Physics toolkit

In the course books of SM358 *The Quantum World* you will meet terms which were defined or discussed in a recommended prerequisite physics course. This toolkit consists of a glossary that lists such terms and gives brief definitions. This should generally be enough to allow you to continue work on SM358; please note, however, that a glossary like this cannot be regarded as a substitute for studying the material in prerequisite courses.

When reading the definition given for a particular term, you may find other terms printed in *italics*. Such terms are themselves entries in this prerequisite glossary.

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absolute temperature scale The *SI* scale of temperature measured in *kelvin* (K). On this scale, the lowest conceivable temperature, *absolute zero*, is 0 K.

absolute zero of temperature The lowest conceivable temperature for any *system*. It is represented by the value 0 K on the *absolute temperature scale*, and corresponds to a temperature of −273.15 °C on the Celsius temperature scale. In classical physics, where temperature is a measure of molecular agitation, absolute zero corresponds to all particles being at rest.

acceleration The acceleration of a *particle* is the instantaneous rate of change of its *velocity*. In general, acceleration is represented by an acceleration *vector*. In terms of the velocity vector $\mathbf{v}$ and the *position vector* $\mathbf{r}$, the acceleration is

$$\mathbf{a} = \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2}.$$

For motion confined to one dimension (the x-axis) acceleration can be represented by a single *scalar*, the *component* $a_x = \mathrm{d}v_x/\mathrm{d}t = \mathrm{d}^2x/\mathrm{d}t^2$.

alpha decay A form of *radioactive decay* in which the *nucleus* of an *atom* ejects an energetic *alpha particle*. The *atomic number* Z of the original nucleus falls by two and the *mass number* falls by four.

alpha particle The *nucleus* of a normal *helium atom* contains two *protons* and two *neutrons*. A doubly-*ionized* helium atom is an alpha particle, although the term is generally used in the context of alpha particles emitted from certain unstable nuclei during *alpha decay*.

ampere The *SI* unit of *electric current*, represented by the symbol A. It is defined in such a way that, if a steady current of one ampere flows in each of two straight parallel infinitely long wires, of negligible cross section, set one metre apart in a vacuum, the *magnitude* of the *magnetic force* experienced by each wire is 2×10^{-7} N per metre of its length. The ampere is colloquially called the amp.

amplitude The maximum deviation of an *oscillation* or *wave* from equilibrium. For a sinusoidal oscillation described by the function $x(t) = A\cos(\omega t + \phi)$, the positive constant A is called the amplitude of the oscillation. For a sinusoidal *wave* described by the function $u(x,t) = A\cos(kx - \omega t + \phi)$, the positive constant A is called the amplitude of the wave.

angular frequency The rate of change of the *phase* of an *oscillation* or *wave*.

The angular frequency ω is given by

$$\omega = 2\pi f = \frac{2\pi}{T},$$

where f is the *frequency* and T is the *period* of the oscillation or wave. The *SI* unit of angular frequency is the inverse second, s^{-1}.

angular momentum A quantity that measures a body's tendency to continue in an existing state of *rotation motion*. For a *particle*, the angular momentum $\mathbf{L}$, about a point O, is defined by the vector product

$$\mathbf{L} = \mathbf{r} \times \mathbf{p},$$

where $\mathbf{r}$ is the *displacement* of the particle from the point O and $\mathbf{p}$ is the *momentum* of the particle. The *SI* unit of angular momentum is $\mathrm{kg\,m^2\,s^{-1}}$.

anode The *electrode* through which an *electric current* flows into a device; if the current is carried by *electrons*, it is the electrode through which electrons leave the device. In a battery, the anode is the negative contact. In a vacuum electronic device (such as a *cathode ray tube*), the anode is given a positive charge by external means; it therefore attracts negatively-charged *electrons* from the partially-evacuated chamber. Compare with *cathode*.

antineutrino The *antiparticle* of a *neutrino*.

antiparticle *Elementary particles* and their antiparticles have the same *mass*, but opposite signs for other attributes, such as *electric charge*. When an elementary particle collides with its own antiparticle, the two may annihilate one another completely, producing *electromagnetic radiation* (usually *gamma rays*).

atom The smallest electrically neutral sample of an *element* that retains the fundamental chemical and physical identity of that element.

atomic number The number of *protons* in the *nucleus* of an *atom*, and hence the number of *electrons* in the neutral atom. The atomic number is usually denoted by the symbol Z. A chemical *element* is identified by its atomic number Z, which determines its chemical properties. *Hydrogen*, *helium* and lithium atoms have $Z =$ 1, 2 and 3 respectively.

beta decay A form of *radioactive decay* in which the *atomic number* Z of the original *nucleus* changes by ± 1 and the *mass number* remains unchanged. There are three distinct types of beta decay. In negative beta decay (β^--decay) the nucleus spontaneously emits an *electron* and an *antineutrino*. In positive beta decay (β^+-decay), also called *positron decay*, the nucleus emits a *positron* and a *neutrino*. In *electron capture* the nucleus spontaneously captures an electron in low-lying atomic energy level and emits a neutrino; an *X-ray* is emitted as an electron in a higher atomic energy level falls into the vacancy left as a result of the capture.

black body An ideal absorber or *electromagnetic radiation* that would absorb all the radiation that was incident upon it. Such a body would also be an ideal emitter and would emit electromagnetic radiation with a *spectrum* that depended only on the temperature of the body.

Bohr model A semi-quantum model of *atoms* introduced by Niels Bohr in 1913. The model assumes (classically) that a central, positively-charged, *nucleus* is orbited by one or more *electrons* that are held in place by *electrostatic forces* given by *Coulomb's law*. It also assumes (non-classically) that the electrons are confined to

Bohr orbits in which the *magnitude* of the *angular momentum* is an integer multiple of $\hbar = h/2\pi$ (where h is *Planck's constant*). It further assumes that electrons do not emit *electromagnetic radiation* as long as they remain in one of the allowed orbits, but that emission (or absorption) of electromagnetic radiation does occur when an electron makes a transition which takes it from one orbit to another.

