中国科技大学物理学院

物理学专业英语

仅供内部学习参考！

2014

目 录

正文标记说明：

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蓝色 Arial 字体加下划线（例如 electromagnetism）：新学的专业词汇

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1 Physics 物理学

Introduction to physics

Physics is a part of natural philosophy and a natural science that involves the study of matter and its motion through space and time, along with related concepts such as energy and force. More broadly, it is the general analysis of nature, conducted in order to understand how the universe behaves.

Physics is one of the oldest academic disciplines, perhaps the oldest through its inclusion of astronomy. Over the last two millennia, physics was a part of natural philosophy along with chemistry, certain branches of mathematics, and biology, but during the Scientific Revolution in the 17th century, the natural sciences emerged as unique research programs in their own right. Physics intersects with many interdisciplinary areas of research, such as biophysics and quantum chemistry, and the boundaries of physics are not rigidly defined. New ideas in physics often explain the fundamental mechanisms of other sciences, while opening new avenues of research in areas such as mathematics and philosophy.

Physics also makes significant contributions through advances in new technologies that arise from theoretical breakthroughs. For example, advances in the understanding of electromagnetism or nuclear physics led directly to the development of new products which have dramatically transformed modern-day society, such as television, computers, domestic appliances, and nuclear weapons; advances in thermodynamics led to the development of industrialization; and advances in mechanics inspired the development of calculus.

Core theories

Though physics deals with a wide variety of systems, certain theories are used by all physicists. Each of these theories were experimentally tested numerous times and found correct as an approximation of nature (within a certain domain of validity).

For instance, the theory of classical mechanics accurately describes the motion of objects, provided they are much larger than atoms and moving at much less than the speed of light. These theories continue to be areas of active research, and a remarkable aspect of classical mechanics known as chaos was discovered in the 20th century, three centuries after the original formulation of classical mechanics by Isaac Newton (1642–1727) 【艾萨克·牛顿】.

These central theories are important tools for research into more specialized topics, and any physicist, regardless of his or her specialization, is expected to be literate in them. These include classical mechanics, quantum mechanics, thermodynamics and statistical mechanics, electromagnetism, and special relativity.

Classical and modern physics

Classical mechanics

Classical physics includes the traditional branches and topics that were recognized and well-developed before the beginning of the 20th century—classical mechanics, acoustics, optics, thermodynamics, and electromagnetism.

Classical mechanics is concerned with bodies acted on by forces and bodies in motion and may be divided into statics (study of the forces on a body or bodies at rest), kinematics (study of motion without regard to its causes), and dynamics (study of motion and the forces that affect it); mechanics may also be divided into solid mechanics and fluid mechanics (known together as continuum mechanics), the latter including such branches as hydrostatics, hydrodynamics, aerodynamics, and pneumatics.

Acoustics is the study of how sound is produced, controlled, transmitted and received. Important modern branches of acoustics include ultrasonics, the study of sound waves of very high frequency beyond the range of human hearing; bioacoustics the physics of animal calls and hearing, and electroacoustics, the manipulation of audible sound waves using electronics.

Optics, the study of light, is concerned not only with visible light but also with infrared and ultraviolet radiation, which exhibit all of the phenomena of visible light except visibility, e.g., reflection, refraction, interference, diffraction, dispersion, and polarization of light.

Heat is a form of energy, the internal energy possessed by the particles of which a substance is composed; thermodynamics deals with the relationships between heat and other forms of energy.

Electricity and magnetism have been studied as a single branch of physics since the intimate connection between them was discovered in the early 19th century; an electric current gives rise to a magnetic field and a changing magnetic field induces an electric current. Electrostatics deals with electric charges at rest, electrodynamics with moving charges, and magnetostatics with magnetic poles at rest.

Modern Physics

Classical physics is generally concerned with matter and energy on the normal scale of

observation, while much of modern physics is concerned with the behavior of matter and energy under extreme conditions or on the very large or very small scale.

For example, atomic and nuclear physics studies matter on the smallest scale at which chemical elements can be identified.

The physics of elementary particles is on an even smaller scale, as it is concerned with the most basic units of matter; this branch of physics is also known as high-energy physics because of the extremely high energies necessary to produce many types of particles in large particle accelerators. On this scale, ordinary, commonsense notions of space, time, matter, and energy are no longer valid.

