Physics Dictionary

M. A. Reynolds

Contents

1 Units

SI system (also called the mks system) — meter, kilogram, second; fundamental units of mechanics (length, mass, time) in the internationally accepted system. The four other fundamental units are the Ampere, Kelvin, mole, candela.

> **second** — originally defined as 1/86400 of a mean solar day. However, because the length of the day is not constant, it is currently defined as "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom." This implies that light from this transition has a frequency of *exactly* 9 192 631 770 Hz.
>
> **meter** — originally defined as one ten millionth of the distance between the Earth's north pole and its equator. If the Earth was a perfect sphere, this would imply $2\pi R_E = 4 \times 10^7$ m, or the Earth's radius $R_E = 6366$ km. However, the Earth's shape is approximately that of an oblate spheroid, with a polar radius of 6357 km and an equatorial radius of 6378 km. Currently defined as "the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second." It follows that the speed of light in a vacuum is *exactly* 299 792 458 m/s.
>
> **kilogram** — this is the most difficult unit to define, since the gravitational force is so weak. It could be defined in terms of a specific number of atoms, but this makes macroscopic measurements difficult, so it is currently defined as "equal to the mass of the international prototype of the kilogram." This prototype is a platinum-iridium bar kept at the *Bureau International des Poids et Mesures* in France.

cgs system — centimeter, gram, second; fundamental units of mechanics that are still used in certain fields. While the second is, of course, identical to the SI unit of time, the centimeter and gram are defined as fractions (10^{-2} and 10^{-3}, respectively) of the SI units. Originally, a gram was defined as the mass of one cubic centimeter of water at standard temperature and pressure.

English system — foot, pound, second; also called the "foot-pound-second" system, denoting the fact that the pound, a unit of force, rather than the slug, a unit of mass, is the fundamental unit. The slug is therefore a derived unit.

> **foot** — defined in terms of the meter as *exactly* 0.3048 m; This definition makes the inch *exactly* 2.54 cm, and the mile (5,280 feet) *exactly* 1,609.344 m.
>
> **pound** — originally defined as the weight of a standard body at a point where the acceleration due to gravity was $g = 9.80665$ m/s^2; currently defined in terms of the kilogram, as the weight of an object with mass $m = 0.45359237$ kg where g has the value given above. This definition means that 1 lb $\approx$ 4.448 N. A simple conversion with only 0.2% error is 1 kg weighs 2.2 lb.

derived units - other units that are formed by multiplying and dividing the fundamental units; for example, force, energy, and power are used in classical mechanics. Other combinations of units, such as those of velocity (m/s) and acceleration (m/s^2) have no independent names.

Newton — 1 N = 1 kg m s^{-2}; derived unit of force in the SI SYSTEM.

Joule — 1 J = 1 N m = 1 kg m^2 s^{-2}; derived unit of energy in the SI SYSTEM.

Watt — 1 W = 1 J/s = 1 kg m^2 s^{-3}; derived unit of power in the SI SYSTEM.

dyne — 1 dyne = 1 g cm s^{-2}; derived unit of force in the CGS SYSTEM. also equal to 10^{-5} N.

erg — 1 erg = 1 dyne cm = 1 g cm^2 s^{-2}; derived unit of energy in the CGS SYSTEM; also equal to 10^{-7} J.

slug — 1 slug = 1 lb s^2 ft^{-1}; unit of mass in the ENGLISH SYSTEM. The slug, therefore, is defined as the mass which will be given an acceleration of 1 ft s^{-2} when a force of 1 lb is applied to it. The weight of 1 slug near sea level is $w = mg =$ (1 lb s^2 ft^{-1}) (32.174 m/s^2) $\approx$ 32.2 lb.

Other units

minute — 60 s.
hour — 60 min = 3600 s.
day — 24 hr = 1440 min = 86 400 s.
year — 365.24219 days = 31 556 925 s.
Ångstrom — 10^{-10} m.
fathom — 1.8288 m; a unit of length in the Imperial system of units; approximately equal to the length of two outstretched arms. The international definition is exactly 2 yards, or 6 feet.
furlong — 660 feet or 0.125 mile; unit of length used in thoroughbred horseracing. Originally from the English "furrow long," the length of a furrow in one acre of a plowed field. An acre is a unit of area such that 640 acres are in one square mile; hence an acre is 43,560 ft^2, which is 660 ft $\times$ 66 ft. Therefore, one square mile can be broken up into a rectangular grid of 8 sections by 80 sections, each of which is one acre.
inch — 2.54 cm.
foot — 12 in = 0.3048 m.
mile — 5280 feet = 1609.344 m.
Astronomical Unit (A.U.) — average Earth-Sun distance; 149.9 million km.
light year — distance that light travels in one year; 9.46×10^{15} m.
gallon — 3.785 412 L.
liter (L) — 1000 cm^3.
metric ton — 1000 kg.
electron Volt (eV) — the energy acquired by a particle of charge e as it falls through a electric potential difference of 1 Volt; 1 eV $\approx 1.602 \times 10^{-19}$ J.

British thermal unit (BTU) — the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit; There are different definitions of the BTU, each based on a different water temperature. The most widespread version equals 1055.05585262 J, which is approximately the value averaged over the range 0°C to 100°C.

calorie — 1 cal = 4.186 J;

Calorie — 1 Cal = 1000 cal = 4186 J;

Avogadro's number — $6.022\,1415(10) \times 10^{23}$ mol^{-1}; The number of molecules in one mole of matter. Also called Loschmidt's number. Hypothesis of Avogadro and Ampere in 1815 states "One gram of any pure body (which occupies in the gaseous state 22.3 liters at standard temperature and pressure) always contains the same number of molecules, whatever the body may be."

Quantities to know

speed of light — $c \equiv 299\,792\,458$ m/s $\approx 3 \times 10^8$ m/s; universal speed limit.

universal gravitational constant — $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, empirical proportionality constant in NEWTON'S LAW OF GRAVITATION.

mass of Sun — $M_\odot = 1.99 \times 10^{30}$ kg;

radius of Sun — $R_\odot = 6.95 \times 10^8$ m;

luminosity of Sun — $L_\odot = 3.85 \times 10^{26}$ W;

mass of Earth — $M_\oplus = 5.97 \times 10^{24}$ kg;

radius of Earth — $R_\oplus = 6371$ km; this is the average sea-level radius. The earth is an oblate spheroid, whose equatorial radius is 6378 km, while the polar radius is 6357 km.

Astronomical Unit (A.U.) — 1.496×10^{11} m $\approx$ 150 million km; average Earth-Sun distance, or the semi-major axis of the Earth's elliptical orbit.

Earth-Moon distance — 384,000 km;

mass of electron — $m_e = 9.109 \times 10^{-31}$ kg;

mass of proton — $m_p = 1.673 \times 10^{-27}$ kg $= 1836\, m_e$;

mass of neutron — $m_n = 1.675 \times 10^{-27}$ kg $= 1839\, m_e \approx m_p$;

radius of nucleon — ≈ 1.2 fm;

2 Basic Math

algebra — the set of two linear equations and two unknowns

$$\begin{aligned} ax + by &= c \\ dx + ey &= f \end{aligned}$$

has as its solution

$$\begin{aligned} x &= \frac{bf - ec}{db - ae} \\ y &= \frac{dc - af}{db - ae} \end{aligned}$$

The solution to $ax^2 + bx + c = 0$ is the quadratic formula

$$2ax = -b \pm \sqrt{b^2 - 4ac}.$$

binomial theorem — the binomial $(a + b)$ raised to an integer power n is given by the sum

$$(a+b)^n = \sum_{k=0}^{n} \begin{pmatrix} n \\ k \end{pmatrix} a^{n-k} b^k = \sum_{k=0}^{n} \frac{n!}{k!(n-k)!} a^{n-k} b^k = a^n + na^{n-1}b + \cdots + nab^{n-1} + b^n$$

where $\begin{pmatrix} n \\ k \end{pmatrix}$ is the number of combinations of n things k at a time, also known as the binomial coefficients. The binomial coefficients can be determined using PASCAL'S TRIANGLE. Newton showed that the binomial theorem was valid even if n was *not an integer*. In this case the sum is infinite and is given by the NEWTON SERIES.

