represented by field lines drawn close together; the more closely spaced, the stronger the field. The magnitude of a magnetic field is proportional to the number of lines of flux passing at right angles through unit area, so that the term 'magnetic flux density' is often used as an alternative name for $\boldsymbol{B}$. The term 'magnetic field strength' is also occasionally (incorrectly) used for $\boldsymbol{B}$ itself, and this glossary avoids that term because it might cause confusion between B and $\boldsymbol{B}$, and also with another quantity introduced in university level physics.

Magnetic fields due to currents in wires

At a distance r from a long straight wire, surrounded by air and carrying a current I:

$$B = \mu_0 I / 2\pi r$$

where μ_0 is the permeability of free space (of a vacuum).

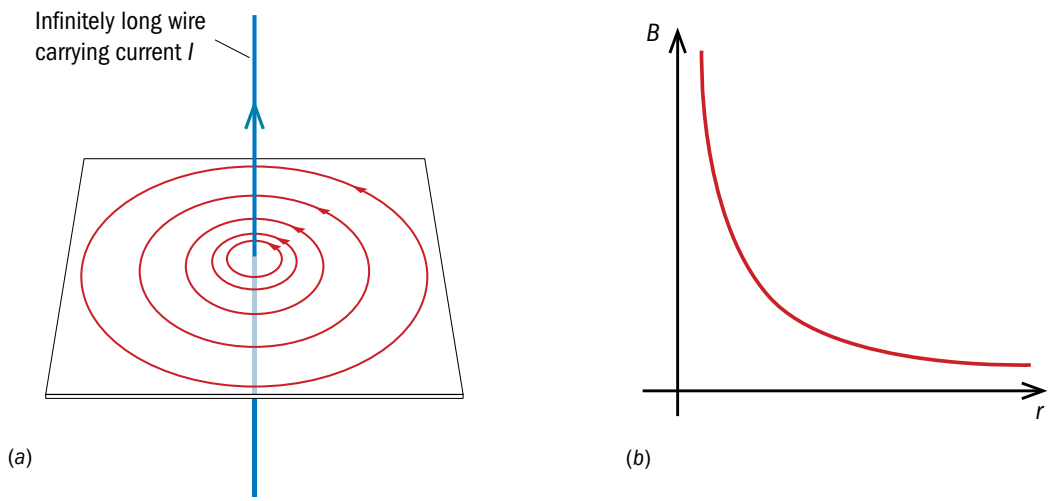


Figure 3
The magnitude, B of the magnetic field around a straight current-carrying wire, can be represented by the spacing of field lines, shown in red (a), or in a graph (b).

The field lines are circular and centred on the wire. The field direction is given by the 'right-hand grip rule' as shown in **figure 3a**.

Inside a long straight solenoid with N turns in a length L, with an air core and carrying a current I:

$B = \mu_0 IN / L$

The field direction is parallel to the axis of the solenoid.

If the solenoid is wound onto a magnetic material such as iron, the field is much stronger:

$B = \mu_0 \mu_r IN / L$

where μ_r is the relative permeability of the core material. Non-magnetic materials have $\mu_r \approx 1$. Materials that can be highly magnetised, such as iron, have high relative permeabilities, depending on their purity. Alloys can be manufactured with relative permeabilities of many thousand.

SI unit(s)

tesla, T; weber per square meter, Wb m^{-2}

Expressed in SI base units

kg s^{-2} A^{-1}

Other commonly used unit/s

N m^{-1} A^{-1}, gauss, G (1 G = 10^{-4} T)

Mathematical expressions

- $F = BIL \sin\theta$

where F is the magnitude of the force exerted on a straight wire of length l carrying a current I at an angle θ to the field direction.

- $F = Bqv \sin\theta$

where F is the magnitude of the force exerted on a positive charge q moving with speed v at an angle θ to the field direction. This is illustrated in **figure 2** for the case $\theta = 90^\circ$.

- At a distance r from a long straight wire, surrounded by air and carrying a current I, the magnetic field magnitude is very nearly

$B = \mu_0 I / 2\pi r$

where the approximation is due to the fact that the magnetic permeabilities of air and of a vacuum are very nearly equal.

- Inside a long straight solenoid with N turns in a length L, with an air core, carrying a current I the magnetic field magnitude is very nearly

$B = \mu_0 IN / L$

where μ_0 is the permeability of free space (vacuum). The field direction is parallel to the axis of the solenoid.

Related entries

- Charge
- Current, electric
- Emf
- Magnetic flux

In context

A magnetic field with magnitude $B = 1$ T is a strong field. The USA National Magnetic Field Laboratory (MagLab) currently hold the record of 45 T for the world's strongest magnet with a continuous field.

The Earth's magnetic field resembles that of a large bar magnet titled at about 10° to Earth's rotation axis. Close to Earth's magnetic poles, the field is vertical and has a magnitude of about 65 μT (6.5×10^{-5} T), and near the equator it is horizontal with a magnitude of about 25 μT. The magnetic fields inside most MRI scanners have a magnitude around 1.5 T. Other naturally occurring magnetic fields range from about 10^{-14} T (in a magnetically shielded room) to about 10^{10} T (at the surface of a pulsar).

Reference

- https://nationalmaglab.org/news-events/news/national-maglab-racks-up-another-record

Magnetic flux

Description

For a uniform magnetic field, ***B***, with direction normal to a plane area of size *A*, the magnetic flux ϕ through the area is

$$\phi = BA$$

In the more general case, as shown in **figure 1**, the magnetic flux is defined as

$$\phi = BA\cos\theta$$

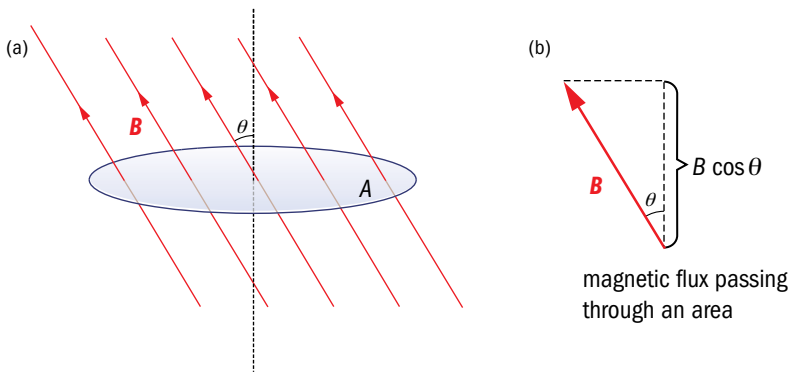


Figure 1
A flat loop of area *A* is in a region where the magnetic field is ***B*** (shown with red field lines in (a)). The component of ***B*** directed normally through the area is shown by the vertical dotted line in (b).

where θ is the angle between the field direction and a line normal to the plane of the area. $B\cos\theta$ is the component of *B* passing at right-angles through the area.

When the field is non-uniform, the flux is calculated using the value of *B* (or $B\cos\theta$) averaged over the area.

Discussion

Magnetic flux is an important quantity that allows us to calculate the emf generated in a coil of wire when the flux through the coil changes, as happens in a dynamo or certain types of microphone. The mechanism for the former typically involves the rotation of a magnet around a stationary coil of wire; the moving magnet creates a time-varying magnetic flux through the coil and hence generates an emf. The size of the emf generated this way is proportional to the rate of change of flux (Faraday's Law) and its direction is such as to oppose the change in flux that caused it (Lenz's Law).