The two chief theories of modern physics present a different picture of the concepts of space, time, and matter from that presented by classical physics.

Quantum theory is concerned with the discrete, rather than continuous, nature of many phenomena at the atomic and subatomic level, and with the complementary aspects of particles and waves in the description of such phenomena.

The theory of relativity is concerned with the description of phenomena that take place in a frame of reference that is in motion with respect to an observer; the special theory of relativity is concerned with relative uniform motion in a straight line and the general theory of relativity with accelerated motion and its connection with gravitation.

Both quantum theory and the theory of relativity find applications in all areas of modern physics.

Difference between classical and modern physics

While physics aims to discover universal laws, its theories lie in explicit domains of applicability. Loosely speaking, the laws of classical physics accurately describe systems whose important length scales are greater than the atomic scale and whose motions are much slower than the speed of light. Outside of this domain, observations do not match their predictions.

Albert Einstein【阿尔伯特·爱因斯坦】 contributed the framework of special relativity, which replaced notions of absolute time and space with space-time and allowed an accurate description of systems whose components have speeds approaching the speed of light.

Max Planck【普朗克】, Erwin Schrödinger【薛定谔】, and others introduced quantum mechanics, a probabilistic notion of particles and interactions that allowed an accurate description of atomic and subatomic scales.

Later, quantum field theory unified quantum mechanics and special relativity.

General relativity allowed for a dynamical, curved space-time, with which highly massive

systems and the large-scale structure of the universe can be well-described. General relativity has not yet been unified with the other fundamental descriptions; several candidate theories of quantum gravity are being developed.

Research fields

Contemporary research in physics can be broadly divided into condensed matter physics; atomic, molecular, and optical physics; particle physics; astrophysics; geophysics and biophysics. Some physics departments also support research in Physics education.

Since the 20th century, the individual fields of physics have become increasingly specialized, and today most physicists work in a single field for their entire careers. "Universalists" such as Albert Einstein (1879–1955) and Lev Landau (1908–1968)【列夫 •朗道】, who worked in multiple fields of physics, are now very rare.

Condensed matter physics

Condensed matter physics is the field of physics that deals with the macroscopic physical properties of matter. In particular, it is concerned with the "condensed" phases that appear whenever the number of particles in a system is extremely large and the interactions between them are strong.

The most familiar examples of condensed phases are solids and liquids, which arise from the bonding by way of the electromagnetic force between atoms. More exotic condensed phases include the super-fluid and the Bose–Einstein condensate found in certain atomic systems at very low temperature, the superconducting phase exhibited by conduction electrons in certain materials, and the ferromagnetic and antiferromagnetic phases of spins on atomic lattices.

Condensed matter physics is by far the largest field of contemporary physics.

Historically, condensed matter physics grew out of solid-state physics, which is now considered one of its main subfields. The term *condensed matter physics* was apparently coined by Philip Anderson when he renamed his research group—previously *solid-state theory*—in 1967. In 1978, the Division of Solid State Physics of the American Physical Society was renamed as the Division of Condensed Matter Physics.

Condensed matter physics has a large overlap with chemistry, materials science, nanotechnology and engineering.

Atomic, molecular and optical physics

Atomic, molecular, and optical physics (AMO) is the study of matter–matter and light–matter interactions on the scale of single atoms and molecules.

The three areas are grouped together because of their interrelationships, the similarity of methods used, and the commonality of the energy scales that are relevant. All three areas include both classical, semi-classical and quantum treatments; they can treat their subject from a microscopic view (in contrast to a macroscopic view).

Atomic physics studies the electron shells of atoms. Current research focuses on activities in quantum control, cooling and trapping of atoms and ions, low-temperature collision dynamics and the effects of electron correlation on structure and dynamics. Atomic physics is influenced by the nucleus (see, e.g., hyperfine splitting), but intra-nuclear phenomena such as fission and fusion are considered part of high-energy physics.

Molecular physics focuses on multi-atomic structures and their internal and external interactions with matter and light.

Optical physics is distinct from optics in that it tends to focus not on the control of classical light fields by macroscopic objects, but on the fundamental properties of optical fields and their interactions with matter in the microscopic realm.