Pascal's triangle — a simple mnemonic device for determining the binomial coefficients

$$\begin{array}{ccccccccc} & & & & 1 & & & & \\ & & & 1 & & 1 & & & \\ & & 1 & & 2 & & 1 & & \\ & 1 & & 3 & & 3 & & 1 & \\ 1 & & 4 & & 6 & & 4 & & 1 \\ & & & & \vdots & & & & \end{array}$$

Newton series — the generalized binomial theorem, in the case where the exponent is not an integer, but is possibly complex, is given by the generalized binomial series

$$(a+b)^r = \sum_{k=0}^{\infty} \begin{pmatrix} r \\ k \end{pmatrix} a^{r-k} b^k = \sum_{k=0}^{\infty} \frac{r(r-1)\cdots(r-k+1)}{k!} a^{r-k} b^k = a^r + ra^{r-1}b + \frac{r(r-1)}{2!} a^{r-2} b^2 + \cdots$$

where $\begin{pmatrix} r \\ k \end{pmatrix}$ is the generalized binomial coefficient. Note that since r is not an integer, there is no value of k such that $r - k + 1 = 0$, which would truncate the series—hence it is an infinite series.

geometry — Circle: $C = 2\pi r$, $A = \pi r^2$; Sphere: $A = 4\pi r^2$, $V = 4\pi r^3/3$.

Pythagorean triples — sets of integers that satisfy $a^2 + b^2 = c^2$; there are, of course, an infinite number, but the first four independent sets are (3, 4, 5), (5, 12, 13), (7, 24, 25), (8, 15, 17). Multiples of these sets also are triples, e.g., (6, 8, 10). (There is exactly one triple such that $a + b + c = 1000$. Can you find it?)

trigonometry — $\cos^2\theta + \sin^2\theta = 1$; $\tan\theta = \sin\theta / \cos\theta$;

approximations — Most approximations can be found by using either a Taylor series or the first few terms of the binomial theorem. Trigonometric functions have simple approximations when $\theta \ll 1$:

$$\begin{aligned} \sin\theta &\approx \theta - \frac{\theta^3}{6} + \cdots \\ \cos\theta &\approx 1 - \frac{\theta^2}{2} + \cdots \\ \tan\theta &\approx \theta + \frac{\theta^3}{3} + \cdots \end{aligned}$$

Binomials have simple approximations when one term is smaller than the other, i.e., in NEWTON'S SERIES, if you make the replacements $a = 1$ and $b \equiv \epsilon \ll 1$, you get for the first two terms:

$$(1+\epsilon)^r \approx 1 + r\epsilon, \qquad \epsilon \ll 1$$

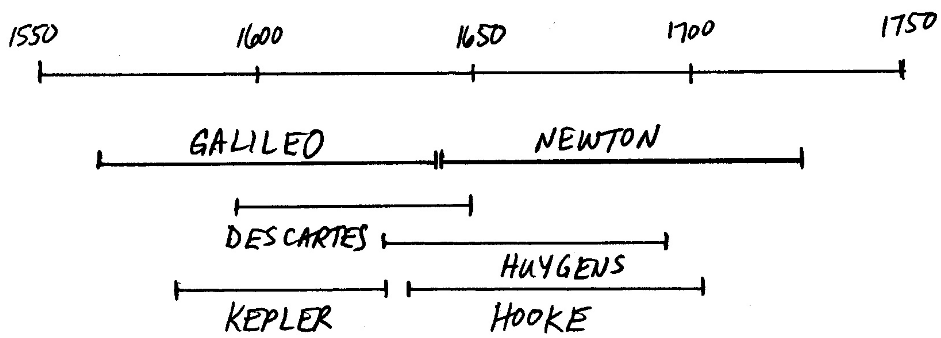
calculus —

$$\frac{dx^n}{dx} = nx^{n-1}$$

$$\int x^n dx = \frac{x^{n+1}}{n+1} + C$$

3 Classical Mechanics

Mechanics is the study of *how* objects move (KINEMATICS) as well as *why* they move (DYNAMICS) or don't move (STATICS). It includes a study of forces and the laws that describe how objects respond to forces. The dynamical laws that describe this response are embodied in Newton's Three Laws — the Second Law is sometimes called an "equation of motion" in that it mathematically describes the motion (position, velocity and acceleration) of an object under a give force. In general the possible motion is in three dimensions, and thus is comprised of free fall (parabolic) motion, circular motion (gravitational orbits), for example. The most elegant description is not, however, in terms of forces and accelerations, but in terms of conservation laws, most importantly the conservation of energy and momentum.



Aristotle (384-322 BCE) — Greek philosopher, scientist.

Galilei, Galileo (1564-1642) — physicist; founder of the scientific method, where experimentation is the final arbiter of scientific truth. He was the first to insist on quantitative measurement rather than qualitative reasoning that Aristotle was so fond of.

Kepler, Johannes (1571-1630) — astronomer, mathematician; famous for discovering (empirically) his three laws of planetary motion, which Newton used to deduce his Law of Gravitation.

Descartes, Rene (1596-1650) — philosopher, physicist; credited with discovering the LAW OF INERTIA, and developing analytic geometry.

Huygens, Christiaan (1629-1695) — physicist; together with Galileo and Descartes laid the foundations for Newton to discover his laws of dynamics and gravity. Credited with the first description of CENTRIPETAL ACCELERATION.

Hooke, Robert (1635-1703) — physicist; famous for HOOKE'S LAW OF ELASTICITY.

Newton, Isaac (1643-1727) — physicist; original founder of mechanics, gravitation, optics, etc.

Einstein, Albert (1886-1953) — physicist; developer of quantum theory and relativity.

Kinematics

The study of the motion of a given object. In general, this study consists of an equation of motion whose solution is the position, velocity, and acceleration of the object as functions of time: $\vec{r}(t)$, $\vec{v}(t)$, $\vec{a}(t)$. In the restricted sense used here, these functions are simple only when the acceleration is constant (see KINEMATIC EQUATIONS).

primitive concepts — space, time; the fundamental concepts that underly all attempts at description of the world around us.

> "The sun and moon and five other stars, which are called the planets, were created by him in order to distinguish and preserve the numbers of time..."
> — Plato, *Timaeus*

> "To Isaac Newton, space and time simply were—they formed an inert, universal cosmic stage on which the events of the universe played themselves out. To his contemporary and frequent rival Gottfried Wilhelm von Liebniz, "space" and "time" were merely the vocabulary of relations between were objects were and when events took place. Nothing more. But to Albert Einstein, space and time were the raw material underlying reality. through his theories of relativity, Einstein jolted our thinking about space and time and revealed the principal part they play in the evolution of physics. They are at once familiar and mystifying; fully understanding space and time has become physics' most daunting challenge and sought-after prize."
> — Brian Greene, *Fabric of the Cosmos*

absolute time — Newton's view was of "*Absolute, true and mathematical time, of itself, and by its own nature, flows uniformly on, without regard to anything external.*" He realized that you could never measure this time, that is, you could only measure time relative to something (e.g., the Earth's rotation), but nonetheless he believed that it existed.

absolute space — "*Absolute space, it its own nature and without regard to anything external, always remains similar and immovable.*" — Newton.

position — $\vec{r}(t)$; given a coordinate system, the three components of the location of a particular object (in general a function of time) collectively describe its position. Using a Cartesian coordinate system, the position can be written $\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$, where $\hat{x}$, $\hat{y}$, and $\hat{z}$ are the unit vectors. The description of the motion of an object requires a specification of its POSITION (in three-dimensional space) and VELOCITY as functions of time.

velocity — $\vec{v} \equiv d\vec{r}/dt$; the rate of change of the position with respect to time.

speed — $v = |\vec{v}|$; magnitude of the velocity.

acceleration — $\vec{a} \equiv d\vec{v}/dt = d^2\vec{r}/dt^2$; the rate of change of the velocity with respect to time.

jerk — $d^3\vec{r}/dt^3$; higher-order derivatives of position with respect to time exist, but in general are not very useful.