Bohr orbit Any of the paths that an *electron* is allowed to follow as it orbits a *nucleus*, according to the *Bohr model* of an *atom*. In the case of the *hydrogen atom*, each value of the Bohr quantum number n, where $n = 1, 2, 3, \ldots$, corresponds to a circular orbit in which the *magnitude* of the *angular momentum* is $L = n\hbar$. The radius of such an orbit is $r_n = n^2 a_0$ and the speed of the electron is $v_n = e^2/4\pi\varepsilon_0\hbar n$. Here, a_0 is the *Bohr radius* and $\hbar = h/2\pi$, where h is *Planck's constant*.

Bohr radius The radius of the lowest circular orbit of the *electron* in the *Bohr model* of the *hydrogen atom*, namely

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = 5.29 \times 10^{-11}\,\mathrm{m}$$

where m_e and e are the *mass* of the electron and the *magnitude* of the *charge* on the electron, respectively, and $\hbar = h/2\pi$ where h is *Planck's constant*.

Boltzmann's constant The constant, denoted by the symbol k, that relates temperature to *thermal energy*. In *SI* units, $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$.

cathode The *electrode* through which an *electric current* flows out of a device; if the current is carried by *electrons*, it is the electrode through which electrons enter the device. In a battery, the cathode is the positive contact. In a vacuum electronic device (such as a *cathode ray tube*), the cathode is given a negative charge by external means; it therefore repels negatively-charged *electrons* from the partially-evacuated chamber. Compare with *anode*.

cathode ray tube A partially evacuated tube in which *electrons* are liberated from a *cathode*, accelerated through a high *voltage* and allowed to strike a fluorescent screen.

centre of mass For an n-particle *system*, whose *particles* have *masses* $m_1, \ldots, m_n$ and *position vectors* $\mathbf{r}_1, \ldots, \mathbf{r}_n$ relative to an origin O, the centre of mass has position vector

$$\mathbf{r}_{\mathrm{cm}} = \frac{m_1\mathbf{r}_1 + \ldots + m_n\mathbf{r}_n}{m_1 + \ldots + m_n} = \frac{\sum_{i=1}^{n} m_i\mathbf{r}_i}{M}$$

where $M = \sum_{i=1}^{n} m_i$ is the total mass of the system. If the total *external force* acting on the system is $\mathbf{F}$, the *acceleration* of the centre of mass is $\mathbf{a} = \mathbf{F}/M$. So, if the system experiences no net external force (e.g. is isolated), its centre of mass moves with constant *velocity*. The centre of mass can therefore be regarded as the point at which *Newton's laws* for particle motion can most easily be applied to a system.

centre-of-mass frame A *frame of reference* used to describe the motion of a *system* of *particles* whose origin is at the *centre of mass* of the system.

charge See *electric charge*.

coherent waves Two *waves* are said to be coherent with one another if knowledge of the *phase* of one wave at a particular position and time enables the phase of the other wave to be predicted at some other position and time.

component The component of a *vector* along a given axis is the *magnitude* of the vector times the cosine of the angle between the direction of the vector and the direction the axis.

Compton effect The phenomenon in which a *photon* scatters from an *electron* and transfers some of its *energy* to the electron. The loss in photon energy is observed by an increase in *wavelength* of the scattered *electromagnetic radiation*, with larger scattering angles corresponding to larger wavelength shifts.

The Compton effect was historically important in establishing that photons behave like *particles*, exchanging energy and *momentum* when they collide with electrons. Relativistic energy and relativistic momentum are conserved during each collision.

conservation of angular momentum The principle that, if a *system* experiences no net external *torque* about a given point, then its total *angular momentum* about that point remains constant.

conservation of energy The principle that, if the total amount of *energy* in an *isolated system* remains constant, although energy may be converted from one form to another. A more informal statement of this principle is that energy may neither be created nor destroyed.

conservation of linear momentum See *conservation of momentum*.

conservation of momentum The principle that, if the total *external force* on a *system* is zero, the total *momentum* of the system is constant. Sometimes called the *conservation of linear momentum*.

conservative force A *force* with the characteristic that the *work* it does when its point of application moves from one point to another is independent of the route followed between those two points. This is equivalent to the requirement that the work done by the force when its point of application moves around a closed loop is equal to zero. In one dimension, a force is conservative if it depends on position only, so that the force has the form $F_x(x)$. In this case, we can define a *potential energy* function $V(x)$, which is related to the force $F_x(x)$ by

$$V(x) = -\int F_x(x)\,\mathrm{d}x + \text{constant}$$

or equivalently,

$$F_x(x) = -\frac{\mathrm{d}V}{\mathrm{d}x}.$$

Cooper pair A bound pair of *electrons* in quantum states with similar wave functions, but characterized by wave propagation in opposite directions and opposite *spin* states. Cooper pairs are formed by electrons in a *superconductor* at low temperatures.

coulomb The *SI* unit of *electric charge*, represented by the symbol C. A coulomb is the charge transferred by a current of one *ampere* flowing for one second. Thus, $1\,\mathrm{C} = 1\,\mathrm{A\,s}$.

Coulomb's law See *Coulomb's law of electrostatic force*.