SI unit(s)

weber, Wb (1 Wb = 1 T m^2)

Expressed in SI base units

kg m^2 s^{-2} A^{-1}

Mathematical expressions

- For a uniform magnetic field of magnitude B, directed normally to the area A, the magnetic flux through the area is

$$\phi = BA$$

- In the more general case, as shown in **figure 1**, the magnetic flux is defined as

$$\phi = BA\cos\theta$$

- When there is a time-varying magnetic flux through a coil of wire with N turns, an emf E is generated, given by a combination of Faraday's Law and Lenz's Law as

$$\varepsilon = -\mathrm{d}(N\phi)/\mathrm{d}t$$

Related entries

- Emf
- Magnetic field

In context

The main coil of a typical MRI scanner has an internal cross-sectional area around $\pi \times (30\,\mathrm{cm})^2 = 0.28\,\mathrm{m}^2$ and a magnetic field of magnitude 1.5 T. Hence the magnetic flux through this coil is around 0.42 Wb.

Reference

- www.healthcare.siemens.co.uk/magnetic-resonance-imaging/0-35-to-1-5t-mri-scanner/magnetom-avanto/technical-details

Momentum

Description

Momentum is a vector quantity associated with motion. In a system upon which no external forces act, total momentum is conserved.

Momentum is usually represented by the symbol $\boldsymbol{p}$.

In Newtonian mechanics, momentum, $\boldsymbol{p}$, of an object is defined as the product of the mass, m, and the velocity, $\boldsymbol{v}$, of the object:

$$\boldsymbol{p} = m\boldsymbol{v}$$

Massless particles can also have momentum. For example, a photon has momentum whose magnitude, p, is related to its energy, E, which in turn is related to the frequency, f, and wavelength, λ, of the corresponding electromagnetic wave:

$$p = E / c = h f / c = h / \lambda$$

where h is the Planck constant and c the speed of light in a vacuum.

Discussion

The momentum of an object is, intuitively, a measure of how much effort one has to make to alter its motion. Given that force is the rate of change of momentum, an object of small mass going quickly can require as much force, applied over the same time (i.e. the same impulse) to stop it as an object of larger mass going more slowly.

The definition of momentum as mv works well in the Newtonian regime at speeds well below the speed of light. The more general definition, which works at all speeds, is

$$\boldsymbol{p} = \gamma m_0 \boldsymbol{v}$$

where m_0 is mass of the object when at rest and $\gamma = (1 - v^2 / c^2)^{-1/2}$. In the limit $v << c$, we have $\gamma \approx 1$, so that the above expression reduces to the Newtonian version.

The importance of momentum is that, for an isolated system, it is conserved in all circumstances. It does not matter how complicated the interactions between different particles are, the total momentum of the system will always be the same before and after the interaction, provided no external forces act upon it.

If a constant resultant force $\boldsymbol{F}$ acts upon an object over a time period Δt, the object's momentum will be changed by an amount $\Delta\boldsymbol{p} = \boldsymbol{F}\,\Delta t$. This is the impulse imparted to the object.

SI unit(s)

N s

Expressed in SI base units

kg m s^{-1}

Mathematical expressions

- In Newtonian mechanics, momentum, $\boldsymbol{p}$, is defined as the product of the mass, m, and the velocity, $\boldsymbol{v}$, of an object:

$$\boldsymbol{p} = m\boldsymbol{v}$$

- More generally, massless particles can also have momentum. For example, a photon has momentum whose magnitude, p, is related to its energy, E, which in turn is related to the frequency, f, and wavelength, λ, of the corresponding electromagnetic wave:

$$p = E / c = hf / c = h / \lambda$$

where h is the Planck constant and c the speed of light in a vacuum.

Related entries

- Force
- Impulse
- Kinetic energy

In context

A photon of visible light with wavelength 660 nm has momentum $p = 10^{-27}$ kg m s^{-1}.

An electron travelling through a cathode ray tube at about 106 m s^{-1} has $p = 10^{-24}$ kg m s^{-1}.

A sprinter of mass 70 kg running at 10 m s^{-1} has $p = 700$ kg m s^{-1}.

In 2013, meteorite fragments crashed to Earth near the Russian city of Chelyabinsk. The largest fragment had a mass over 570 kg. When it was travelling at about 20 m s^{-1} (typical of large meteorites) its momentum was about 1.1×10^4 kg m s^{-1}.

Reference

- http://cams.seti.org/Popova2013-ms.pdf

Period

Description

The period, or periodic time, of a periodic variation of a quantity is defined as the time interval between two successive repetitions. See **figure 1**.

Period is usually represented by the symbol *T*.

The period of the variation is related to its frequency, *f*, by

$T = 1 / f$

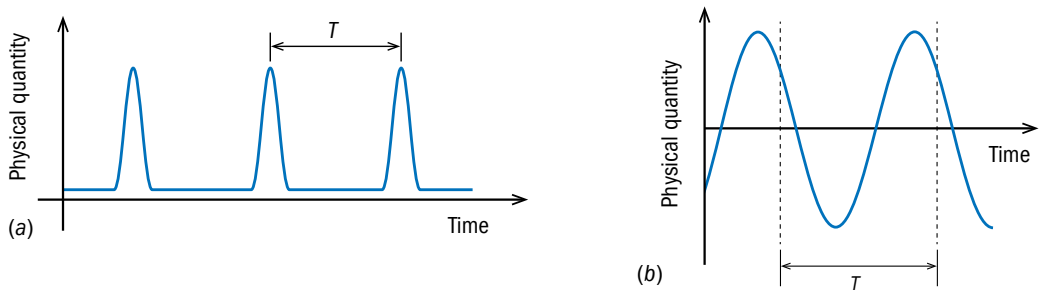


Figure 1
The period of a periodically varying quantity may be measured between successive 'equivalent' points on a plot of the quantity over time.

Discussion

It is usually easy to measure a period directly if the corresponding frequency is very low. For example, the rotation of the Earth on its axis has a period of approximately 24 hours and we measure its period. But for motion where the period is of the order of a second, or less, then it is usually easier to measure the number of oscillations in a given time interval and calculate the frequency and hence the period. The frequency of vibration of a loud-speaker cone is of the order 10^3 Hz and the number of times it vibrates in one second is typically measured, e.g. by using a laser beam reflected from its surface to determine its velocity.

SI unit(s)

seconds, s

Expressed in SI base units

s

Other commonly used unit/s

minutes, hours, days, years

Mathematical expressions

- The period *T* of a periodic phenomenon is related to the frequency *f* by

$T = 1 / f$

- The period of a simple pendulum of length l, oscillating with small amplitude, is given by

$T = 2\pi\sqrt{(l / g)}$

where g is the gravitational field

- The period of a mass m suspended from a spring of stiffness k is given by

$T = 2\pi\sqrt{(m / k)}$

Related entries

- Frequency

In context

Historically, periodic motion has been the principal means of keeping time. The length of the year is related to the periodic motion of Earth around the Sun, and the length of the day to the periodic rotation of the Earth about its own axis. Pendulum clocks depend on the fact that, for small angles, the period of a pendulum is independent of the amplitude of its motion and can be adjusted by altering the pendulum's length. For example, a pendulum a 1 m long has a period around 2 seconds. Many electronic watches use the vibration of a quartz crystal as the basis of timekeeping; the vibration frequency is just under 33 kHz, corresponding to a period of 30 μs.

Power

Description

Power is defined as the rate at which energy is transferred to or from a system. The transfer may involve heating, working or both.

Power is usually represented by the symbol *P*.

When the energy of a system changes by ΔE in time Δt,

$P = \Delta E / \Delta t$

Discussion

Power ratings

The power rating of a domestic electrical device indicates the electrical power input when a device is connected across the potential difference for which it has been designed. If a device is connected across a higher (or lower) potential difference, the current in the device will be greater (or less) than that for which the device is designed, and the input power will be greater (or less) than the stated power rating. For example, a kettle manufactured for use in the UK might be rated at 1 kW. Provided it is connected to the UK mains, so that p.d. across the kettle is 230 V, then the kettle operates with a power of 1 kW (the current in the kettle is about 4.3 A). But if it is connected to the USA mains supply, which provides 120 V, then the current is only about 2.3 A and the kettle operates with a power of about 270 W. It will therefore take the kettle around four times as long to heat the same quantity of water in the US as in the UK.