Galilean relativity — the notion that there is a universal (absolute) time, and that in all INERTIAL REFERENCE FRAMES Newton's LAWS OF DYNAMICS are valid. Or, as Max Born puts it

> "Relative to a coordinate system moving rectilinearly and uniformly through absolute space, the laws of mechanics have exactly the same expression as when referred to a coordinate system at rest in space."

In practice, this means that the position of an object measured in coordinate system A, $\vec{r}_A$, and the position of the *same* object measured in coordinate system B, $\vec{r}_B$, are related by

$$\vec{r}_A = \vec{r}_B + \vec{U}t,$$

where B is moving with constant velocity $\vec{U}$ relative to A. (It was also assumed that at $t = 0$ the origins of the two coordinate systems were colocated. Since $\vec{r}_A$ and $\vec{r}_B$ are, in general, functions of time, we can obtain the velocities of the object (as measured in the two frames) by differentiation, $\vec{v}_{OA} = \vec{v}_{OB} + \vec{U}$, where $\vec{v}_{OA}$ is the velocity of the object in frame A, and $\vec{U} = \vec{v}_{BA}$ is the relative velocity of the two frames.

velocity addition rule — $\vec{v}_{AC} = \vec{v}_{AB} + \vec{v}_{BC}$; here, the subscripts AB on $\vec{v}_{AB}$ signifies the velocity of A with respect to B. This rule is a consequence of GALILEAN RELATIVITY.

kinematic equations — solutions to the equation of motion restricted to the case when acceleration is constant.

$$\vec{r}(t) = \vec{r}_0 + \vec{v}_0 t + \tfrac{1}{2}\vec{a}t^2$$
$$\vec{v}(t) = \vec{v}_0 + \vec{a}t$$

The vector function $\vec{r}(t)$ is the solution, and the velocity $\vec{v}(t)$ is obtained by differentiation. Further differentiation results in the (constant) acceleration. In one dimension (the x direction) they are

$$\begin{aligned} x &= x_0 + v_{0x}t + \tfrac{1}{2}a_x t^2 && (1)\\ v_x &= v_{0x} + a_x t && (2)\\ v_x^2 &= v_{0x}^2 + 2a_x(x - x_0) && (3)\\ x &= x_0 + \tfrac{1}{2}(v + v_{0x})t && (4) \end{aligned}$$

Only Eqs. (1) and (2) are independent. They can be regarded as determining the position $x(t)$ and velocity $v_x(t)$ as functions of time as long as the INITIAL CONDITIONS are known, x_0 and v_{0x}. Of course, the acceleration as a function of time $a_x(t)$ is also needed in KINEMATICS, but in this restricted case, it is constant. Equation (3) can be obtained from (1) and (2) by eliminating time t, and Eq. (4) can also be obtained from (1) and (2) by eliminating the acceleration a_x. These third and fourth equations are useful in situations where the time or the acceleration is not known or needed. NOTE: Equation (3) describes the conservation of energy, and Eq. (4) describes the fundamental relation between distance traveled, velocity, and time ($d = vt$), where $\frac{1}{2}(v + v_{0x})$ is the average velocity of the object.

initial conditions — $\vec{r}_0 = \vec{r}(0)$ and $\vec{v}_0 = \vec{v}(0)$; the initial position and velocity are all that is needed to prediction the subsequent trajectory of an object (assuming, of course, that its acceleration is known). The acceleration (and hence the force) acting on it need not be constant.

reference frame — choice of an origin, as well as directions of the mutually perpendicular Cartesian coordinates.

inertial reference frame — a REFERENCE FRAME that is moving with constant velocity with respect to ABSOLUTE SPACE. In practice, any frame in which NEWTON'S LAWS OF DYNAMICS are valid is an inertial reference frame.

Projectile Motion

When the force (typically gravitational) acting on an object is constant, it's trajectory through space is parabolic, and lies in a plane defined by the initial velocity vector and the force vector. Galileo derived this parabolic trajectory before Newton used his laws to prove it.

range — R, the distance a projectile travels before hitting the ground; if the projectile is fired from ground level across level ground with speed v_0 at an angle θ_0 above the horizontal, the range formula is

$$R = \frac{2v_{0x}v_{0y}}{g} = \frac{v_0^2 \sin 2\theta_0}{g},$$

where the second form was obtained using the double-angle formula. When the ground is not level (or the projectile is not fired from ground level) there is no general formula for the range. For this reason it is useful to know *how* to obtain the range formula, as it is usually only two lines of algebra.

law of free fall — all objects fall with the same acceleration; deduced by Galileo. See FREE FALL.

Dynamics

The study of an object and its interaction with its surroundings. In general, this study consists of determining the equation of motion for an object when the FORCES acting upon that object are known. whose solution is the position, velocity, and acceleration of the object as functions of time: $\vec{r}(t)$, $\vec{v}(t)$, $\vec{a}(t)$. In the restricted sense used here, these functions are simple only when the acceleration is constant (see KINEMATIC EQUATIONS).

Newton's Laws of Dynamics — three laws that describe the motion of an object when forces act upon it.

Newton's first law — "*Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.*" Sometimes called the LAW OF INERTIA. While Galileo certainly knew and understood this law—its implications appeared many times in his writings—it was Descartes who formulated the general statement.

Newton's second law — "*The change of motion* [velocity] *is proportional to the motive force impressed; and is made in the direction of the line in which that force is impressed.*" In modern mathematical notation it is written $\vec{F} = d\vec{p}/dt$, or, in the special case where the mass

m of the object is constant, $\vec{F} = m\,\vec{a}$. This equation is sometimes called the EQUATION OF MOTION because replacing $\vec{a}$ with $d^2\vec{r}/dt^2$ results in a differential equation that governs the trajectory $\vec{r}(t)$ of the object. In general, the force is a function of the position and velocity of the object, as well as time, $\vec{F}(\vec{r},\vec{v},t)$. The restricted case, when the force is constant (both in magnitude and direction) results in solutions that are the KINEMATIC EQUATIONS.

Newton's third law — "*To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*" Also known as the LAW OF ACTION AND REACTION. This is the only one of Newton's three laws that he alone discovered.

law of inertia — see NEWTON'S FIRST LAW.

law of action and reaction — see NEWTON'S THIRD LAW.

mass — m; a quantitative measure of an object's inertia, i.e., it's resistance to ACCELERATION. See NEWTON'S SECOND LAW.

momentum — $\vec{p} \equiv m\vec{v}$; the momentum of an object with mass m and velocity $\vec{v}$. Einstein modified this Newtonian formula for objects moving fast compared with the speed of light: $\vec{p} \equiv \gamma m\vec{v}$, where γ is the RELATIVISTIC FACTOR.

conservations laws — mass, energy, momentum, angular momentum. If the entire system is considered, these four quantities are exactly constant. Einstein, of course, showed that only the sum of mass and energy is constant, and that they can transform from one to the other according to $E_0 = mc^2$.

law of conservation of mass —

law of conservation of energy —

law of conservation of momentum — $\sum_i \vec{p}_i = C$; for a system of objects that are not acted on by an external force, the sum of the momenta of all the objects remains constant. This can be easily seen by considering NEWTON'S THIRD LAW as applied to two objects, $\vec{F}_{12} = -\vec{F}_{21}$, and using NEWTON'S SECOND LAW to express each force

$$\frac{d\vec{p}_1}{dt} = -\frac{d\vec{p}_2}{dt},$$

or

$$\frac{d}{dt}\left(\vec{p}_1 + \vec{p}_2\right) = 0.$$

The generalization to many objects is trivial.

law of conservation of angular momentum — $\sum_i \vec{L}_i = C$; for a system of objects that are not acted on by an external *torque*, the sum of the angular momenta of all the objects remains constant. This follows as the rotational analogue to the LAW OF CONSERVATION OF MOMENTUM.

free fall — $a_y = -g$; an object is in free fall when the only force acting on it is the Earth's gravitational force, which means that its acceleration is only in the negative y direction and has a magnitude 9.8 m/s^2.