Coulomb's law of electrostatic force A law that describes the *electrostatic force* on a stationary charged *particle* due to another stationary charged particle, located some distance away, in a vacuum. Coulomb's law can be represented mathematically by the equation

$$\mathbf{F}_{12} = \frac{q_1 q_2}{4\pi\epsilon_0 r_{12}^2}\,\widehat{\mathbf{r}}_{12}$$

where $\mathbf{F}_{12}$ is the *force* on particle 1, q_1 and q_2 are the *charges*, r_{12} is the distance between the particles, ϵ_0 is the *permittivity of free space* and $\widehat{\mathbf{r}}_{12}$ is a *unit vector* directed towards particle 1 from particle 2. Thus, $\widehat{\mathbf{r}}_{12} = \mathbf{r}_{12}/r_{12}$, where $\mathbf{r}_{12}$ is the *displacement* of the particle 1 relative to particle 2. In agreement with *Newton's third law*, this law implies that there is also a force $\mathbf{F}_{21} = -\mathbf{F}_{12}$ acting on particle 2. Coulomb's law is consistent with the rule that like charges repel and unlike charges attract.

current See *electric current.*

cycle Part of an *oscillation* or *wave* that occupies exactly one *period.*

decay See *nuclear decay.*

density The density at a given point is the *mass* per unit volume in the immediate vicinity of that point.

deuterium atom An *isotope* of *hydrogen* with *mass number* 2. A deuterium atom has a *nucleus* that consists of a bound state of a *proton* and a *neutron* (a *deuteron*) with a single *electron* outside the nucleus.

deuteron A bound state of a *proton* and a *neutron.* A deuteron is the *nucleus* of a *deuterium atom.*

diatomic A term used to describe a *molecule* consisting of two *atoms* bound together by *forces.*

diffraction The spreading of a *wave* that occurs when it passes through an aperture or around an obstacle. Diffraction is caused by the *interference* of waves taking different routes. Classical examples include the diffraction of water waves, sound waves and classical *light* waves. In quantum mechanics, the wave could be the wave function that describes an *electron* propagating according to Schrödinger's equation.

diffraction pattern The *intensity* pattern of a *wave* that has been diffracted by passing through an aperture or around an obstacle. The diffraction arises as a result of *interference*, so the diffraction pattern generally displays *interference maxima* and *interference minima.*

displacement The change in position in going from the one point to another. The *magnitude* of the displacement is equal to the distance between the two points. The direction of the displacement is the direction of the line from the first point to the second. If a *particle* moves in two- or three-dimensional space, its displacement is represented by a displacement *vector.*

electrical conductivity A measure of the ease with which a material conducts an *electric current.* If a slab of the material of length l and cross-sectional area A has a *potential difference* V maintained across its ends, the current flowing through it is

$$i = \frac{\sigma A V}{l},$$

where σ is the electrical conductivity.

electrical resistivity The reciprocal of electrical conductivity.

electric charge A fundamental property of *matter* that determines the electric and magnetic interactions of *particles*. They are two types of charge: positive and negative. *Protons* are positively charged (with charge e) and *electrons* are negatively charged (with charge $-e$). The *SI* unit of charge is in the *coulomb* (C).

electric current The electric current flowing along a wire is the rate at which *electric charge* flows through a fixed plane perpendicular to the axis of the wire. If the current is carried by *electrons* (which are negatively-charged), the current is in the opposite direction to the direction of flow of electrons.

electric field A *field* which determines the *electric force* on a charged *particle* placed at any given point. The electric field at a point P is a *vector* quantity equal to the electric force per unit *charge* experienced by a small test charge placed at P.

electric force The *force* experienced by a charged *particle* or charged body due to an *electric field*.

electrode A conducting plate at which charged *particles* (usually *electrons*) are collected or emitted in a cell, battery, vacuum electronic device, etc. The *electric current* enters the device via the *anode* and leaves it via the *cathode*.

electromagnetic radiation *Electromagnetic waves*, ranging from *gamma rays* at short *wavelengths* through *X-rays*, *ultraviolet radiation*, *visible light*, *infrared radiation* and *microwaves* to *radio waves* at long wavelengths.

electromagnetic wave A *transverse wave* in which an *electric field* and a *magnetic field* oscillate in phase with one another. The simplest type of electromagnetic wave is *monochromatic*; such a wave is sinusoidal, with a single *wavelength* λ, *frequency* f and *speed* $c = f\lambda$ which, in a vacuum, is equal to the speed of *light*. Another term for *electromagnetic radiation*.

electron A negatively-charged *particle* currently regarded as structureless, with about one two-thousandth the *mass* of a *hydrogen atom*. The carrier of *electric current* in metallic conductors.

electron capture see *beta decay*.

electronvolt The *energy* gained when an *electron* is accelerated through a *potential difference* of one *volt*. An electronvolt is represented by the symbol eV, and is equal to 1.60×10^{-19} J. According to the conventional rules for *SI* prefixes, $1\,\text{meV} = 10^{-3}\,\text{eV}$, $1\,\text{keV} = 10^{3}\,\text{eV}$, $1\,\text{MeV} = 10^{6}\,\text{eV}$ and $1\,\text{GeV} = 10^{9}\,\text{eV}$. The units meV, eV, MeV and GeV are convenient for discussing molecular vibrations, electronic transitions, nuclear physics and high-energy particle physics, respectively.

electrostatic force The *force* between two stationary charged *particles*. For particles separated by a vacuum, this force is described by *Coulomb's law*.

electrostatic potential The electrostatic potential at a given point, due to a given arrangement of stationary *electric charges* is the electrostatic *potential energy* per unit charge at the given point.

element Traditionally, a substance which cannot be divided by chemical means, heating or the passage of an *electric current*. More specifically, a sample of any given element consists of matter entirely composed of *atoms* with the same number of *protons* in their *nuclei*.

elementary particle A piece of *matter* that is of sub-nuclear size. Such particles include *protons* and *neutrons*, as well as *electrons* and *quarks*. They may or may not be truly fundamental constituents of matter.

energy The property of a *system* that measures its capacity for doing *work*. The *SI* unit of energy is the *joule*, represented by the symbol J, where $1\,\mathrm{J} = 1\,\mathrm{N\,m} = 1\,\mathrm{kg\,m^2\,s^{-2}}$.

event An ideal physical occurrence that occupies a point in space and occurs at an instant in time. Real processes, occurring in a small region of space, during a brief interval of time, can be modelled as events.

external force A *force* acting on a *system*, caused by agencies outside the system.

field A quantity which, at a given instant, has definite values throughout a continuous region of space. Examples include gravitational fields, *electric fields* and *magnetic fields*. Many fields determine the *forces* acting on *particles*, but this need not be so (e.g. a temperature field).