Power and efficiency

The performance of a machine might be described in terms of the power input required to operate it, or in terms of its useful power output. A machine's efficiency is defined as

efficiency = useful power output / total power input

and is often quoted as a percentage. The efficiency of a machine can never be greater than 100% and is often considerably lower.

The power ratings of domestic appliances generally refer to the electrical power input, rather than the useful power output.

For example, an electric drill typically has a power rating of 500 W, meaning that energy is transferred to the drill at a rate of 500 J s^{-1}. The efficiency of an electric drill might be about 50%, in which case the useful power output is about 250 W.

SI unit(s)

watt, W; J s^{-1}

Expressed in SI base units

kg m^2 s^{-3}

Other commonly used unit/s

horsepower, hp (1 hp ≈ 746 W)

Mathematical expressions

- If the energy of a system changes by ΔE in time Δt, then

$P = \Delta E / \Delta t = (W + Q) / \Delta t$

where energy Q or W, or both, may be transferred by heating or working, respectively.

- $P = VI = I^2R = V^2 / R$

applies to an electric circuit where P is the power dissipated in a component with resistance R, V is the potential difference (voltage) across the component and I is the current.

Related entries

- Energy of a system
- Heat
- Internal energy
- Temperature
- Work

In context

Power ratings are commonly used to describe the performance of industrial machinery and domestic appliances. Often, though not always, power ratings refer to electrical power *input*. For example, a torch bulb in normal use might have a current of 0.5 A when connected to a 3 V battery, so the electrical power input to the bulb is 1.5 W. An electric kettle typically has a power of about 1 kW.

Coal- and gas-fired power stations generally produce *output* powers of many MW. One of the largest in the UK is Drax in Yorkshire, which has an output power of about 3,900 MW, supplying, on average, around 7,400,000 homes. Nuclear power stations have similar output powers, for example the Heysham 2 nuclear power plant in Lancashire produces about 1,200 MW. Power stations using renewable sources, such as hydropower, solar or biomass, generally have lower outputs; for example the small hydro power station at Kielder Water in Northumberland produces about 12 MW.

Pressure

Description

Pressure is a bulk property of fluids (liquids and gases). A fluid exerts a force normal to any surface with which it is in contact. The magnitude of the force on a surface depends on the area of the surface and not on its orientation; at any given position, the magnitude of the force per unit area is constant. Pressure has no defined direction; it is a scalar quantity.

Pressure is usually represented by the symbol p.

For a plane surface of area A, pressure is defined as

$$p = F / A$$

where F is the magnitude of the force the fluid exerts on the surface.

Discussion

For a body of liquid in which gravity and temperature variations can be ignored, the pressure is nearly the same in all parts of the liquid. This allows a modest force applied over a small area to the liquid to be translated into a much larger force acting over a larger area, which forms the basis for hydraulic systems, for example in the brakes of motor vehicles.

In a gas, the microscopic origin of pressure can be understood in terms of the motion of its molecules. The molecules of the gas move freely, colliding with each other and the walls of the container. When a molecule collides with a wall and bounces off at the same speed, there is a momentum transfer to the wall. To determine the total force on the wall due to the gas, the effect of all the molecules of the gas colliding with the wall is added up. The equivalent pressure depends on the mass of each molecule, m, the number of them per unit volume, n, and the average squared speed of the molecules, $\overline{v^2}$, via the formula $p=1/3nm\overline{v^2}$

Note that it is incorrect to use the concept of pressure in describing the forces between two solids; pressure should be strictly reserved for fluids and fluids in contact with solids. When dealing with solids, stress is the relevant quantity.

SI unit(s)

pascal, Pa

Expressed in SI base units

$kg\ m^{-1}\ s^{-2}$

Other commonly used unit/s

$N\ m^{-2}$, ($1\ N\ m^{-2} = 1$ Pa), bar (1 bar = 10^5 Pa), mmHg (1 mm Hg = 133 Pa), atm (1 atm = 1.013×10^5 Pa), torr (1 torr = 133 Pa), psi (1 psi = 6.9×10^{3}Pa)

Mathematical expressions

- $p = F / A$

where F is the magnitude of the force a fluid exerts on an area A

For an ideal gas

- $pV = nRT$

where V is the volume, n is the number of moles of gas molecules, R is the molar gas constant and T is the temperature measured in kelvin

and

- $pV = NkT$

where N is the number of molecules (number per unit volume) and k is the Boltzmann constant

and

- $p = \frac{1}{3} nm\overline{v^2}$

where n is the number of molecules per unit volume, m is the average mass of each molecule and $\overline{v^2}$ is the mean square speed of the molecules.

- In a column of fluid, the change of pressure Δp due to an increase of column height Δh is

$\Delta p = \rho g \Delta h$

where ρ is the density of the fluid and g is the gravitational field.

Related entries

- Stress

In context

Close to sea level, the pressure exerted by the Earth's atmosphere is about 1.01×10^5 Pa.

The world record for free deep-sea diving (without breathing apparatus) is currently (February 2017) held by Herbert Nitsch, who in 2012 reached a depth of 253.2 m, where the pressure is 2.6×10^6 Pa (26 atm).

In the Sun's interior, where the number density is about 2×10^{57} m^{-3} and the temperature about 10^7 K, the pressure is about 2×10^{14} Pa.

In interstellar space, where number densities range from about 10^5 to about 10^{10} m^{-3}, and temperatures range from about 3 K to 10^6 K, the pressure varies by only about two orders of magnitude and most regions have pressures of the order 10^{-13} Pa.

Reference

- www.deeperblue.com/herbert-nitsch-the-deepest-man-on-earth/

Refractive index

Description

Refractive index is a material property that describes how the material affects the speed of light travelling through it.

Refractive index is usually represented by the symbol n, or sometimes μ.

The refractive index, n, of a material is defined as

$n = c / v$

where c is the speed of light in a vacuum and v the speed of light in the material.

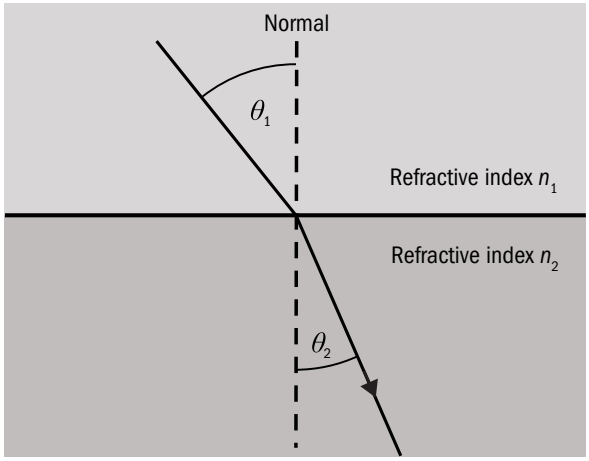


Figure 1
Light passes from a material of refractive index n_1 at incidence angle θ_1 into a material of refractive index n_2 at refraction angle θ_2.

Discussion

Refractive index determines how much a ray of light changes direction when it travels from one medium into another. This property allows the construction of lenses that can, for example, focus the light to form real images, as in a cinema projector.

SI unit(s)

none

Expressed in SI base units

n is dimensionless

Mathematical expressions

- $n = c / v$

where c is the speed of light in a vacuum and v the speed of light in the material.

- Snell's law states that, at the boundary between two materials of refractive indexes n_1 and n_2

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

where θ_1 and θ_2 are the incident and refracted angles to the normal (see **figure 1**).

Related entries

- Speed

In context

In general, n depends on the frequency of the light. In the visible range, a typical glass might have a 2% difference between the refractive index of glass for red light with $n = 1.513$, and for violet light, with $n = 1.532$.