center of mass — $\vec{R}_{cm} = \sum_i m_i\vec{r}_i/M$; the center of mass of a system of objects is the (vector) location at which the system acts like a single particle with all its mass concentrated at that point. In the case of an extended object with nonuniform density, the sum becomes and integral

$$\vec{R}_{cm} = \frac{\int \rho\,\vec{r}\,dV}{\int \rho\,dV}$$

where the integrals are triple (volume) integrals. The concept of "center of mass" only has meaning in a uniform gravitational field, such as exists near the surface of the Earth.

center of gravity — see CENTER OF MASS; sometimes used—in contrast to "center of mass"—to imply that the gravitational field is nonuniform. However, this distinction is not useful. The term *barycenter* is sometimes used to denote the center of mass of a multiple star system.

fundamental forces — gravity, electromagnetic, strong nuclear, weak nuclear; these are the four interactions that are currently considered to be fundamental, i.e., all MECHANICAL FORCES and CONTACT FORCES are really manifestations of these fundamental forces.

mechanical forces — gravity, normal, friction, tension; except for gravity, these are the macroscopic manifestation of the electromagnetic force.

contact forces — normal, friction, tension; each of these forces originates in the electromagnetic interaction between two objects, and is commonly described as having no effect unless the two objects are touching, i.e., in *contact*.

equation of motion — $\vec{F} = d\vec{p}/dt$; equivalent to NEWTON'S SECOND LAW. In general, the force is a function of the position and velocity of the object, as well as time, $\vec{F}(\vec{r}, \vec{v}, t)$. The restricted case, when the force is constant (both in magnitude and direction) results in solutions that are the KINEMATIC EQUATIONS.

work — $W = \int \mathbf{F}\cdot d\mathbf{r}$; Forces do work only when they act on an object over a displacement.

kinetic energy — $K \equiv \frac{1}{2}mv^2$; the energy associated with an object's motion. This approximate expression is only valid in the nonrelativistic limit ($v \ll c$), and the correct expression is $K = (\gamma - 1)mc^2$, where γ is the RELATIVISTIC FACTOR.

work-energy theorem — $W = \Delta K$; the WORK done *on* an object is equal to its change of kinetic energy.

potential energy — $\Delta U = \int dU \equiv \int \mathbf{F} \cdot d\mathbf{r}$; Only the *change* in potential energy is defined, which implies that the zero point of the potential energy is a free choice. Only CONSERVATIVE FORCES have meaningful potential energies.

gravitational potential energy — $U = -GMm/r$; general form for two point masses M and m (see NEWTON'S FIRST SHELL THEOREM) a distance r apart. In this case, the zero point, $U = 0$, is chosen to be when $r \to \infty$, i.e., when M and m are infinitely far apart. The approximate formula, $U = mgy$, is restricted to a uniform gravitational field of strength g, usually near the surface of the Earth ($g = 9.8$ m/s^2), but valid in any uniform gravitational field.

gravitational potential energy — $-GMm/r$, potential energy associate with two objects of mass M and m that are a distance r apart. Near the surface of a planet of mass M and radius R it is approximately mgh, where $g = GM/R^2$ and $h = r - R$. NOTE: the location where $-GMm/r$ is zero is $r \to \infty$, while mgh is zero at $h = 0$ or $r = R$.

elastic potential energy — $U = \frac{1}{2}kx^2$; associated with a HOOKE'S LAW force.

conservative force — force who's WORK is path independent; admits a POTENTIAL ENERGY.

law of conservation of energy — $E = \frac{1}{2}mv^2 + U$; "The energy of the universe is constant." –Rudolf Clausius, 1865. The expression given is generally referred to as MECHANICAL ENERGY, as it consists of kinetic plus potential (usually gravitational and perhaps elastic) energy only. However, the law of energy conservation is much broader than this, and several forms of energy have been discovered since Clausius's time, including thermal, electrical, and most notably, rest energy, resulting in Einstein's famous $E_0 = mc^2$.

mechanical energy — that portion of the total energy of an object that consists of KINETIC ENERGY, GRAVITATIONAL POTENTIAL ENERGY, and ELASTIC POTENTIAL ENERGY.

elastic collision — an interaction in which the interacting objects do not change their internal state (i.e., temperature, quantum state, etc.). In Newtonian physics, this implies that mechanical energy (see the LAW OF CONSERVATION OF ENERGY) is conserved.

inelastic collision — an interaction in which a change occurs in the internal state of the interacting objects; macroscopically, some of the mechanical energy appears to be lost. Quantified by NEWTON'S LAW OF RESTITUTION.

stopping distance — $D = v^2/2\mu g$; the minimum distance required for an automobile to stop when it is traveling at speed v over a level surface with a coefficient of friction μ between the tires and the road. This is a combination of the third KINEMATIC EQUATION and NEWTON'S SECOND LAW.

following time (two-second rule) — the minimum safe time for following the automobile in front of you. The common "two-second rule" suggests that your following distance be determined by maintaining a two-second difference between you and the car in front of you. However, this maintains a distance $d = vt$ that is proportional to your speed v. For a given μ and low speeds, the stopping distance is less than this following distance ($D < d$), which means that you should be able to safely stop without hitting the car in front of you. However, above a critical speed, typically 50 mph for dry roads, this method of following results in an unsafe distance between automobiles.

applications — parabolic motion (free fall), circular motion (gravity orbits, Kepler's laws), airplanes (thrust, drag, lift, weight), driving/sliding on a surface or banked curve.

Collisions

Newton's Law of restitution —

coefficient of restitution — $e = (v_{1f} - v_{2f})/(v_{2i} - v_{1i})$; the ratio of the final relative speed to the initial relative speed (for a two-body collision in one dimension). A measure of the loss of energy in a collision: $e = 0$ is a perfectly inelastic collision, $e = 1$ is an elastic collision, and in general, $0 < e < 1$ is an inelastic collision (which most collisions are).

Statics

The study of the forces acting on an object such that the net force is zero and the acceleration is therefore also zero. Usually, a further restriction to zero velocity is also made, although constant velocity is the only requirement.

principle of the lever —

principle of the inclined plane —

mechanical advantage — see LEVERAGE.

leverage – the use of a simple mechanism to multiply force.

equilibrium — state of an object (or objects) on which the net external force is zero, and the net external TORQUE is zero. $\Sigma\mathbf{F} = 0$; $\Sigma\vec{\tau} = 0$. An equilibrium can be STABLE or UNSTABLE.

stable equilibrium —
couple —

Rotational Motion

angular velocity — $\omega = d\theta/dt$;
angular acceleration — $\alpha = d\omega/dt$;

parallel axis theorem — $I = I_{cm} + Md^2$; the moment of inertia of an object I about any axis is equal to the moment of inertia about a parallel axis that passes through the center of mass I_{cm} plus Md^2, where d is the perpendicular distance between the two axes, and M is the object mass. This was first derived by Lagrange in 1783.

perpendicular axis theorem (plane figure theorem) — $I_z = I_x + I_y$; for an object that lies entirely in the xy plane, the moment of inertia about the z axis, I_z, is equal to sum of the moments of inertia about the x and y axes. NOTE: all three axes must pass through the same point.

third angular momentum theorem — from AJP

angular momentum — $\vec{L} \equiv \vec{r}\times\vec{p}$; for extended objects rotating as a rigid body $\vec{L} = I\vec{\omega}$, where I is the MOMENT OF INERTIA.

moment of inertia — $I \equiv \int r^2 dm$; inertial response to rotational acceleration. Here, r is the perpendicular distance from the mass element dm to the axis of rotation. Note that I depends on the choice of an axis (see the PARALLEL AXIS and PERPENDICULAR AXIS THEOREMS). For a point object moving in circular motion, $I = MR^2$. For extended objects, the integral must be evaluated. For example, a sphere about an axis through its center, $I = \frac{2}{5}MR^2$.

centripetal acceleration — $a_c = v^2/r$; this is the acceleration due to a change in the direction of $\vec{v}$, and always points toward the center of the circular path of the object.

angular momentum — $\vec{L} \equiv \vec{r}\times\vec{p}$; the angular momentum of an object with momentum $\vec{p}$ depends on the point from which you measure it. Here, $\vec{r}$ is the position vector of the object as measured from this point.

law of conservation of angular momentum — $d\vec{L}/dt = 0$; Can be obtained from the fact that space is isotropic.

torque — $\vec{\tau} \equiv \vec{r} \times \vec{F}$; the torque exerted by a force $\vec{F}$ when acting at a distance $\vec{r}$ (the LEVER ARM) from the axis of rotation.

lever arm — sometimes called the *moment arm*. A vector extending from the axis of rotation to the point of application of the force.