force Informally, this is the amount of 'push' or 'pull' exerted on a *particle* which, if unopposed, causes it to depart from the uniform motion predicted by *Newton's first law*. It is, therefore, that which causes (or tends to cause) *acceleration*. The relationship between the acceleration $\mathbf{a}$ of a particle of *mass* m and the total force F acting on the particle is

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

which is *Newton's second law*. The *SI* unit of force is the *newton*, represented by the symbol N, where $1\,\mathrm{N} = 1\,\mathrm{kg\,m\,s^{-2}}$.

force constant The positive constant k, that appears in *Hooke's law* $F_x = -kx$ for a *simple harmonic oscillator*, and in the expression for the *potential energy* function of a harmonic oscillator, $V(x) = \frac{1}{2}kx^2$.

frame of reference A set of coordinate axes and synchronized clocks, that makes it possible to specify uniquely the location in space and time of any given *event*.

free particle A *particle* that is subject to no *forces*, and for which the *potential energy* is a constant independent of position (usually set equal to zero).

frequency The number of *cycles* per unit time of an *oscillation* or *wave*. The frequency f is related to the *period* T by $f = 1/T$. The *SI* unit of frequency is the *hertz* ($1\,\mathrm{Hz} = 1\,\mathrm{s^{-1}}$).

fusion See *nuclear fusion*.

gamma ray *Electromagnetic radiation* with a *wavelength* shorter than $10^{-11}\,\mathrm{m}$, or equivalently a *frequency* greater than about $3 \times 10^{19}\,\mathrm{Hz}$. A common source of such radiation is *nuclei* which undergo *radioactive decay*.

gluon Any member of the family of eight *elementary particles* with *spin*-1 that are currently believed to be responsible for mediating the *strong interaction*.

harmonic motion See *simple harmonic motion*.

harmonic oscillator See *simple harmonic oscillator*.

helium atom An *atom* with *atomic number* 2 (and therefore with two protons in its *nucleus*). Helium atoms generally contain one or two *neutrons*, and two *electrons* outside the nucleus.

hertz The *SI* unit of *frequency*, represented by the symbol Hz. A frequency of $1\,\mathrm{Hz}$ is equivalent to one *cycle* per second, so $1\,\mathrm{Hz} = 1\,\mathrm{s^{-1}}$.

Hooke's law The *force* F_x on a *particle* in one dimension is said to obey Hooke's law if it is a *restoring force* (always acting towards the equilibrium position) and is proportional to the *displacement* of the particle from equilibrium. So we can write

$$F_x = -kx,$$

where x is the displacement from equilibrium and the proportionality constant k is called the *force constant*. In classical physics, such a force leads to *simple harmonic motion*.

hydrogen atom An *atom* with *atomic number* 1 (and therefore with one *proton* in its *nucleus*) and a single *electron* outside the nucleus. Hydrogen *molecules* consist of two hydrogen atoms bound together.

inertial frame of reference A *frame of reference* set up and moving in such a way that *Newton's first law* is true for all *free particles*. The laws of physics (including those of Newtonian mechanics and quantum mechanics) are normally expressed in terms of observations made in inertial frames of reference.

infrared radiation *Electromagnetic radiation* with a *wavelength* between about 7×10^{-7} m and 1×10^{-3} m, or equivalently a *frequency* between about 4×10^{14} Hz and 3×10^{11} Hz.

intensity The intensity of a classical *wave* is the amount of *energy* transported by the wave per unit time per unit area perpendicular to the direction of wave propagation. The intensity is proportional to the square of the *amplitude* of the wave. If a point source of waves radiates *energy* equally in all directions, the intensity of the waves is proportional to the inverse square of the distance from the source. The *SI* unit of intensity is the *watt* per square metre ($\mathrm{W\,m^{-2}}$).

interference The phenomenon arising from the superposition of two or more *coherent waves*, resulting in a pattern of *interference maxima* and *interference minima*.

interference maxima Features of *interference patterns* produced when two or more *coherent waves* interfere with one another. Interference maxima occur at points where the contributing waves reinforce one another, leading to a local maximum in the *intensity* of the wave (constructive interference).

interference minima Features of *interference patterns* produced when two or more *coherent waves* interfere with one another. Interference minima occur at points where the contributing waves cancel one another, leading to a local minimum in the *intensity* of the wave (destructive interference).

interference pattern A pattern of peaks and troughs in *intensity* that occurs when *coherent waves* from a spatially extended source (or more than one source) are allowed to interfere with one another.

ion An electrically-charged *atom* formed when a neutral atom loses one or more *electrons* (a positive ion) or gains one or more electrons (a negative ion).

ionic crystal A crystal composed mainly of negative and positive *ions* held together by the attractive *electrostatic force* between ions of opposite sign. A well known example is the crystal of common salt, NaCl.

ionization The process in which a neutral *atom* loses one or more *electrons* to produce a positive *ion* and one or more unbound electrons.

isolated system A *system* which is not acted upon by any *external forces* and which exchanges no *energy* or matter with the rest of the Universe.

isotope Different *nuclei* with the same number of *protons* and different numbers of *neutrons* (and therefore the same *atomic number* Z but different *mass numbers* A) are called isotopes of the *element* characterized by Z. The usual symbol for an isotope is $^{\mathrm{A}}\mathrm{Sy}$, where Sy is the chemical symbol for the element and A is the mass number. Since Sy determines Z, the fuller notation $^{\mathrm{A}}_{\mathrm{Z}}\mathrm{Sy}$ is strictly redundant, but may be helpful for elements for which Z is not widely remembered. The full specification $^{\mathrm{A}}_{\mathrm{Z}}\mathrm{Sy}_{\mathrm{N}}$ is sometimes given, where N is the number of neutrons in the nucleus. For example, the isotope of silicon with $A = 27$ and $Z = 14$ can be written as $^{27}_{14}\mathrm{Si}_{13}$ or $^{27}_{14}\mathrm{Si}$ or $^{27}\mathrm{Si}$. Less formally, this isotope is referred to as silicon-27.