Since it is always the case that $v \leq c$, it is always the case that $|n| \geq 1$. Although $n = 1$ only applies in a vacuum, $n_{air} = 1.0003$ at sea-level atmospheric pressure, so n_{air} is generally taken to be 1. In some special materials, n may be negative.

When spectacles were first invented (in the 13th century) they were lenses made from glass with $n \sim 1.6$. In the 20th century, polymer lenses were introduced that had $n \sim 1.3$. These lenses needed to be very highly curved and much thicker than glass ones to achieve the necessary deviation of the light rays. Advances in technology have led to polymers with values of n up to 1.757 so that much thinner lenses can now be used.

Reference

- www.google.com/patents/US20040158021

Resistance, electrical

Description

The electrical resistance of a component in an electric circuit is a property that describes how the electric current in the component is related to the electrical potential difference (voltage) across it. The greater the resistance, the smaller the current for a given potential difference, and the greater the potential difference, for a given current.

Electrical resistance is usually represented by the symbol *R*.

Electrical resistance is defined, for some component, by the equation

$R = V / I$

where *V* is the electrical potential difference across the component and *I* the corresponding electric current.

Discussion

Resistance and Ohm's law

For a component that obeys Ohm's law, the electric current, *I*, in the component is directly proportional to the potential difference, *V*, across it, provided the component's temperature and other physical conditions remain constant. A graph of *V* against *I*, or *I* against *V*, is then a straight line passing through the origin. The component has this characteristic behaviour and characteristic graph because its resistance does not change as the current changes.

Ohm's law is not a law of physics. It is an observation and formalisation of the behaviour of some materials. As such, it is a useful way of distinguishing 'ohmic conductors' (those that obey Ohm's law) from 'non-ohmic' ones.

If a component does not obey Ohm's law, the graph is not a straight line. Its resistance changes as the current changes.

In both cases (ohmic and non-ohmic behaviour), the resistance of the component at any given value of current or potential difference can be calculated from the definition of resistance:

$R = V / I$

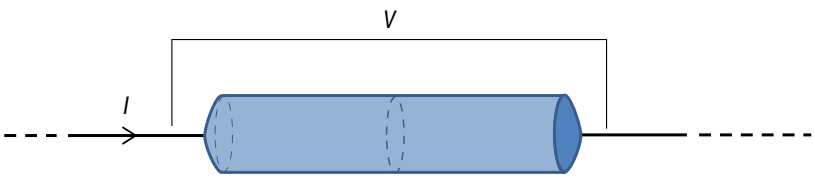


Figure 1
A current *I* flows in a sample of material in an electrical circuit. The potential difference across the sample is *V*.

Resistance and temperature
Resistance is affected by temperature, see electrical resistivity.

The resistance of manufactured resistors is usually quoted for a specific temperature. A maximum operating power is often also specified, above which the resulting temperature rise significantly alters the component's resistance.

Resistance and conductance
Electrical resistance is the reciprocal of electrical conductance.

SI unit(s)
ohm, Ω

Expressed in SI base units
$kg\ m^2\ s^{-3}\ A^{-2}$

Mathematical expressions
- $R = V / I$

where V is the electrical potential difference across a component with resistance R and I the corresponding current.

- $P = VI = I^2R = V^2 / R$

where P is the power dissipated in a component with resistance R, V is the electrical potential difference across it and I is the current.

- $R = \rho L / A$

where R is the resistance of a sample of material with length L, uniform cross-sectional area A and resistivity ρ.

Related entries
- Conductance, electrical
- Conductivity, electrical
- Current, electric
- Emf
- Potential difference, electrical
- Power
- Resistivity, electrical
- Voltage

In context

Circuit components have a huge range of resistances. Suppliers of components for electronic circuits typically sell resistors ranging from a few ohms to several MΩ. The heating element of an electric kettle, designed to have a power of about 1 kW when connected to a 230 V mains supply, has a resistance of about 50 Ω. A torch bulb designed for use with a 3 V battery has a resistance of about 10 Ω when in use.

The connecting wires in a circuit are usually treated as having negligible resistance as their resistance is very small compared to that of other components in the circuit. For example, a 0.1 m length of copper wire of diameter 0.5 mm has a resistance of about 0.01 Ω. Insulators, such as the coverings of electrical leads, are usually treated as having infinite resistance as their resistances are very much larger than those of other items in the circuit. For electrical safety, the resistance between a live circuit (designed to operate from a 230 V supply in the UK) and the Earth near the location of the device should be at least 25 MΩ.

Resistivity, electrical

Description

The electrical resistivity of a material is an intrinsic, bulk property that determines the electrical resistance of a sample of that material given the sample's physical dimensions.

Resistivity is usually represented by the symbol ρ.

Resistivity is defined by the equation

$$\rho = R\,A / L$$

where R is the resistance of a piece of material of length l and cross-sectional area A, as shown in **figure 1**.

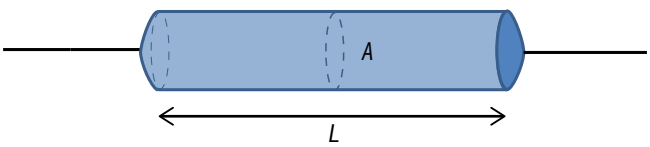


Figure 1
A sample of material of length L and cross-sectional area A.

Discussion

The resistance of a sample, such as a wire, depends on its physical dimensions and the resistivity of the material from which it is made. The resistivity depends in detail on the nature and crystal structure of the material and, in general, depends strongly on temperature; the resistivity of a metal, such as copper or silver, increases roughly linearly with temperature around room temperature. The resistivity at lower temperatures is strongly dependent on the purity of the metal. Resistors made from platinum and other easily purified metals are often used as thermometers. The resistivity of most non-metals decreases as temperature rises.

Resistivity has an enormous range of values. It is common to refer to materials with low values of ρ as conductors and those with high values as insulators. Semiconductor materials are insulators in their pure state but their electrical resistivity may be greatly reduced by the addition of a relatively small amount of impurity. Different amounts of different impurities can be used to produce semiconductors with particular electrical properties (for example, resistivity that changes in response to external conditions such as temperature or illumination); this is one of the main reasons why semiconductors are so important in the electronics industry.

Resistivity is the reciprocal of electrical conductivity.

SI unit(s)

ohm-metre, Ω m

Expressed in SI base units

$m^3\,kg\,s^{-3}\,A^{-2}$

Mathematical expressions

- $\rho = R\,A / L$

where R is the resistance of a piece of material of length l and cross-sectional area A.

- $\rho = 1 / \sigma$

where σ is the electrical conductivity of the material.

Related entries

- Conductivity, electrical
- Resistance, electrical

In context

Electrical resistivity has a huge range of values for everyday materials. The resistivity at room temperature for a good conductor such as silver is around 22 orders of magnitude lower than that of a good insulator such as rubber. The resistivity of silver at room temperature is about 1.6×10^{-8} Ω m, whereas that of rubber is of the order 10^{13}–10^{15} Ω m.

Specific heat capacity

Description

Specific heat capacity is a material property that relates changes in a material's temperature to the energy transferred to or from the material by heating (either heating the material or by allowing it to heat its surroundings).

When raising the temperature of a material by transferring energy into the material by heating, the specific heat capacity of the material is defined as the energy transferred per unit mass per unit temperature rise.

Specific heat capacity is usually represented by the symbol c.

If the temperature of a mass m of the material changes by ΔT, the associated energy Q transferred into the material by heating is

$$Q = m\,c\,\Delta T$$

Discussion

In general, the specific heat capacity is a measure of how much energy it takes to change the temperature of a system. But in the definition, it is important to realise that the energy input must be by heating. If work is done on the system, in general, its temperature will increase but it is not correct to try to calculate the temperature rise using the heat capacity and the amount of work done on it.