Gravity

Newton's Law of Gravitation — the force between any two objects with mass is attractive, and its magnitude is proportional to the product of the two masses, and inversely proportional to the square of the distance between them

$$F_{\text{gravity}} = G\frac{m_1 m_2}{r^2}.$$

This is the famous "inverse-square" force law, whose effect is sometimes called "action-at-a-distance," i.e., objects exert forces on other objects *without touching them!* Newton was unable to explain *how* a force such as gravity could act across empty space. In fact, Newton thought of his gravitational theory as "mathematical," in that it gave the proper prediction of how the planets moved, but it did not *explain* anything in the sense that it supplied no "physical" interpretation of *how* the gravitational force acted as it did, nor *why* it should do so.

Newton's first shell theorem — the net gravitational force on an object that lies inside a spherical shell of matter is zero. The proof of this theorem is simple, showing that points of matter on the shell in opposite directions exert equal and opposite forces on the object.

Newton's second shell theorem — the net gravitational force on an object that lies outside a spherical shell of matter is the same as it would be if all the shell's matter were concentrated at a point at its center. Along with Newton's first shell theorem, this result allows the calculation of gravitational forces to be greatly simplified. Newton's own statement of the theorem was: "*A corpuscle placed without the spherical surface is attracted towards the centre of the sphere with a force inversely proportional to the square of its distance from that centre.*"

Newton's cannonball — Newton's thought experiment in which projectiles (cannonballs) are fired horizontally with increasing initial speed. Low launch speeds result in sub-orbital flights, MINIMUM ORBITAL SPEED results in a circular, SURFACE-GRAZING ORBIT, while high speeds result in stable elliptical, parabolic, or hyperbolic orbits.

escape velocity — v_{esc}; speed needed to just barely reach a distance infinitely far from an object $v_{\mathrm{esc}} = \sqrt{2GM/R}$, where M is the mass of the object being escaped from, R is the initial radial distance. Compare with the circular orbit speed obtained from the CIRCULAR ORBIT EQUATION.

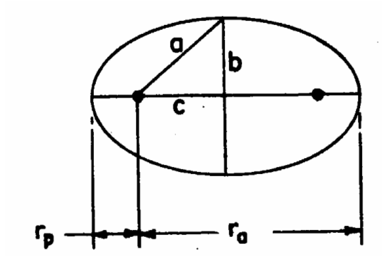
circular orbit equation — $GM = v^2 r$, relation between the tangential speed v and the orbital radius r for a stable circular orbit around an object of mass M. Equivalent to KEPLER'S THIRD LAW. Note that the mass m of the orbiting object and the radius R of the central object do not appear.

minimum orbital speed — $v = \sqrt{GM/R}$; this speed results in a stable circular orbit with a radius r equal to the planet's radius R. NOTE: this is not the smallest possible stable circular orbit speed (that would be zero as $r \to \infty$), but the minimum horizontal launch speed resulting in a stable circular orbit.

surface-grazing orbit — an orbit who's periapsis is equal to the radius of the central body.

Kepler's laws — empirical relationships obtained by Johannes Kepler (1571-1630) from the observation of the orbit of Mars.

Kepler's first law — Each planet in the solar system moves in an elliptical orbit with the sun at one focus.



Kepler's second law — The radius vector drawn from the sun to any planet sweeps out equal areas in equal time intervals.

Kepler's third law — The square of the orbital period of any planet is proportional to the cube of the semimajor axis of the elliptical orbit. Equivalent to the CIRCULAR ORBIT EQUATION.

$$T^2 = \left(\frac{4\pi^2}{GM_\odot}\right) a^3.$$

Special Relativity

rest energy — $E_0 = mc^2$;

relativistic factor — $\gamma = (1-\beta^2)^{-1/2}$; a function of the relative speed $\beta \equiv v/c$.

total energy — $E = \gamma mc^2 = E_0 + K$; the total energy of a particle consists of its REST ENERGY and its KINETIC ENERGY.

kinetic energy — $K = E - E_0 = (\gamma - 1)mc^2 \approx \frac{1}{2}mv^2$; the kinetic energy can take on any value, but in the low velocity limit ($v \ll c$) it can be approximated by the well-known non-relativistic expression.

momentum — $\vec{p} = \gamma m\vec{v}$;

4 Intermediate Math

chain rule —
product rule —
quotient rule —
reciprocal rule —

$$\frac{dx}{dt} = \left(\frac{dt}{dx}\right)^{-1}$$

5 Oscillations and Waves

Elasticity

Hooke's Law of Elasticity — $\vec{F} = -k\vec{r}$, the restoring force $\vec{F}$ exerted by a spring is proportional to the displaced distance from equilibrium $\vec{r}$. Hooke expressed it in Latin: *Ut tensio, sic vis* [As the extension, so the force].
stress —
strain —
Young's modulus —

Oscillations

harmonic motion — anything governed by the differential equation

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

whose general solution is

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

where A and ϕ are determined by the initial conditions. This describes a SPRING-MASS SYSTEM, a SIMPLE PENDULUM, and a PHYSICAL PENDULUM.

energy conservation — the harmonic motion equation admits a *first integral of the motion*, obtained by multiplying by dx/dt and integrating once:

$$\frac{1}{2}\left(\frac{dx}{dt}\right)^2 + \frac{1}{2}\omega^2 x^2 = C.$$

For a SPRING-MASS SYSTEM, this implies that the sum of kinetic and elastic potential energy is constant. For a SIMPLE PENDULUM, the sum of kinetic plus gravitational potential energy must be conserved, and the above first integral guarantees that — for small angles. That is, let $x \to \theta$, and approximate $\cos\theta \approx 1 - \theta^2/2$.

spring-mass system —

law of length — $T \propto \sqrt{\ell}$; the period of a pendulum is proportional to the square root of its length. Galileo discovered this using experiment and stated it in (date?) in his 'Discourses.'

simple pendulum — mechanical system consisting of bob of mass m hanging at the end of a massless rod of length ℓ. For small angles of displacement, the restoring TORQUE is proportional to the displacement, and hence it is an example of HOOKE'S LAW OF ELASTICITY, with an angular frequency given by

$$\omega = \sqrt{\frac{g}{\ell}}.$$

physical pendulum — an extended rigid body of mass m that pivots around a point P that is a distance d from its center of mass. For small angles, the restoring TORQUE is proportional to the displacement, and hence it is an example of HOOKE'S LAW OF ELASTICITY, with an angular frequency given by

$$\omega = \sqrt{\frac{mgd}{I}},$$

where I is the moment of inertia about the pivot axis.

center of oscillation — an imaginary point of a PHYSICAL PENDULUM chosen such that if all the mass were concentrated at this point, the resulting SIMPLE PENDULUM would have the same frequency as the original physical pendulum. This point is a distance

$$L_0 = \frac{I}{md}$$

from the pivot point in the direction of the center of mass. "Thus, as far as its period of vibration is concerned, the mass of a physical pendulum may be considered to be concentrated at a point whose distance from the pivot is L_0.' — F. W. Sears.

damped, driven, harmonic oscillator — system whose dynamics is represented by the second-order differential equation

$$\frac{d^2x}{dt^2} + b\frac{dx}{dt} + \omega^2 x = F\cos(\omega t),$$

where b is the damping coefficient, and the driving force is sinusoidal. The response of the system (after a long time, i.e., ignoring transient effects) is also sinusoidal is at the same frequency as the driving frequency ω,

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

but whose amplitude A and phase ϕ depends on the driving frequency's relationship to the natural frequency $\omega_0 = \sqrt{k/m}$ of the undamped oscillator:

Waves

speed of sound — $\sqrt{B/\rho}$, speed of a compressional acoustic wave in a fluid. Here, B is the BULK MODULUS and ρ is the density of the medium.

bulk modulus — a measure of the volume strain in response to a volume stress

fluid — gas or liquid.