High-energy physics (particle physics) and nuclear physics

Particle physics is the study of the elementary constituents of matter and energy, and the interactions between them. In addition, particle physicists design and develop the high energy accelerators, detectors, and computer programs necessary for this research. The field is also called "high-energy physics" because many elementary particles do not occur naturally, but are created only during high-energy collisions of other particles.

Currently, the interactions of elementary particles and fields are described by the Standard Model.

- The model accounts for the 12 known particles of matter (quarks and leptons) that interact via the strong, weak, and electromagnetic fundamental forces.
- Dynamics are described in terms of matter particles exchanging gauge bosons (gluons, W and Z bosons, and photons, respectively).
- The Standard Model also predicts a particle known as the Higgs boson. In July 2012 CERN, the European laboratory for particle physics, announced the detection of a particle consistent with the Higgs boson.

Nuclear Physics is the field of physics that studies the constituents and interactions of atomic nuclei. The most commonly known applications of nuclear physics are nuclear power generation and nuclear weapons technology, but the research has provided application in many fields, including those in nuclear medicine and magnetic resonance imaging, ion implantation in materials engineering, and radiocarbon dating in geology and archaeology.

Astrophysics and Physical Cosmology

Astrophysics and astronomy are the application of the theories and methods of physics to the study of stellar structure, stellar evolution, the origin of the solar system, and related problems of cosmology. Because astrophysics is a broad subject, astrophysicists typically apply many disciplines of physics, including mechanics, electromagnetism, statistical mechanics, thermodynamics, quantum mechanics, relativity, nuclear and particle physics, and atomic and molecular physics.

The discovery by Karl Jansky in 1931 that radio signals were emitted by celestial bodies initiated the science of radio astronomy. Most recently, the frontiers of astronomy have been expanded by space exploration. Perturbations and interference from the earth's atmosphere make space-based observations necessary for infrared, ultraviolet, gamma-ray, and X-ray astronomy.

Physical cosmology is the study of the formation and evolution of the universe on its largest scales. Albert Einstein's theory of relativity plays a central role in all modern cosmological theories. In the early 20th century, Hubble's discovery that the universe was **expanding**, as shown by the Hubble diagram, prompted rival explanations known as the steady state universe and the Big Bang.

The Big Bang was confirmed by the success of Big Bang nucleo-synthesis and the discovery of the cosmic microwave background in 1964. The Big Bang model rests on two theoretical pillars: Albert Einstein's general relativity and the cosmological principle (On a sufficiently large scale, the properties of the Universe are the same for all observers). Cosmologists have recently established the Λ CDM model (the standard model of Big Bang cosmology) of the evolution of the universe, which includes cosmic inflation, dark energy and dark matter.

Current research frontiers

In condensed matter physics, an important unsolved theoretical problem is that of high-temperature superconductivity. Many condensed matter experiments are aiming to fabricate workable spintronics and quantum computers.

In particle physics, the first pieces of experimental evidence for physics beyond the Standard Model have begun to appear. Foremost among these are indications that neutrinos have non-zero mass. These experimental results appear to have solved the long-standing solar neutrino problem, and the physics of massive neutrinos remains an area of active theoretical and experimental research. Particle accelerators have begun probing energy scales in the TeV range, in which experimentalists are hoping to find evidence for the super-symmetric particles, after discovery of the Higgs boson.

Theoretical attempts to unify quantum mechanics and general relativity into a single theory

of quantum gravity, a program ongoing for over half a century, have not yet been decisively resolved. The current leading candidates are M-theory, superstring theory and loop quantum gravity.

Many astronomical and cosmological phenomena have yet to be satisfactorily explained, including the existence of ultra-high energy cosmic rays, the baryon asymmetry, the acceleration of the universe and the anomalous rotation rates of galaxies.

Although much progress has been made in high-energy, quantum, and astronomical physics, many everyday phenomena involving complexity, chaos, or turbulence are still poorly understood. Complex problems that seem like they could be solved by a clever application of dynamics and mechanics remain unsolved; examples include the formation of sand-piles, nodes in trickling water, the shape of water droplets, mechanisms of surface tension catastrophes, and self-sorting in shaken heterogeneous collections.

These complex phenomena have received growing attention since the 1970s for several reasons, including the availability of modern mathematical methods and computers, which enabled complex systems to be modeled in new ways. Complex physics has become part of increasingly interdisciplinary research, as exemplified by the study of turbulence in aerodynamics and the observation of pattern formation in biological systems.