Another factor that can be important is the constraint under which the system is held. The specific heat capacity of a system held at constant volume is different from that of one held at constant pressure as the latter does work on its surroundings as it expands. Such differences can usually be ignored for solids but they are very important when dealing with gases.

SI unit(s)

$\mathrm{J\,kg^{-1}\,K^{-1}}$

Expressed in SI base units

$\mathrm{m^2\,s^{-2}\,K^{-1}}$

Other commonly used unit/s

°C, °F

Mathematical expressions

- If the temperature of a mass m of the material changes by ΔT, the associated energy transferred into the material by heating is

$$Q = m\,c\,\Delta T$$

Related entries

- Energy of a system
- Internal energy

In context

The specific heat capacity of water at room temperature is 4181 J kg^{-1} K^{-1}, that of copper is 390 J kg^{-1} K^{-1} and that of a typical oil is 2000 J kg^{-1} K^{-1}. Ceramic materials such as concrete or brick have specific heat capacities around 850 J kg^{-1} K^{-1}.

The relatively high specific heat capacity of water means that it is very useful in central heating systems, because it is able to transfer a great deal of energy by heating while its temperature changes by a relatively small amount. In storage heaters, where the relevant substance remains in the heater, solids such as clay bricks or other ceramic materials are preferred as they do not leak, or corrode their containers, although their lower specific heat capacity means that they have to be raised to a very high temperature to supply useful heating over several hours.

Strain

Description

A stretched or compressed material will experience strain. If the material is of uniform cross-sectional area, strain describes the size of a deformation produced by the application of a force or stress, expressed as a fraction of the relevant dimension of the undeformed material.

Tensile strain refers to the strain in a material stressed so as to stretch the material without bending it. Similarly, compressive strain occurs in a situation where the material is stressed so as to compress without bending. See **figure 1**.

Tensile strain and compressive strain are usually represented by the symbol ε (the Greek letter epsilon). Tensile strain and compressive strain are defined, respectively, as the ratio of the extension, or compression, to the original undeformed length of a material:

$$\varepsilon = \Delta x / x$$

where x is the undeformed length of the material and Δx the increase in length when the sample is subjected to a force. If there is a compression Δx will be negative. (NB other symbols are also commonly used e.g. x for extension and l for original length.)

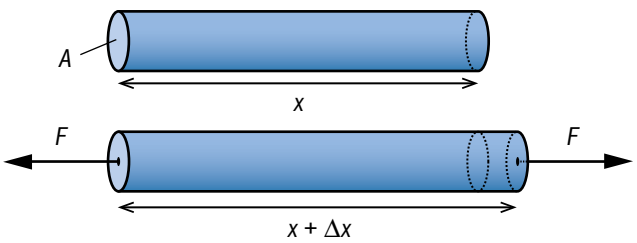


Figure 1
An object lengthening under a pair of forces.

Discussion

Strain can be expressed as a decimal fraction or as a percentage e.g. 0.001 or 0.1%. In calculations using the Young modulus to relate stress to strain, the strain should always be expressed as a fraction not a percentage.

Describing strain

In a simple model of material deformation, the deformation is in the same direction as the force that produces it. But in practice this is an over-simplification – for example, stretching a wire also reduces its diameter.

If the opposing forces are not aligned, then they produce a torque, rotating the sample rather than stretching or compressing it. If there is an opposing torque of the same magnitude, then the sample will be subjected to a shear stress as in **figure 2**. As the deformation is now at right angles to the original length, the shear strain is the tangent of the angle shown in **figure 2** – which in practice is a very small angle.

A full description of the way that an object responds to stress is complicated, even when the material of the sample is uniform. The size and direction of any forces inside an object may vary with position throughout the object; the resulting deformations also vary and are not solely in the same direction as these forces. Mathematical techniques, such as calculus and tensors, as well as computers, are usually required to represent and analyse the situation.

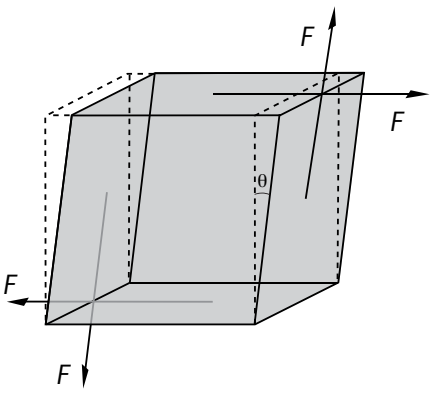


Figure 2
An object subject to two opposing torques being deformed. The strain in this type of deformation (shear) is given by tan θ.

SI unit(s)
None

Expressed in SI base units
ε is dimensionless

Mathematical expressions
- $\varepsilon = \Delta x / x$

where x is the undeformed length of a material and Δx the increase in length when the sample is subjected to a force. If there is a compression Δx will be negative. (NB other symbols are also commonly used e.g. x for extension and l for original length.)

- $\varepsilon = \sigma / E$

where E is the Young modulus of a material, σ the stress and ε the corresponding strain.

Related entries
- Stress
- Young modulus

In context
Many materials break when relatively small strains are applied, and often the associated 'extensions' are barely perceptible to the naked eye. For example, a steel wire can only undergo a strain of about 2×10^{-3} before breaking, so a steel wire with an initial length of 1 m only extends by about 2 mm. Measurements of strain in laboratory samples therefore usually involve carefully designed experimental arrangements, for example, using long lengths of wire so that the actual extension is as large as possible, and Vernier instruments that enable small extensions to be measured.

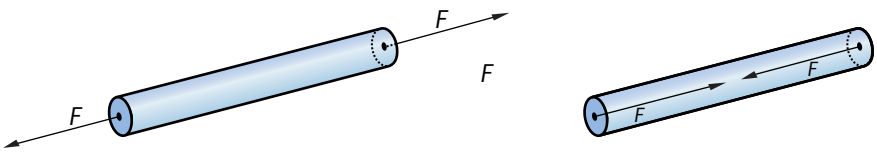
However, some polymer materials, such as rubber, can undergo extremely large strains. This property is exploited in applications where large strains are desirable, for example in ropes used by rock-climbers; a falling climber can be brought to rest over a relatively long time as a 'dynamic rope' made from polymer materials extends by many centimetres, rather than the climber being halted abruptly by a steel cable.

Stress

Description

A stretched or compressed material will experience stress. For simplicity, it is best to consider static situations. In these situations, if the material is of uniform cross-sectional area, stress is a measure of the force that the material is experiencing per unit cross-sectional area.

In a static situation, tensile stress refers to the stress in a material when equal forces are applied to each end of the material so as to stretch the sample without bending it. Similarly, compressive stress refers to a situation where equal forces are applied to each end so as to compress without bending. See **figure 1**. Tensile and compressive stresses are uniform across the material.



(*a*) Bar in tension (*b*) Bar in compression

Figure 1
A bar is in tension (a), and in compression (b). In each case, *F* is the magnitude of the force acting upon each end.

Tensile stress and compressive stress are usually represented by the symbol σ (the Greek letter sigma). Tensile stress and compressive stress are defined, respectively, as tensile or compressive force per unit cross-sectional area.