Doppler Effect — The tendency of stupid ideas to seem smarter when they come at you rapidly.

Superposition, interference, and diffraction

Fluid Mechanics

Archimedes (287-212 BCE) — Greek mathematician, physicist. Developed hydrostatics, including ARCHIMEDES' PRINCIPLE, and explained the principle of the lever.

Evangelista Torricelli (1608-1647) — Italian physicist, mathematician. Invented the BAROMETER.

Blaise Pascal (1623-1662) — French mathematician, physicist. Generalized Torricelli's work on pressure and vacuum.

Daniel Bernoulli (1700-1782) — Swiss physicist, mathematician. First to develop of a coherent theory of fluids (liquids and gases). Published *Hydrodynamica* in 1738.

Giovanni Battista Venturi (1746-1822) — Italian physicist. Discovered the VENTURI EFFECT.

Fluid statics

pressure — $F_\perp/A$; the force exerted normal to a surface divided by the surface area. The SI unit is *Pascal*: 1 Pa = 1 N/m. The pressure in a fluid acts in all directions.

gauge pressure — $p_{\text{gauge}} = p - p_{\text{atm}}$; the pressure as measured by a pressure gauge, which is the total pressure minus atmospheric pressure. Pressure gauges can only measure differences in pressure, and their comparison is usually atmospheric pressure.

atmospheric pressure — $p_{\text{atm}} = 101,325$ Pa; This is the *standard atmosphere*, agreed upon in 1954 by the 10th Conférence Générale des Poids et Mesures to represent the mean atmospheric pressure at mean sea level at the latitude of Paris, France. In 1982, the International Union of Pure and Applied Chemistry defined the STANDARD PRESSURE to be 10^5 Pa, also known as 1 bar.

standard pressure — 10^5 Pa.

density — $\rho = M/V$; the density of an object is equal to its total mass divided by its total volume. Of course, density may vary within an object (as it does within the Earth) and the local density of a volume element dV is $\rho = dm/dV$, where dm is the mass of the volume element.

specific gravity — ρ/ρ_{water}; a unitless quantity that expresses the density of a substance relative to the density of water (when both are at the same temperature).

barometer — device for measuring pressure; relies on the VARIATION OF PRESSURE WITH DEPTH.

Archimedes' principle — the BUOYANT FORCE exerted on a submerged (or partially submerged) object is equal to the weight of the fluid displaced.

buoyant force — $B = \rho g V$; Here, ρ is the density of the fluid in which the object is submerged, and V is the volume of the fluid that is displaced (not necessarily the volume of the object, as is the case for floating objects).

Pascal's Law, 1653 — for a motionless fluid, the pressure at any given height will be identical; Also expressed as the fact that any pressure change applied at one point will be transmitted throughout the fluid. See the VARIATION OF PRESSURE WITH DEPTH.

variation of pressure with depth — $dp = -\rho g dy$; in a uniform gravitational field $\vec{g} = -g\hat{y}$, the pressure increases with decreasing vertical coordinate, y. If, at the top surface of a fluid the pressure is p_0, then $p(y) = p_0 - \rho g y$.

barometric equation — $p(y) = p_0 e^{-(Mg/kT)y}$; the pressure as a function of altitude in the Earth's atmosphere, assuming the temperature T to be constant (isothermal). Here, M is the mean molecular mass and k is Boltzmann's constant.

hydrostatic paradox — liquid poured into interconnected vessels stands at the same level in each; also stated as "water seeks its own level.

Fluid dynamics

incompressible flow — flow in which the fluid density remains constant.

laminar flow — flow in which the fluid elements trace out trajectories that don't change with time; also called "steady flow." The fluid element trajectories are called "streamlines."

continuity equation — $\rho A v$ = constant; if the flow is INCOMPRESSIBLE, then ρ is separately constant and therefore the volume flow rate, Av, is constant along the streamline.

Bernoulli equation — $p + \rho v^2/2 + \rho g y$ = constant; expression of energy conservation in laminar fluid flow.

Torricelli's theorem — $v = \sqrt{2gh}$; the speed of fluid outflow from a small hole in a large tank is the same as an object dropped from the height of the surface in the tank to the height of the hole.

> **Torricelli's trumpet** — a finite volume enclosed by an infinite surface area. Also known as Gabriel's horn. Take the curve $y = 1/x$ from $1 < x < \infty$, and revolve it around the x axis. Torricelli realized that the surface area of this horn-shaped object is infinite, but that the volume it encloses is finite ($V = \pi$). Incredibly enough, he did this without calculus!

Venturi effect — reduction in pressure when a fluid flows through a constricted section of pipe. An application of the BERNOULLI EQUATION and the CONTINUITY EQUATION, and a method for measuring flow velocity.

Pitot tube — instrument to measure flow velocity; invented by Henri Pitot, and modified by Henry Darcy. An application of the BERNOULLI EQUATION.

aerodynamic lift — force exerted on an object due to fluid flow; commonly attributed to the difference in pressure across the object, but in reality is due to molecular collisions and momentum transfer.

Advanced topics

viscosity — a measure of internal friction in fluid flow;

surface tension —

Stoke's law — $F = 6\pi\eta r v$; the drag force exerted by a fluid on a sphere depends on the viscosity η, the radius of the sphere r, and its speed v.

Poiseuille's law — $Q = (\pi R^4/8\eta L)\,(p_1 - p_2)$ — total flow rate of a viscous fluid through a cylindrical pipe due to a pressure difference.

Darcy law of diffusion — phenomenological equation describing fluid flow through a porous medium.

$$\frac{Q}{A} = -\frac{\kappa}{\mu}\,\frac{\Delta P}{\Delta x}$$

where Q/A is the volume "flux" [$\mathrm{m}^3/\mathrm{s}/\mathrm{m}^2$], κ is the permeability of the porous medium, μ is the dynamic viscosity of the fluid, and $\Delta P/\Delta x$ is the pressure gradient. Similar in character to Newton's law of cooling, Fick's law of diffusion, and Ohm's law of electrical resistance.

Brunt-Vaisala frequency — the frequency of gravity mode oscillations in the Earth's atmosphere. Due the buoyant force in a stable stratified fluid immersed in a gravitational field.

6 Optics

Fraunhofer, Joseph von (1787-1826) — optical physicist; discovered absorption lines in the Sun's spectrum (they are now called "Fraunhofer lines"). To make this measurement, he invented the spectroscope in 1814, and later he invented the diffraction grating.

Young —

Fermat —

Huygens, Christiaan —

Hero of Alexandria (10-70) — explained reflection by invoking the PRINCIPLE OF LEAST DISTANCE.

Ångstrom —

Fermat's principle — the "Principle of Least Time"; explains Snell's law of refraction as well as the law of reflection. Light traveling from a source to a detector chooses the path that takes the least time.

Huygens' principle —

Principle of least distance — an explanation of the the straight line propagation of light, as well as the law of reflection ($\theta_i = \theta_r$); Light traveling from a source to an observer takes the shortest path, which is a straight line unless the light must reflect off a mirror. Then, its reflection obeys the law of reflection because the total path length between the source and observer is a minimum.

Scattering — see RAYLEIGH SCATTERING, MIE SCATTERING, OPTICAL SCATTERING.

Rayleigh scattering — $\lambda \gg d$

Mie scattering — $\lambda \sim d$

Optical scattering — $\lambda \ll d$

diffraction —

Fraunhofer diffraction — the incident light is a) parallel and b) monochromatic, and c) the image plane is far compared with the size of the diffracting object. FRESNEL DIFFRACTION is the general case where these restrictions are relaxed.

Fresnel diffraction —

Rayleigh criterion — $\theta_m in = \lambda/a$ for a 1D slit of width a; $\theta_m in = 1.22\lambda/D$ for a circular aperture of diameter D; the smallest angular separation that can be resolved.

Brewster's angle — $\tan\theta_B = n_2/n_1$; If unpolarized light in medium 1 is incident on medium 2 at an angle θ_B then the reflected light is polarized (electric field vector) purely in the direction perpendicular to the plane containing the normal and the incident ray. `http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polar.html#c1`.