Vocabulary

★ natural science 自然科学

academic disciplines 学科

astronomy 天文学

in their own right 凭他们本身的实力

intersects 相交，交叉

interdisciplinary 交叉学科的，跨学科的

★ quantum 量子的

theoretical breakthroughs 理论突破

★ electromagnetism 电磁学

dramatically 显著地

★ thermodynamics 热力学

★ calculus 微积分

validity

★ classical mechanics 经典力学

chaos 混沌

literate 学者

★ quantum mechanics 量子力学

★ thermodynamics and statistical mechanics 热力学与统计物理

★ special relativity 狭义相对论

is concerned with 关注，讨论，考虑

acoustics 声学

★ optics 光学

statics 静力学

at rest 静息

kinematics 运动学

★ dynamics 动力学

ultrasonics 超声学

manipulation 操作，处理，使用

infrared 红外

ultraviolet 紫外

radiation 辐射

reflection 反射

refraction 折射

★ interference 干涉

★ diffraction 衍射

dispersion 散射

★ polarization 极化，偏振

internal energy 内能

Electricity 电性

Magnetism 磁性

intimate 亲密的

induces 诱导，感应

scale 尺度

★ elementary particles 基本粒子

★ high-energy physics 高能物理

particle accelerators 粒子加速器

valid 有效的，正当的

★ discrete 离散的

continuous 连续的

complementary 互补的

★ frame of reference 参照系

★ the special theory of relativity 狭义相对论

★ general theory of relativity 广义相对论

gravitation 重力，万有引力

explicit 详细的，清楚的

★ quantum field theory 量子场论

★ condensed matter physics 凝聚态物理

astrophysics 天体物理

geophysics 地球物理

Universalist 博学多才者

★ Macroscopic 宏观

Exotic 奇异的

★ Superconducting 超导

Ferromagnetic 铁磁质

Antiferromagnetic 反铁磁质

★ Spin 自旋

Lattice 晶格，点阵，网格

★ Society 社会，学会

★ microscopic 微观的

hyperfine splitting 超精细分裂

fission 分裂，裂变

fusion 熔合，聚变

constituents 成分，组分

accelerators 加速器

detectors 检测器

★ quarks 夸克

lepton 轻子

gauge bosons 规范玻色子

gluons 胶子

★ Higgs boson 希格斯玻色子

CERN 欧洲核子研究中心

★ Magnetic Resonance Imaging 磁共振成像，核磁共振

ion implantation 离子注入

radiocarbon dating 放射性碳年代测定法

geology 地质学

archaeology 考古学

stellar 恒星

cosmology 宇宙论

celestial bodies 天体

Hubble diagram 哈勃图

Rival 竞争的

★ Big Bang 大爆炸

nucleo-synthesis 核聚合，核合成

pillar 支柱

cosmological principle 宇宙学原理

ΛCDM model Λ-冷暗物质模型

cosmic inflation 宇宙膨胀

fabricate 制造，建造

spintronics 自旋电子元件，自旋电子学

★ neutrinos 中微子

superstring 超弦

baryon 重子

turbulence 湍流，扰动，骚动

catastrophes 突变，灾变，灾难

heterogeneous collections 异质性集合

pattern formation 模式形成

2 Classical mechanics 经典力学

Introduction

In physics, classical mechanics is one of the two major sub-fields of mechanics, which is concerned with the set of physical laws describing the motion of bodies under the action of a system of forces. The study of the motion of bodies is an ancient one, making classical mechanics one of the oldest and largest subjects in science, engineering and technology.

Classical mechanics describes the motion of macroscopic objects, from projectiles to parts of machinery, as well as astronomical objects, such as spacecraft, planets, stars, and galaxies. Besides this, many specializations within the subject deal with gases, liquids, solids, and other specific sub-topics.

Classical mechanics provides extremely accurate results as long as the domain of study is restricted to large objects and the speeds involved do not approach the speed of light. When the objects being dealt with become sufficiently small, it becomes necessary to introduce the other major sub-field of mechanics, quantum mechanics, which reconciles the macroscopic laws of physics with the atomic nature of matter and handles the wave–particle duality of atoms and molecules. In the case of high velocity objects approaching the speed of light, classical mechanics is enhanced by special relativity. General relativity unifies special relativity with Newton's law of universal gravitation, allowing physicists to handle gravitation at a deeper level.