If a force of magnitude *F* is applied at right-angles to an area *A*, then the tensile or compressive stress is

$$\sigma = F / A$$

Discussion

Stress and pressure

You may sometimes find that the term pressure is mistakenly used in place of stress. This often happens when one solid surface experiences a force by being in contact with another solid surface. A common example is the analysis of the relative sizes of the dents made in a wooden floor by a person in stiletto heels and by an elephant. This analysis often refers, erroneously, to the relative 'pressures' under their feet. This cannot be the case because pressure is a feature of liquids and gases and it acts in all directions. Therefore, when one solid surface is in contact with another one, the analysis will not involve pressure. The analysis ought to be:

The elephant is heavier than the person. However, the elephant leaves no mark on the floor but the person does. The heavier elephant causes less damage because it produces less stress in the top layer of the floor – where its feet make contact. The stress is less because the contact force it exerts is spread over a larger area:

$$F_1 / A_1 = \sigma_1 > \sigma_2 = F_2 / A_2$$

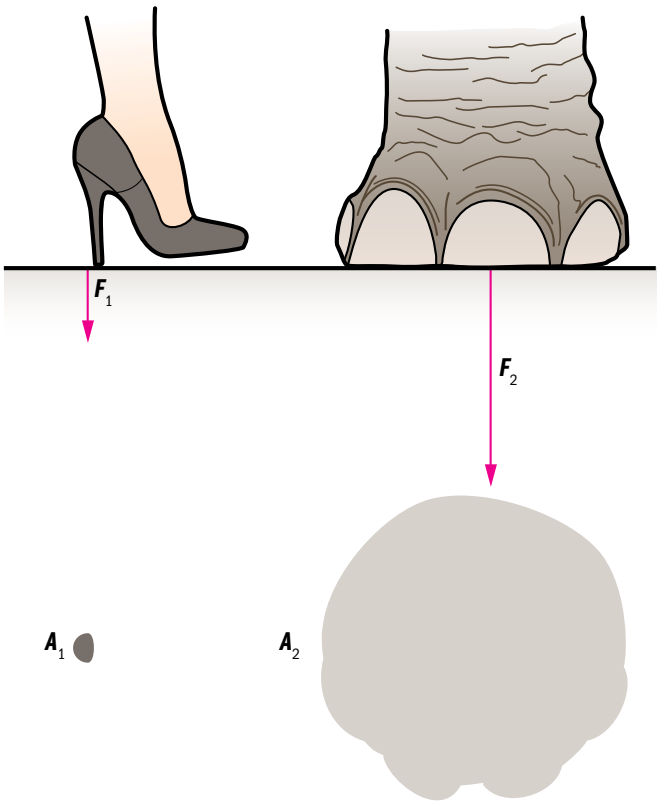


Figure 2
A person in stilettos exerts a relatively small force, $\boldsymbol{F}_1$, over a very small area, A_1. An elephant exerts a large force, $\boldsymbol{F}_2$, over a much larger area, A_2. The resulting stress under each foot is indicated by the shading of the contact area.

A less-simple picture of stress
The simple picture of tensile or compressive stress shown in **figure 1**, in which two equal opposing forces act uniformly over an area and produce some deformation along their line of action, is an over-simplification. Even if the forces are uniformly applied and are exactly aligned, there is some deformation transverse to their line of action; for example, stretching a wire reduces its diameter as well as increasing its length. Also, forces are rarely applied uniformly over the cross-section of a sample, so stress varies with position.

If opposing forces upon a material sample are not aligned, then they produce a torque, rotating the sample rather than stretching or compressing it. If there is an opposing torque of the same magnitude, then the sample will be subjected to a shear stress as in **figure 3**. Shear stress is defined as F/A, with F and A as shown in **figure 3**.

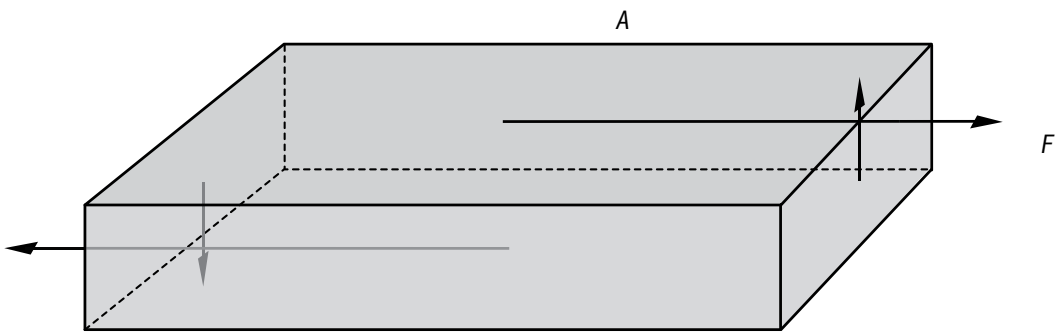


Figure 3
An object is subjected to a shear stress. Pairs of equal and opposite forces (black arrows) act upon opposite faces.

A sample may also be subject to torsion (twisting), which happens when it is subjected to opposing torques that do not act in the same plane.

A full description of the way that an object responds to stress is therefore complicated, even when the object is a uniform sample of a material. The size and direction of any forces inside an object may vary with position throughout the object; the resulting deformations also vary and are not solely in the same direction as these forces. Advanced mathematical techniques are required to represent and analyse the situation.

SI unit(s)

pascal, Pa

Expressed in SI base units

$m^{-1}\,kg\,s^{-2}$

Other commonly used unit/s

$N\,m^{-2}$; pounds per square inch, psi

Mathematical expressions

- $\sigma = F / A$

gives the stress in a material in which a force of magnitude F acts upon an area of size A.

- $\sigma = \varepsilon E$

where E is the Young modulus of a material, σ the stress and ε the corresponding strain.

Related entries

- Force
- Strain
- Young modulus

In context

Both the tensile and compressive strength may need to be considered when selecting materials for use in a particular application. For example, a civil engineer designing a bridge needs to know which parts will be subject to tensile stress and which to compressive stress and to select suitable materials. In general metals are stronger in tension than in compression, and the reverse is true for materials such as concrete and brick. **Table 1** lists some typical values of ultimate tensile and compressive stress. These are the values at which the materials will fail mechanically.

Material	Ultimate tensile stress/MPa	Ultimate compressive stress/MPa
Steel	400–550	170–310
Copper	220–430	approx. 220
Concrete	2–4	20–60
Silicone rubber	2.4–5.5	10–30
Bone	100–120	approx. 170

Wavelength

Description

Wavelength is the distance at a given instant in time between successive identical points on a wave, for example the distance between two successive maxima. A wave is a pattern that is said to exist where a physical quantity varies both periodically at each point in space, and repetitively in one or more spatial directions, when considered at a fixed instant in time.

A travelling wave is one that moves as a whole with a constant speed.

Wavelength is usually represented by the symbol λ.

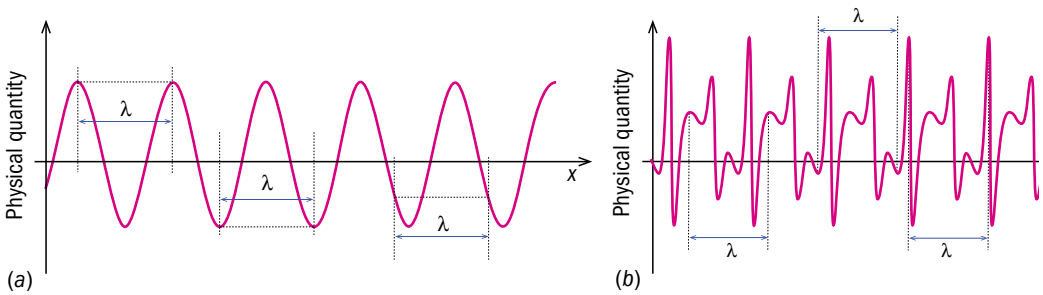


Figure 1
The wavelength of a wave is the distance between consecutive points on a wave which are spatially 'equivalent'. This is shown for two different waves, (a) and (b), each in one spatial co-ordinate, *x*.

Discussion

The wavelengths of waves that produce a visible distortion of matter (such as surface water waves and some seismic waves) can be measured directly. However, in general, other methods must be used to determine wavelength.