joule The SI unit of *work* and *energy*, represented by the symbol J. One joule is the work done on a body by a *force* of *magnitude* one *newton* when the body moves one metre in the direction of the force. So $1\,\mathrm{J} = 1\,\mathrm{kg\,m^2\,s^{-2}} = 1\,\mathrm{N\,m}$.

kelvin The *SI* unit of temperature represented by the symbol K. A temperature difference of one kelvin (1 K) is equivalent to a temperature difference of one degree Celsius (1 °C), but the two scales have different origins. See *absolute temperature scale*.

kinetic energy *Energy* due to motion. The kinetic energy of a *particle* is given by $\frac{1}{2}mv^2$, where m is the particle's *mass* and v its *speed*.

laser A device which when stimulated with incident *electromagnetic radiation* produces an intense *coherent source* of *light* in the form of a narrow beam. The word 'laser' is an acronym for Light Amplification by the Stimulated Emission of Radiation.

lepton One of the major families of *elementary particles*, consisting of six particles and their *antiparticles*. Leptons are currently believed to be truly elementary particles. They participate in the *weak interaction*, but not in the *strong interaction*.

Leptons are classified into three generations: *electron* and electron neutrino; muon and muon neutrino; tauon and tauon neutrino and their corresponding antiparticles.

light This term normally means *visible light*. Some authors use the term to mean any type of *electromagnetic radiation*.

longitudinal wave A *wave* composed of *oscillations* that take place in a direction parallel to the direction of propagation of the wave. Contrast with *transverse wave*.

magnetic field A *field* which determines the *magnetic force* on a charged *particle* moving through a given point. The magnetic field at a point P is a *vector* quantity $\mathbf{B}$ such that the magnetic force on a particle of *charge* q, passing through P with *velocity* $\mathbf{v}$, is given by the vector product

$$\mathbf{F} = q\big(\mathbf{v} \times \mathbf{B}\big).$$

magnetic force A velocity-dependent *force* experienced by a *particle* with an *electric charge* moving in a magnetic field. The force is perpendicular to both the *velocity* of the particle and the magnetic field.

magnitude The magnitude of a *scalar* Q is a non-negative quantity $|Q|$ describing the size of Q, irrespective of its sign. The magnitude of a *vector* $\mathbf{a}$ is a non-negative quantity $|\mathbf{a}|$, describing the size of $\mathbf{a}$, irrespective of its direction. The magnitude of a vector $\mathbf{a}$ is usually written as a, omitting both the bold print and the modulus signs.

mass A quantity that represents the amount of *matter* in an object and is independent of the object's position in the Universe. It is proportional to the weight of the object (which is dependent on the object's position in the Universe), and occurs as a constant in *Newton's second law*. The *SI* unit of mass is the kilogram (kg).

mass number The total number of *protons* and *neutrons* in a *nucleus*, $A = Z + N$, where Z is the *atomic number* and N is the number of neutrons.

matter A general term for material substances, irrespective of their form.

meson A term used to describe any *elementary particle* that participates in the *strong interaction* and has zero or integer *spin*. Each meson is a combination of a *quark* and antiquark.

microwave *Electromagnetic radiation* with a *wavelength* between about 1×10^{-3} m and 1×10^{-1} m, or equivalently a *frequency* between about 3×10^{11} Hz and 3×10^{9} Hz.

molecule The smallest part of a given pure substance that retains the chemical identity of that substance. From a microscopic point of view, a molecule is a particular group of *atoms* bound together in a given way.

momentum A quantity useful in various situations as a measure of the tendency of a body to continue in its existing state of *translational motion*. In *Newtonian mechanics*, for a particle of *mass* m travelling with *velocity* $\mathbf{v}$, the momentum is

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

The *SI* unit of momentum is $\mathrm{kg\,m\,s^{-1}}$. Also called *linear momentum*. See also *angular momentum*.

monochromatic wave A *wave* of a single *frequency*.

neutrino A very weakly-interacting *lepton*. Neutrinos exist in three types: the electron neutrino, the muon neutrino and the tauon neutrino.

neutron An electrically neutral *elementary particle* which is a constituent of atomic *nuclei*, having a *mass* slightly greater than that of a *proton*. The neutron is stable within an atomic nucleus, but is unstable in a vacuum where it has a half-life of 914 s.

neutron star A highly compact stellar object composed of *matter* rich in *neutrons*. Neutron stars have a typical *density* of order $10^{15}\,\mathrm{kg\,m^{-3}}$ (about 10^{12} times the density of water). Measured neutron star masses are typically 1.4 times the mass of the Sun and their radii are thought to be about 8 to 10 km. Neutron stars are formed when massive stars collapse under their own weight.

newton The *SI* unit of *force*, represented by the symbol N. A total force of *magnitude* 1 N will cause a *particle* of *mass* 1 kg to accelerate at $1\,\mathrm{m\,s^{-2}}$ in the direction of the force. So, $1\,\mathrm{N} = 1\,\mathrm{kg\,m\,s^{-2}}$.

Newtonian mechanics A branch of physics which attempts to explain the motion of objects in terms of the *forces* acting on them. It is based on *Newton's laws* and incorporates other important principles, such as the law of *conservation of energy*.

Newton's first law A law stating that a body remains at rest or in a state of *uniform motion* unless it is acted on by an unbalanced *force*.

Newton's laws A set of three laws: *Newton's first law*, *Newton's second law* and *Newton's third law*.

Newton's second law A law stating that an unbalanced *force* acting on a body of finite fixed *mass* will cause that body to accelerate in the direction of the force and that the force $\mathbf{F}$ is equal to the product of the mass m and the *acceleration* $\mathbf{a}$, namely

$$\mathbf{F} = m\mathbf{a}.$$

For a system of *particles*, or an extended body, the law implies that the total *external force* is equal to the total mass times the acceleration of the *centre of mass*. Newton's second law may be expressed in terms of *momentum* $\mathbf{p}$ as follows. The total force acting on a body is equal to the rate of charge of the body's momentum:

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}.$$

For a system of particles or an extended body this implies that the total external force is equal to the rate of change of the total momentum.