Bragg's Law — $2d\sin\theta = m\lambda$; condition for constructive interference by X-ray diffraction by crystals. Note: θ is not measured from the 'normal.'

Lloyd's mirror — a mirror that reflects the rays from a light source, and together the reflected ray and the original ray act similarly to a double-slit experiment.

Klein-Nishina formula — correct, QED version of Compton scattering, giving

lateral magnification - image height divided by the object height, h'/h.

paraxial ray — in optical systems, a ray that is close to and nearly parallel with the optical axis.

rutile — titanium dioxide, TiO_2, has among the highest refractive indices, and high dispersion. May contain iron, niobium and tantalum. The relative permittivity is $\kappa = 100$, which means $n = 10$, since $n = \sqrt{\kappa}$.

total internal reflection — occurs when a ray is incident upon an interface at an angle of incidence that is greater than the CRITICAL ANGLE, $\theta_i > \theta_c$.

critical angle — θ_c; when passing from a medium of high index of refraction n_1 to a medium of low index of refraction n_2, the angle of incidence above which only reflection (not refraction) occurs, $\sin\theta_c = n_2/n_1$. See TOTAL INTERNAL REFLECTION.

angle of incidence — angle between an incident ray and the *normal* to the interface.

angle of reflection — angle between a reflected ray and the *normal* to the interface.

angle of refraction — angle between a refracted ray and the *normal* to the interface.

refraction — phenomenon where rays of light change direction at an interface between two media with different indices of refraction.

double-slit interference —

rainbows —

convex mirror — a real object forms an image that is always virtual, upright, and smaller than the object ($0 < M < 1$, where M is the lateral magnification). $M = (-f)/(p - f) < 1$, where $f < 0$ is the focal length.

lateral magnification — $M = \frac{h'}{h} = -\frac{q}{p}$;

7 Thermodynamics & Statistical Mechanics

Timeline

1824 CARNOT proves the maximum efficiency of a reversible engine

1842 MAYER proves the equivalence of work and heat

1851 KELVIN proposes a 'dynamics theory of heat'

Celsius, Anders (1701-1744) — Swedish astronomer; performed the first careful experiments investigating the dependence of the freezing and boiling points of water on atmospheric pressure. His original scale had 0 for the boiling point and 100 for the freezing point.

Carnot, Sadi (1796-1832) —

Mayer, Julius (1814-1878) — physicist; first enunciated the principle of the conservation of energy, 1841.

Maxwell, James Clerk (1831-1879) — English physicist; unifier of electric and magnetic theories, and developer of statistical thermodynamics.

Boltzmann, Ludwig (1844-1906) — theoretical physicist; one of the first to believe in the reality of atoms. Committed suicide when his ideas were not well received.

Gibbs, Josiah Willard (1839-1903) — American mathematical physicist; developed statistical mechanics and thermodynamics.

Clausius, Rudolf (1822-1888) — physicist; formulated the 2nd Law of Thermodynamics in 1865.

Nernst, Walther (1864-1941) — developed the third law of thermodynamics, using quantum principles.

Rumford (Thomson) —
Clapeyron —
Kelvin
Joule
Maxwell
Helmholtz
Gibbs

Thermodynamics

state variable — a quantity that takes on the same value whenever the system is in a particular "state." Examples: pressure, volume, temperature, internal energy, entropy.

caloric —

equipartition theorem — each DEGREE OF FREEDOM has, on average, $\frac{1}{2}kT$ of energy; for example, there are three translational degrees of freedom (x, y, and z) so that the average kinetic energy of a molecule of a monatomic gas is $\frac{3}{2}kT$. Both the IDEAL GAS LAW and the LAW OF DULONG AND PETIT can be derived assuming equipartition.

virial theorem — ; first stated by Clausius in 1870.

degree of freedom — a motion in which a system is free to move.

heat capacity — the heat energy needed to raise the temperature of an object by 1 K. *Objects* have a heat capacity, whereas *materials* have a SPECIFIC HEAT CAPACITY.

specific heat capacity — $c = dQ/mdT$; the ratio of the (heat) energy added to the temperature increase per-unit-mass. Sometimes called just "specific heat." In general, c is a function of T, so that the correct expression for the heat energy is an integral

$$Q = \int m\, c(T)\, dT.$$

Units: $[c]$ =J/kg °C (or J/kg K, since the two temperature scales differ only in their calibration values).

molar specific heat capacity — $C = dQ/ndT$; the ratio of the (heat) energy added to the temperature increase per-mole. The statement about the temperature dependence of the SPECIFIC HEAT CAPACITY also applies here. Units: $[c]$ =J/mol °C. Molar heat capacity is useful when dealing with solids and gases.

ideal gas law — $pV = NkT = nRT$; the equation of state applicable to a gas whose constituent molecules interact via billiard-ball type collisions only.

vapor pressure — the pressure of a gas that is in equilibrium with its liquid phase; a function of temperature. Liquids boil when their vapor pressure equals the surrounding gas pressure. Hence, water at 100 °C has a vapor pressure of one atmosphere.

Law of Dulong and Petit — $C = 3R$; In 1819, Dulong and Petit noticed that the molar heat capacity of most solids (at constant volume) is $3R = 24.9$ J/mole K = 6 cal/mol deg. The notable exceptions were diamond powder (i.e., carbon) with $C \approx 1.4$, as well as boron and silicon.

Newton's Law of Cooling — the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings:

$$\frac{dT}{dt} = -\alpha(T - T_s);$$

this is only strictly true in the limit that $T - T_s \approx 0$.

Fick's First Law — $\vec{J} = -D\nabla\phi$; A general relation relating the flux of *stuff* $\vec{J}$ to the gradient of the density of the same stuff ϕ. When the gradient is small, the relationship is linear. Can be applied to numerous situations where *stuff* is mass, electric charge, probability, temperature, etc. In conjunction with the continuity equation, it results in FICK'S SECOND LAW.

Fick's Second Law —

Fourier's Law of heat conduction — Fourier considered how to determine the temperature T in a homogeneous and isotropic body as a function of x, y, z, and t, and proved that it must satisfy the partial differential equation

$$\nabla^2 T = \kappa^2 \frac{\partial T}{\partial t},$$

where κ is a constant that depends on the material of the body. This is the "heat equation." When solving this in one dimension, subject to certain boundary conditions (i.e., the temperatures at the ends of the body) he developed the theory of Fourier series.

Joule's constant — 1 cal = 4.186 J; Also known as "the mechanical equivalent of heat."

reversibility — a reversible process is one where the system *and* its surroundings can be brought back to their original state. There are two required conditions: (a) no dissipative forces which produce heat (i.e., friction), and (b) no heat conduction due to finite temperature differences. Note, this does not mean that the system returns to its original state spontaneously, but only that such a return can be arranged.

entropy — $S = k \ln w$; where w is the multiplicity of microstates. Classically, in 1865 Rudolf Clausius defined a function S by

$$S = S_0 + \int \frac{dQ}{T},$$

and showed that the integral was path independent — hence, S is a state variable. In his talk on 24 April to the Zurich Society of Natural Scientists, he stated

> "If one looks for a name that would characterize S, then—in analogy to the way one says the the quantity U is the heat- and work-content of the body—one could say that the quantity S is the transformation content [*Verwandlungsinhalt* in German] of the body. I consider it better, however, to extract the names for such scientifically important quantities from the classical languages, so that they can be applied without change in all modern languages; therefore, I propose to name the quantity S the entropy [*Entropie*] after the Greek word $\eta\ \tau\rho o\pi\eta$, the transformation. I have intentionally constructed the word entropy to be as similar as possible to the word energy [*Energie*] because the two quantities, which are to be known by these words, are so nearly related in their physical significance that a certain similarity in the naming seems appropriate."