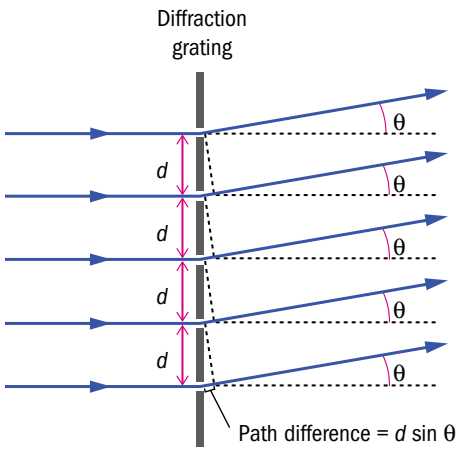
Many of the methods used to determine wavelength exploit the principle of superposition: when two or more waves of the same type meet at the same time and place, they superpose and the resulting disturbance is the algebraic sum of those of the individual waves. If the superposing waves are coherent, meaning that there is a constant phase relationship between them, then a stationary interference pattern is produced, from which the wavelength of the original waves can be determined.

For example, when light passes through a diffraction grating, superposition of waves from neighbouring slits ensures that strong beams emerge only in certain directions. See **figure 2**. The condition for constructive interference is that the path difference, $d \sin \theta$, between neighbouring slits must be a whole number of wavelengths; the diffraction grating equation, which describes this condition, is

$$n\lambda = d \sin \theta_n$$

where n is an integer and λ the wavelength of the light, d is the grating spacing, and θ_n the angle between the nth order intensity maximum and the straight-through direction (which has $n = 0$).

Figure 2
Light impinges on a grating with slit-spacing *d* and is diffracted through an angle θ.



If the grating spacing is known, measurements of θ_n can be used to calculate the value of the wavelength.

SI unit(s)

metre, m

Expressed in SI base units

m

Mathematical expressions

- $v = f\lambda$

where v is wave speed and f is frequency.

- When radiation of wavelength λ is incident normally on a diffraction grating with spacing d, waves travelling from the different grating slits will superpose so that interference maxima are observed at angles θ to the normal such that

$n\lambda = d \sin \theta$

where n is an integer.

- If electromagnetic radiation of wavelength λ is incident on a crystalline material at an angle θ to the material's lattice planes, then peaks of reflected intensity will be observed when

$n\lambda = 2d \sin \theta$

where n is an integer and d is the spacing between lattice planes. This relationship is known as Bragg's Law.

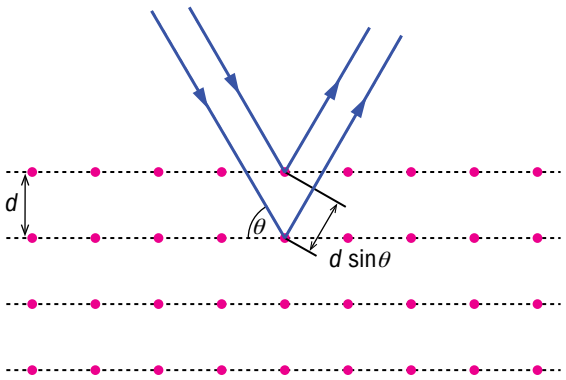


Figure 3
The two blue rays represent light incident at an angle θ to the surface of a crystal, with interatomic spacing *d*. The pink dots represent atoms in the crystal, and the dashed lines represent crystal lattice planes.

Related entries

- Frequency

In context

Sound waves, seismic waves and electromagnetic waves all have a large range of wavelengths.

For example, gamma rays are electromagnetic radiation with wavelengths (in air) shorter than about 10 pm (10^{-11} m), whereas radio waves, which are also electromagnetic in nature, have wavelengths ranging from about 1 cm up to many kilometres. Visible light wavelengths lie between around 400 nm and 700 nm.

In principle, there is no upper or lower limit to the wavelengths of electromagnetic waves. But for sound waves, which require a material medium for propagation, the wavelength must be at least of the order of twice the interatomic spacing, for a solid or liquid, and twice the mean free path for a gas.

Weight

Description

In physics, weight denotes a force. However, the term has come to be used to describe both the gravitational force pulling something down and the upward contact force at a surface. As weight is not a well defined quantity and should not be used in a scientific context, other physical quantities, such as contact force or gravitational force, should be used.

Related entries

- Force
- Mass

Work

Description

A force is said to do work when there is a displacement of the point of application of the force in the direction of the force. Some common examples of work include the mechanical work done in compressing a spring and the electrical work done in moving a charged particle.

Work is usually represented by the symbol W or ΔW.

When a force, $\boldsymbol{F}$, of magnitude F, produces a displacement $\Delta \boldsymbol{x}$ of magnitude Δx, the work done is

$$\Delta W = F \Delta x$$

provided that $\boldsymbol{F}$ is in the direction of the resulting displacement. In the more general case, as shown in **figure 1**, the work done is defined as $\Delta W = F \Delta x \cos \theta$

where θ is the angle between the force and the resulting displacement.

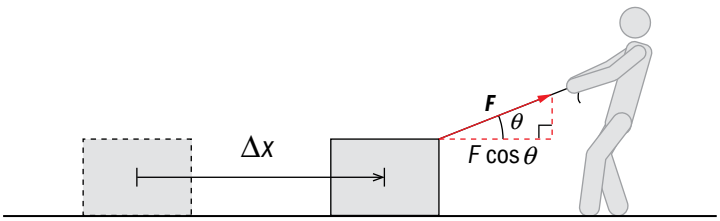


Figure 1
A force $\boldsymbol{F}$ is applied to an object, which is then displaced by Δx. The angle between the force and the displacement is θ.

Work is a scalar quantity. It has magnitude and sign but no direction.

Discussion

Heat, work and energy conservation

A system's internal energy can be changed as a result of heating or working – or a combination of both. Thermodynamics, the branch of physics concerned with heat, temperature, energy and work, has its origins in attempts to quantify heat and work in the context of machinery.

Work, force, displacement and direction

While work is a scalar quantity, the work done in a given situation depends on two vector quantities: force and displacement. Work was originally defined, in Sadi Carnot's 1824 book *Reflections on the Motive Power of Fire* in terms of lifting a load through a height. In such situations, both the force, $\boldsymbol{F}$, and displacement $\Delta \boldsymbol{x}$ are in the same direction (vertical) and the work ΔW is

$$\Delta W = F \Delta x$$

If there is an angle θ between the displacement and the line of action of the force, then

$$\Delta W = F \Delta x \cos \theta$$

Mathematically, the equation for work can be written as the dot product (scalar product) of the force and displacement vectors:

$$\Delta W = \boldsymbol{F} \cdot \Delta \boldsymbol{x}$$

If the force is at right-angles to the displacement, so that the angle θ is 90°, then cos θ is zero and no work is done by the force. For example, an object moving in a circle at constant speed requires the action of a force (centripetal force) directed to the centre of the circle to change its direction of motion. But the object's displacement during any (infinitesimally) small time interval is always at right-angles to the direction of the force at that time. The force does no work on the object. No energy is transferred to or from the object; its kinetic energy and hence its speed remain constant. Similarly, when a body is moved in a horizontal direction no work is done by the gravitational force upon it, as this acts in a vertical direction.

Electrical work
The definition of work does not specify the type of force – it applies equally to any force that produces a displacement. The term 'electrical work' is sometimes used in the context of electric circuits and fields, and refers to the work done on charged particles by electrostatic forces and fields, conceived as an emf. In an electric field $\boldsymbol{E}$, the electrostatic force $\boldsymbol{F}$ on a particle with charge q is

$$\boldsymbol{F} = q\boldsymbol{E}$$

so for motion through a distance Δx parallel to the field of magnitude E:

$$\Delta W = qE\,\Delta x$$

This equation can be written in terms of an electrostatic potential difference, ΔV, where

$$\Delta V = E\,\Delta x$$

hence the equation for electrical work becomes

$$\Delta W = q\Delta V$$

Note that this is just a way of writing the more general equation for work, which applies specifically to charged particles acted on by electrostatic forces; it is not a different definition of work.