Newton's third law A law stating that if body A exerts a *force* on body B, then body B exerts a force on body A, and that these two forces are equal in *magnitude* but act in opposite directions. The law implies that

$$\mathbf{F}_{AB} = -\mathbf{F}_{BA}$$

where $\mathbf{F}_{AB}$ is the force on A due to B, and $\mathbf{F}_{BA}$ is the force on B due to A.

node A fixed point at which there is permanently no disturbance in a *standing wave* (although end-points of the disturbance are not always counted as nodes).

nuclear decay A general process whereby an (unstable) *elementary particle* can spontaneously change into two or more other elementary particles.

nuclear fusion A process in which two nuclei 'fuse' together to form a heavier *nucleus*. If the nucleus produced has *mass number* $A \leq 56$ (e.g. ^{56}Fe) or thereabouts, the process is likely to release *energy*. Fusion is crucial in stars for both energy release and for the production of the lighter *elements*, from *helium* up to iron, from primordial *hydrogen*. Fusion reactions are also the basis for the energy released in hydrogen bombs.

nuclei The plural of *nucleus*.

nucleus The positively-charged, very compact, central part of an *atom*. The nucleus is some 10^4 times smaller in radius than an atom, and contains almost all the *mass*, the *protons* and *neutrons* of which it is composed being some 2000 times more massive than *electrons*. The number of positively-charged protons, the *atomic number*, Z, determines the number of electrons in a neutral atom and hence the chemical properties of the *element* that is characterized by Z.

nuclide A species of atomic *nucleus* that is characterized by the number of *protons* and *neutrons* that it contains. Sometimes called an *isotope*.

oscillation A to-and fro motion, also called a *vibration*.

particle (a) In the context of classical physics, a particle is an object that has no spatial extent and can therefore be thought of as existing at a single point in space. It has no size, shape or internal motion though it may have intrinsic properties such as *mass* and *charge*, as well as *position*, *velocity* and *acceleration*.
(b) In the context of particle physics, a particle (also known as an *elementary particle* in this context) is a piece of *matter* that is of sub-nuclear size. Such particles

include *protons*, *neutrons* and *electrons*, and may or may not be truly fundamental constituents of matter.

period The time T taken for one complete *cycle* of an *oscillation* or *wave*; the reciprocal of the *frequency*, $T = 1/f$.

permittivity of free space The fundamental constant, denoted by ε_0, that appears in *Coulomb's law* and plays a role in determining the *magnitude* of the *electrostatic force* between two charged *particles* separated by a vacuum. In *SI* units $\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$.

phase For a sinusoidal *oscillation* $x(t) = A\cos(\omega t + \phi)$, where A is positive, the phase is the argument of the cosine, i.e. $\omega t + \phi$.

For a sinusoidal *wave* $u(x,t) = A\cos(kx - \omega t + \phi)$, where A is positive, the phase is the argument of the cosine, i.e. $kx - \omega t + \phi$. Do not confuse the phase with the *phase constant*.

phase constant For a sinusoidal *oscillation* $x(t) = A\cos(\omega t + \phi)$, where A is positive, the phase constant is ϕ.

For a sinusoidal *wave* $u(x,t) = A\cos(kx - \omega t + \phi)$, where A is positive, the phase constant is ϕ. Do not confuse the phase constant with the *phase*.

photoelectric effect The effect whereby *electrons* are emitted from *matter* (usually from a metallic *electrode*) when *electromagnetic radiation* of sufficiently high *frequency* is incident on it.

photon A packet of *electromagnetic radiation*. For radiation in free space of *frequency* f and *wavelength* λ, each photon has *energy* $E = hf$ and *momentum* $p = h/\lambda$, where h is *Planck's constant*.

Planck-Einstein formula The formula

$$E = hf$$

that relates the *energy* E of a *photon* of *electromagnetic radiation* to the *frequency* f of that radiation, where h is *Planck's constant*.

Planck's constant The constant $h = 6.63 \times 10^{-34}\,\mathrm{J\,s}$ introduced by Max Planck to explain the *spectrum* of *electromagnetic radiation* emitted by *black bodies*. It also appears In Einstein's theory of the *photoelectric effect* and in the *Planck-Einstein formula*. In fact, it appears in practically every equation of quantum mechanics but never in those of classical physics.

plane polarized wave See *polarization*.

plane wave A *wave* of constant *frequency* for which points of constant *phase* lie in planes perpendicular to the direction of propagation of the wave.

polarization The property of a *transverse wave* that implies the existence of a restriction on the direction of the transverse vibrations. For example, for a plane polarized *wave*, the transverse vibrations occur in the same plane at all points on the path of the wave. In such cases the plane containing the direction of the oscillating variable and the direction of propagation of the wave is called the plane of polarization of the wave.

position vector A *vector* that defines the position of a *particle* in space.

positron A positively-charged *elementary particle*, the *antiparticle* of an *electron*.

positron decay See *beta decay*.

potential Often a term used for *electrostatic potential*.

potential difference A term used for the difference in *electrostatic potential* between two points.

potential energy The potential energy of a *particle* is its ability to do *work* due to its position. In one dimension, the potential energy function $V(x)$ is given in terms of the *conservative force* $F_x(x)$ acting on the particle by

$$V(x) = -\int F_x(x)\,\mathrm{d}x + \text{constant}$$

or equivalently,

$$F_x(x) = -\frac{\mathrm{d}V}{\mathrm{d}x}.$$

The point at which the potential energy function is zero can be chosen to be any convenient point.