blackbody radiation spectrum — Max Planck, using the idea of quantized energy, predicted the correct spectrum for radiation from a perfect blackbody

$$R(\lambda)d\lambda =$$

8 Electrodynamics

Faraday
Biot
Savart
Maxwell
conductivity — σ, a measure of how freely charges move within a material.
conductor — a material in which electrons, and any excess charge, is free to move. It also satisfies OHM'S LAW.
insulator — the opposite of a conductor, charge is not free to move. In general, it also satisfies Ohm's Law, but with a low conductivity.
Ohm's Law — An approximation, good for many materials, where the current density is proportional to the applied electric field $\vec{j} = \sigma\vec{E}$. When integrated over the cross section of a conducting wire, the more familiar form is obtained, $V = IR$.
resistivity — $\rho = 1/\sigma$, the inverse of the CONDUCTIVITY.
variation of resistance with temperature —
Volta effect —
Kerr effect —
Faraday rotation —
Coulomb's Law —
Laplace's electromagnetic type of interaction (?) — see experiments of Jean Perrin

Modern Physics

"Old Quantum Theory"

Principle of complementarity — Bohr's assertion that a complete physical description must include both the wave and particle properties of an object.
Heinsenberg indeterminacy relationships — $\Delta x \Delta p_x \leq \hbar/2$; in general, any two canonically conjugate variables satisfy this relationship.
de Broglie wavelength — $\lambda = h/p$;
electron diffraction —
Davisson-Germer experiment —
Bohr model — E_n and r_n etc
de Broglie wavelength — h/p;
Davisson-Germer experiment — the 1927 confirmation of de Broglie's hypothesis.
Heisenberg inequalities — also known as the uncertainty relations
Compton wavelength — h/mc; the wavelength shift in a Compton effect experiment. For an electron, this wavelength is 2.426×10^{-12} m.
de Broglie wavelength — h/p;
Zeeman effect —

anomalous Zeeman effect —

Franck-Hertz experiment — in 1914, James Franck and Gustav Hertz fired electrons through mercury vapor and found that the current was sharply reduced at potentials that matched energy-level shifts in mercury. They were awarded the Nobel Prize in Physics in 1925.

Stern-Gerlach experiment —

Quantum Mechanics

Schrodinger equation — the time-dependent version is

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + U(\vec{r})\Psi,$$

where $\Psi(\vec{r},t)$. Applying the technique of "separation of variables," i.e., assuming $\Psi(\vec{r},t) = \psi(\vec{r})f(t)$ is a product of two functions, each only of one variable, one obtains the time-independent Schrodinger equation

$$H\psi = E\psi,$$

where

$$H \equiv -\frac{\hbar^2}{2m}\nabla^2 + U(\vec{r})$$

is a differential operator, called the HAMILTONIAN.

Hamiltonian — in quantum mechanics, an operator representing the total energy of a particle.

wave function — $\Psi(\vec{r},t)$;

probability density — $|\Psi|^2$;

probability

particle-in-a-box — energy levels are given by $E = \frac{\hbar^2\pi^2}{2mL^2}n^2$

wave packet —

phase velocity — $\lambda\nu = \omega/k$;

group velocity — $d\omega/dk$; the speed at which a WAVE PACKET moves that consists of many wavelengths.

spin —

fine structure —

hyperfine structure —

1D infinite square well — also known as a "particle in a box"; The energies are

$$E_n = \frac{\hbar^2\pi^2}{2mL^2}\,n^2$$

and the wave functions are

$$\psi_n(x) = \sqrt{\frac{2}{L}}\,\sin\left(\frac{n\pi x}{L}\right)$$

Compton effect — light scattering off free electrons that requires the particle picture of light for a correct explanation; The scattered photons, in order to conserve energy and momentum, must emerge with a smaller wavelength (rather than a lower intensity as the wave picture predicts)

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

where $h/m_e c$ is the "Compton wavelength" of the electron.

Larmor precession — a particle in an external magnetic field experiences a torque due to that field which makes its magnetic moment moment precess at a frequency $\omega = geB/2m$, where g is its gyromagnetic ratio, and B is the strength of the external field.

Special Relativity

aberration of starlight —

Nuclear Physics & Radioactivity

isotope —
isomer —
isotone —
Chadwick —-
Chadwick's experiment — no new physics but new interpretattion. $\alpha + Be \rightarrow X + n$ n induces protons to eject from parrafin.
alpha particle —

Atomism

Law of constant proportions —
Law of multiple proportions —
Brownian motion —
Mendeleev's periodic table —

Miscellaneous

decibel scale —
Lorentz-Lorenz law —
Clausius-Mossotti formula —
betatron acceleration
Raman scattering
Fraunhofer diffraction
Fresnel diffraction
Golden ratio
geodesy
radiance

irradiance —

luminescence — emission of light by means other than COMBUSTION or INCANDESCENCE. An atom is excited and when the electron returns to a lower energy level, it emits a photon. If this takes a short time: FLUORESCENCE (e.g., television screen). If this takes a long time: PHOSPHORESCENCE. NOTE: fluorescent lamps are filled with argon gas and mercury vapor, and they are coated with a fluorescent material, e.g., phosphor powder. The mercury emits UV radiation, and the phosphor converts this to visible.

Pederson conductivity —

aerosol — a suspension of solid or liquid particles in a gas. They tend to disperse rather than settle. True aerosols are 10^{-7} - 10^{-4} cm in diameter,m e.g., smoke, dist fog, smog. Turbulence keeps $d < 10^{-2}$ cm dispersed.

Ramsauer-Townsend effect — scattering resonance of low energy (a few eV) electrons off noble atoms.

combustion — rapid oxidation

incandescence — light by heated materials

UV-B — wavelength range 290 - 330 nm

Lecher line — two parallel conducting wires used as elements in resonant circuits.

Jacob's ladder

van de graff generator

Voltaic pile — first modern battery; invented by Alessandro Volta in 1800.

electrostatic precipitator

golden ratio — the most "pleasing" aspect ratio of a rectangle

divine proportion — see GOLDEN RATIO.

Space Physics

invariant latitude — Λ; the latitude at which a given magnetic field line intersects the Earth's surface. For a pure DIPOLE FIELD, $\cos^2\Lambda = L$, where L is MCILWAIN'S L PARAMETER, and labels the equatorial position (in units of the Earth's radius) of the particular magnetic field line.

dipole field —

McIlwain's L parameter —

Fermi acceleration —

betatron acceleration —

Chapman-Ferraro layer —- magnetopause

pick-up ion — Photoionization of a neutral atom (from a planet or comet) forms ions. These low-energy ions are accelerated in the solar wind electric field direction, and they also execute cyclotron motion in the solar wind magnetic field. The combined motion is cycloidal in the direction of the solar wind, so they speed up and slow down over one cyclotron period.

Advanced Mechanics

calculus of variations — The main problem of this field can be stated as follows. Given a functional

$$J = \int_{t_1}^{t_2} f(y, \dot{y}, t) dt,$$

for which you wish to find the extremum, where $y(t)$ and $\dot{y} = dy/dt$, the function $y(t)$ that makes J an extremum (locally with respect to "nearby" functions) is given by the solution to

$$\frac{\partial f}{\partial y} - \frac{d}{dt}\frac{\partial f}{\partial \dot{y}} = 0.$$

This last equation is called Euler's equation in general, and Lagrange's equation when applied to mechanical situations where the function f is taken to be the Lagrangian L.

irrational number —

transcendental number —

algebraic number —

complex number —

Advanced Mathematics

Fundamental theorem of algebra —

> If P is any polynomial function of degree $n > 0$ with complex coefficients, then P has a zero that is a complex number.

A related theorem that is more useful is

> If the polynomial P is real coefficients and $P(a + bi) = 0$, with $b \neq 0$, then $P(a - bi) = 0$.

Euler's identity — $e^{i\pi} + 1 = 0$; Sometimes called the most beautiful equation ever. However, there is some question if Euler derived this. Certainly, he knew of it, but some think he learned it from Johann Bernoulli, and it is thought that Cotes derived it before either of them. In any case, it is one of my favorite equations.

fundamental lemma of the calculus of variations — if $\int_{t_1}^{t_2} M(t)\eta(t)dt = 0$ for all *arbitrary* functions $\eta(t)$ that are continuous, then $M(t)$ must vanish identically in the interval (x_1, x_2).

dyad — a juxtaposition of two vectors $\vec{A}\vec{B}$; see Symon p 403.