Also note that if a charged particle is moving in a magnetic field, it experiences a force at right-angles to its direction of motion. Such a force therefore does no work.

SI unit
joule, J

Expressed in SI base units
kg m^2 s^{-2}

Mathematical expressions

- $\Delta W = mg\,\Delta x$

is the work done by the force due to the Earth's gravitational field, g, on an object of mass m as it falls through a vertical distance Δx near the surface of the Earth.

- $\Delta W = qE\,\Delta x$

is the work done by an electrostatic force, due to an electric field of magnitude E, upon a particle of charge q as it moves through a distance Δx in the direction of $\boldsymbol{E}$.

- $\Delta W = q\Delta V$

is the work done upon a particle with charge q as it moves through an electrostatic potential difference ΔV.

Related entries

- Energy of a system
- Heat
- Internal energy
- Power

In context

Tasks performed by people and machines in everyday situations may involve anything from a few joules of work to several thousands. For example, lifting an object of mass 100 g (e.g. a small apple) through 1 m involves doing about 1 J of work. Picking up a 10 kg bag of books and raising it through 1 m involves about 100 J. If a crane lifts a 1 tonne concrete block through 20 m (about the height of a five-storey building), the work done is about 200 kJ.

Young modulus

Description

The Young modulus of a material is an intrinsic, bulk property that describes how the material deforms when subjected to stress. It relates the size of the applied compressive or tensile stress to the corresponding strain. The larger the Young modulus, the less a material deforms to a given stress, i.e. the stiffer the material.

The Young modulus is usually represented by the symbol E (sometimes Y).

For a material of uniform cross-sectional area

$$E = \sigma / \varepsilon$$

where σ is the stress and ε the strain.

Discussion

Young modulus and stress-strain graphs

Stress is proportional to strain provided the strain is small; this is sometimes referred to as Hooke's law, although it is just a description of a linear dependence under particular circumstances, not strictly a physical law. The Young modulus of some material under a particular stress and strain is obtained by dividing the stress by the strain, whether or not the relationship between stress and strain is linear. Note that this is *not* necessarily the same as the gradient of the graph at that point, although it happens to coincide with the gradient if stress is proportional to strain.

The maximum stress (or strain) for which a linear relationship holds between them is called the limit of proportionality.

The elastic limit of a material is the maximum stress (or strain) for which there is no permanent deformation, so that when the applied stress is reduced to zero, a sample returns to its original size and shape. The elastic limit is usually slightly greater than the limit of proportionality.

Material properties

When some materials are subjected to a sufficiently large stress, they yield, undergoing increasing permanent deformation without any increase in applied stress (see **figure 1**).

A material that yields under tensile stress is described as ductile ('leadable': can be drawn into wires), and one that yields under compressive stress is described as malleable ('hammerable': can be beaten into thin sheets). Samples of many metals, for example copper, can be both ductile and malleable depending on how they have been treated.

A material's ultimate tensile stress (also called tensile strength) specifies the maximum tensile stress that can be applied a sample of the material without breaking it. Similarly, ultimate compressive stress is the maximum compressive stress that can be applied to a sample of a material without causing it to shatter or buckle.

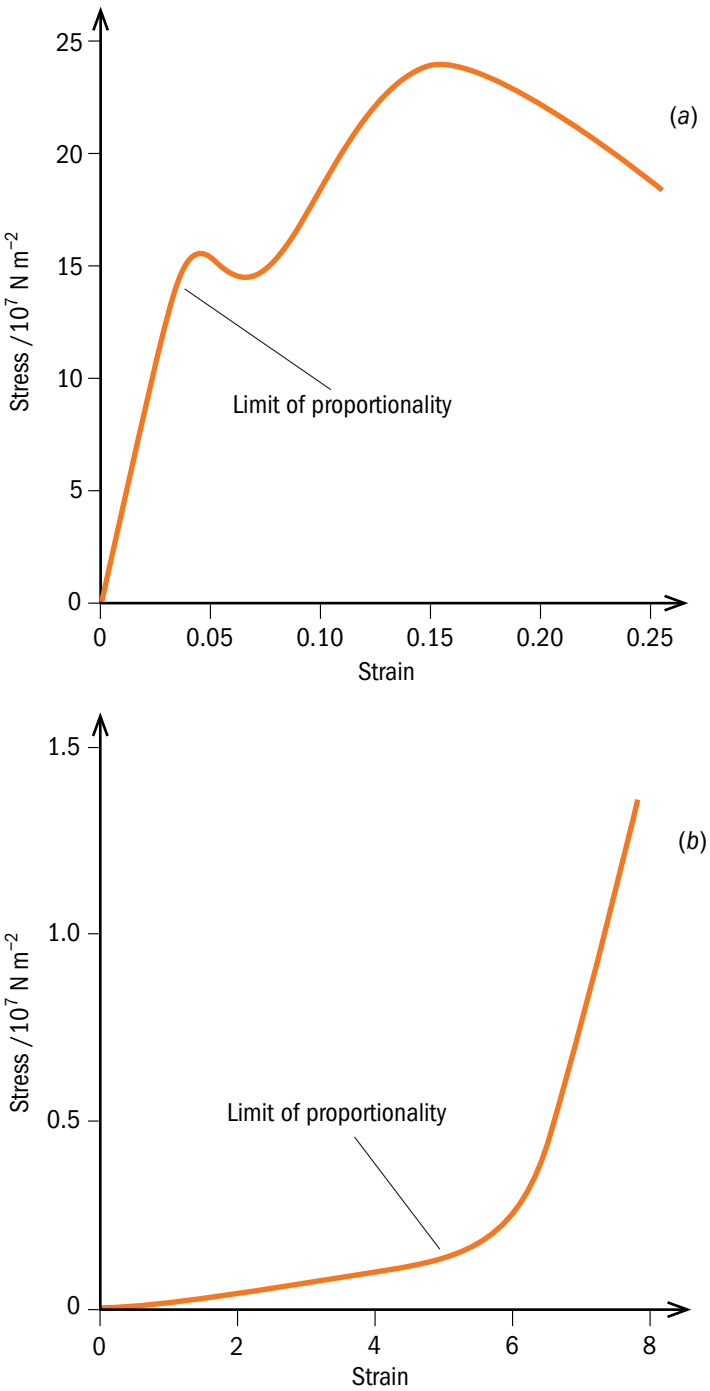


Figure 1
Typical stress-strain curves for low-carbon steel (a) and cross-linked natural rubber (b).

SI unit

pascal, Pa; N m^{-2}

Expressed in SI base units

m^{-1} kg s^{-2}

Other commonly used unit/s

pounds per square inch, psi

Mathematical expressions

- For any material under tensile or compressive stress σ and corresponding strain ε, the Young modulus is given by

$$E = \sigma / \varepsilon$$

Related entries

- Strain
- Stress

In context

The Young modulus is an important property when selecting a material for a particular purpose. For example, the materials used to replace bone in artificial hip and knee joints should ideally have a Young modulus that is close to that of real bone. If the replacement material has a much lower Young modulus (meaning that it is less stiff than bone) then deformation of the material will cause greater stresses within the remaining bone than would be natural, which may cause it to fracture. If the replacement material has a much higher Young modulus, the remaining natural bone will be subject to lower stresses than would be natural, which, for biological reasons, inhibits its ability to regrow.

Materials have been developed for replacement joints whose Young moduli are a close match to that of bone, but other properties make them undesirable. Ceramic materials such as hydroxyapatite are too brittle, and polymers such as high-density polyethylene deform over time. Currently, good compromise materials are metals such as titanium, although their Young moduli are higher than desirable.

Material	Young modulus *E*/GPa
Human bone	0.03–30
Titanium	110
Steel	200
Hydroxyapatite	80–100
High-density polyethylene	0.8

Notes

Notes

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