proton A positively-charged *elementary particle* which is a constituent of atomic *nuclei*. The *mass* of a proton is slightly less that of a *neutron* and is almost 2000 times greater than that of an *electron*. The *charge* of a proton is positive and has the same *magnitude* as that of a negatively-charged electron.

quark Any of the charged *elementary particles* that are currently believed to be fundamental constituents of *protons* and *neutrons*. Quarks are not expected to be observed as isolated particles. Six kinds of quark are currently known. The six types are up (u), down (d), charm (c), strange (s), top (t) and bottom (b). The quarks all have *spin* $\frac{1}{2}$ and a *charge* that is a multiple of $\frac{1}{3}e$.

radiation A term used either as an abbreviation for *electromagnetic radiation* or when referring to *particles* emanating from a source (particularly those resulting from the *radioactive decay* of *nuclei*).

radiative transition A process in which a quantum system (such as an *atom*) undergoes a transition from one energy level to another by the emission or absorption of *electromagnetic radiation* (i.e. a *photon*).

radioactive decay See *nuclear decay*.

radioactivity The phenomenon whereby an unstable *nucleus* spontaneously *decays* and, as a consequence, emits *particles* or *electromagnetic radiation*.

radio wave *Electromagnetic radiation* with a *wavelength* greater than around 10^{-1} m, or equivalently a *frequency* less than about 3×10^9 Hz.

reduced mass A *mass* used to characterize a two-particle *system*. If the two *particles* have masses m_1 and m_2, the reduced mass of the two-particle system is

$$\mu = \frac{m_1 m_2}{m_1 + m_2}.$$

The relative motion of the two particles can be analysed by considering a single particle with a mass equal to the reduced mass, subject to a *potential energy* function.

restoring force A *force* that acts in a direction which tends to restore a *particle* towards its equilibrium position.

rotational motion Motion in which all the *particles* of a *system* move at the same angular rate in circular paths, and the centres of all the circles are on a single line called the axis of rotation. Contrast with *translational motion*.

Rutherford model of the atom The *atomic* model put forward by Ernest Rutherford, in which the *electrons* in the atom are assumed to orbit outside a tiny core or *nucleus* which contains all the positive *charge* and almost all the *mass* of the atom.

scalar A quantity that is completely specified by a single number, or by a number times an appropriate unit of measurement. Contrast with *vector*.

selection rules Rules that govern whether particular *radiative transitions* are allowed or (to a first approximation at least) forbidden.

semiconductor Material of *electrical conductivity* intermediate between a good conductor (such as a metal) and an insulator. Examples are silicon, germanium and gallium.

SI An internationally agreed system of units of measurement. The system employs seven base units, including the kilogram (abbreviated to kg), the metre (abbreviated to m), the second (abbreviated to s), the *ampere* (abbreviated to A) and the *kelvin* (abbreviated to K). It also includes a number of derived units obtained by combining base units in various ways. The system uses certain standard prefixes such as kilo $= 10^3$, mega $= 10^6$, giga $= 10^9$, tera $= 10^{12}$, milli $= 10^{-3}$, micro $= 10^{-6}$, nano $= 10^{-9}$ and pico $= 10^{-12}$. It also recognizes a number of standard symbols and abbreviations. SI itself is one of these symbols and stands for Système International.

simple harmonic motion A particular form of *oscillation* about a specified equilibrium position, characterized by the fact that the *acceleration* is always directed towards the equilibrium position and is proportional to the *displacement* from that point. In one dimension, any simple harmonic motion may be described by a differential equation of the form

$$\frac{d^2x}{dt^2} + \omega_0^2 x = 0$$

which has the general solution

$$x(t) = A\cos(\omega_0 t + \phi),$$

where A is the *amplitude* of the motion, ω_0 is the *angular frequency* and ϕ is the *phase constant* of the motion.

simple harmonic oscillator A *particle* or *system* that performs *simple harmonic motion*.

solid state A term used to describe the field of physics in which the properties of solids are studied. It is also used to describe any electronic circuit or device containing solid-based (usually silicon) *semiconductors*.

spectra The plural of *spectrum*.

spectral lines Narrow lines (corresponding to narrow ranges of *wavelength* or *frequency*) seen in the *spectra* of substances and characteristic of those substances. Each spectral line results from a *radiative transition* and has a *frequency* $f = \Delta E/h$, where ΔE is the difference in energy between two states in the *system* and h is *Planck's constant*.

spectrum Any particular pattern of *electromagnetic radiation*, often expressed as a function of *intensity* versus *wavelength*, *frequency* or a related quantity such as *photon energy*. Many spectra consist of *spectral lines*, observed when electromagnetic radiation is emitted or absorbed by a quantum *system*. The spectrum can provide an identifiable 'fingerprint' of the system.

speed The *magnitude* of *velocity*.

spin A type of angular momentum possessed as an intrinsic property of by certain *particles*. Spin in often characterized by the spin quantum number s, which is equal to $\frac{1}{2}$ for *electrons*, *protons*, *neutrons* and *quarks*.

standing wave A *wave* that oscillates without travelling through space. All points in the disturbance that constitutes the wave oscillate in phase, with the same *frequency* but with different *amplitudes*. The fixed points of zero disturbance are called the *nodes* of the wave (although end-points of the disturbance are not always counted as nodes).

A familiar example is a standing wave on a string stretched between fixed endpoints. In such a case the standing waves that may be excited are restricted by the requirement that the distance between the fixed ends of the string must be equal to a whole number of half *wavelengths*.

A standing wave may be regarded as the sum of two *travelling waves*, propagating in opposite directions.

strong force See *strong interaction*.

strong interaction A very short-range attractive *force* (also called the *strong force* or the *strong nuclear force*, that acts between *protons* and *neutrons*. It does not act on *electrons* and is almost independent of *electric charge*. The strong interaction is responsible for holding the *nucleus* together, despite the mutual electrostatic repulsion of its constituent protons.

strong nuclear force See *strong interaction*.

superconductivity The phenomenon exhibited by a number of materials, whereby, at a sufficiently low temperature, the *electrical resistivity* becomes zero (i.e. the *electrical conductivity* becomes infinitely large) and magnetic flux is expelled.

superconductor See *superconductivity*

superposition In the context of *waves*, the adding of two or more wave disturbances. More generally, given a set of n functions Ψ_1, Ψ_2, $\ldots \Psi_n$, any expression of the form

$$\Psi = c_1\Psi_1 + c_2\Psi_2 + \cdots c_n\Psi_n$$

where c_1, c_2, $\ldots c_n$ are constants, is said to be a linear superposition of Ψ_1, Ψ_2, $\ldots \Psi_n$.

system The portion of the Universe chosen as the subject of a scientific investigation. See also *isolated system*.

thermal energy A term for the sum of the *kinetic energies* and mutual *potential energy* of all basic *particles* (e.g. *molecules*) in a *system*. The typical thermal energy of a molecule in a gas that is in thermal equilibrium at temperature T is approximately equal to kT, where k is *Boltzmann's constant*.

torque The torque of a *force* $\mathbf{F}$ about a fixed point O measures the turning effect of the force about the fixed point. It is given by the vector product

$$\mathbf{\Gamma} = \mathbf{r} \times \mathbf{F},$$

where $\mathbf{r}$ is the *displacement* of the point of action of the force from the fixed point O.

total (mechanical) energy The total (mechanical) energy of a particle is the sum of its *kinetic energy* and its *potential energy*.

trajectory The trajectory of a *particle* is the particle's path as it moves through space.

translational motion Motion in which every *particle* of a *system* moves at the same rate in the same direction. Contrast with *rotational motion*.

transverse wave A *wave* composed of *oscillations* that take place in a direction perpendicular to the direction of propagation of the wave. Contrast with *longitudinal wave*.

travelling wave A *wave* that propagates from one place to another. One example of such a wave is represented by the function $u(x,t) = A\cos(kx - \omega t + \phi)$, where $A > 0$ is the *amplitude* of the wave, k is the *wave number*, ω is the *angular frequency* and ϕ is the *phase constant*. The quantity $kx - \omega t + \phi$ is the *phase* of the wave.

tunnelling The quantum-mechanical phenomenon whereby a *particle* confined in a finite region of space penetrates some distance into a classically-forbidden region (where the particle's *potential energy* is more than the *total energy*). If this classically-forbidden region is of finite width, it is possible for the particle to tunnel through the classically-forbidden region and be detected in some other classically-allowed region where its potential energy is again less than its total energy.

ultraviolet radiation *Electromagnetic radiation* with *wavelength* between about 1×10^{-8} m and 4×10^{-7} m, or equivalently with *frequency* between about 3×10^{16} Hz and 8×10^{14} Hz.

uniform motion A type of motion in which a *particle* travels with constant *velocity* in a straight line and does not accelerate.

unit vector A *vector* of unit *magnitude* in a given direction. A unit vector is dimensionless (it has no units).

vector A quantity that has a definite *magnitude* and a definite direction in space. Vectors can be specified by giving their *components* in a given coordinate system

velocity The velocity of a *particle* is the instantaneous rate of change of its *position*. In general, velocity is represented by a velocity *vector*. In terms of the *position vector* $\mathbf{r}$, the velocity is

$$\mathbf{v} = \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}.$$

For motion confined to one dimension (the x-axis), velocity can be represented by a single *scalar*, the *component* $v_x = \mathrm{d}x/\mathrm{d}t$. The *magnitude* of velocity is called *speed*.

vibrational motion A to-and-fro motion. See also *oscillation*.

visible light *Electromagnetic radiation* with *wavelength* between about 4×10^{-7} m (400 nm, violet) and 7×10^{-7} m (700 nm, red), or equivalently with *frequency* between about 8×10^{14} Hz and 4×10^{14} Hz.

volt The *SI* unit of *electrostatic potential*, *potential difference* or emf, represented by the symbol V. If an *electric charge* of one *coulomb* has its *electric potential* increased by one volt, its *potential energy* increases by one *joule*, so that $1\,\mathrm{V} = 1\,\mathrm{J\,C^{-1}}$.

voltage Any quantity, such as *electrostatic potential*, *potential difference* or emf, that can be measured in *volts.*

watt The *SI* unit of the rate at which *work* is done or *energy transferred*, represented by the symbol W. One watt is defined by $1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}}$.

wave A periodic disturbance that can convey *energy* from one point to another. If the wave travels through a material medium, no *particle* in the medium is permanently displaced by passage of the wave. Waves may be *standing* or *travelling.* Some waves may be *transverse* or *longitudinal.* Waves may also be characterized by their *frequency*, *wavelength* and direction of propagation. Transverse waves may also be characterized by their *polarization.*

wavelength The spatial separation λ, measured along the direction of propagation, of successive points in a *wave* that differ in *phase* by 2π at any fixed time t. More crudely, the distance between successive peaks of the wave.

wave number The quantity $k = 2\pi/\lambda$, where λ is the *wavelength* of a *wave.*

weak interaction A very short-range *force* that is responsible (among other things) for *beta decay.*

white dwarf star A compact stellar object with a *mass* similar to that of the Sun, which, following a fuel shortage, has collapsed to a size similar to that of the Earth. Consequently the average *density* of the object is very high, roughly a million times that of the Sun.

work If a constant *force* $\mathbf{F}$ acts on a *particle* as it moves through a *displacement* $\mathbf{s}$, the work done by the force on the particle is $\mathbf{F}\cdot\mathbf{s}$. For a *conservative force* the work done depends only on the initial and final positions of the particle.

X-rays *Electromagnetic radiation* with *wavelength* between $1\times10^{-8}\,\mathrm{m}$ and $1\times10^{-11}\,\mathrm{m}$, or equivalently *frequency* between about $3\times10^{16}\,\mathrm{Hz}$ and $3\times10^{19}\,\mathrm{Hz}$

zero of potential energy A point at which the *potential energy* of a *particle* is set equal to zero.