The initial stage in the development of classical mechanics is often referred to as Newtonian mechanics, and is associated with the physical concepts employed by and the mathematical methods invented by Newton himself, in parallel with Leibniz【莱布尼兹】, and others.

Later, more abstract and general methods were developed, leading to reformulations of classical mechanics known as Lagrangian mechanics and Hamiltonian mechanics. These advances were largely made in the 18th and 19th centuries, and they extend substantially beyond Newton's work, particularly through their use of analytical mechanics. Ultimately, the mathematics developed for these were central to the creation of quantum mechanics.

Description of classical mechanics

The following introduces the basic concepts of classical mechanics. For simplicity, it often

models real-world objects as point particles, objects with negligible size. The motion of a point particle is characterized by a small number of parameters: its position, mass, and the forces applied to it.

In reality, the kind of objects that classical mechanics can describe always have a non-zero size. (The physics of *very* small particles, such as the electron, is more accurately described by quantum mechanics). Objects with non-zero size have more complicated behavior than hypothetical point particles, because of the additional degrees of freedom—for example, a baseball can spin while it is moving. However, the results for point particles can be used to study such objects by treating them as composite objects, made up of a large number of interacting point particles. The center of mass of a composite object behaves like a point particle.

Classical mechanics uses common-sense notions of how matter and forces exist and interact. It assumes that matter and energy have definite, knowable attributes such as where an object is in space and its speed. It also assumes that objects may be directly influenced only by their immediate surroundings, known as the principle of locality.

In quantum mechanics objects may have unknowable position or velocity, or instantaneously interact with other objects at a distance.

Position and its derivatives

The *position* of a point particle is defined with respect to an arbitrary fixed reference point, *O*, in space, usually accompanied by a coordinate system, with the reference point located at the *origin* of the coordinate system. It is defined as the vector *r* from *O* to the particle.

In general, the point particle need not be stationary relative to *O*, so *r* is a function of *t*, the time elapsed since an arbitrary initial time.

In pre-Einstein relativity (known as Galilean relativity), time is considered an absolute, i.e., the time interval between any given pair of events is the same for all observers. In addition to relying on absolute time, classical mechanics assumes Euclidean geometry for the structure of space.

Velocity and speed

The *velocity*, or the rate of change of position with time, is defined as the derivative of the position with respect to time. In classical mechanics, velocities are directly additive and subtractive as vector quantities; they must be dealt with using vector analysis.

When both objects are moving in the same direction, the difference can be given in terms of speed only by ignoring direction.

Acceleration

The *acceleration*, or rate of change of velocity, is the derivative of the velocity with respect to time (the second derivative of the position with respect to time).

Acceleration can arise from a change with time of the magnitude of the velocity or of the direction of the velocity or both. If only the magnitude *v* of the velocity decreases, this is sometimes referred to as *deceleration*, but generally any change in the velocity with time, including deceleration, is simply referred to as acceleration.

Inertial frames of reference

While the position and velocity and acceleration of a particle can be referred to any observer in any state of motion, classical mechanics assumes the existence of a special family of reference frames in terms of which the mechanical laws of nature take a comparatively simple form. These special reference frames are called inertial frames.

An inertial frame is such that when an object without any force interactions (an idealized situation) is viewed from it, it appears either to be at rest or in a state of uniform motion in a straight line. This is the fundamental definition of an inertial frame. They are characterized by the requirement that all forces entering the observer's physical laws originate in identifiable sources (charges, gravitational bodies, and so forth).

A non-inertial reference frame is one accelerating with respect to an inertial one, and in such a non-inertial frame a particle is subject to acceleration by fictitious forces that enter the equations of motion solely as a result of its accelerated motion, and do not originate in identifiable sources. These fictitious forces are in addition to the real forces recognized in an inertial frame.

A key concept of inertial frames is the method for identifying them. For practical purposes, reference frames that are un-accelerated with respect to the distant stars are regarded as good approximations to inertial frames.

Forces; Newton's second law

Newton was the first to mathematically express the relationship between force and momentum. Some physicists interpret Newton's second law of motion as a definition of force and mass, while others consider it a fundamental postulate, a law of nature. Either interpretation has the same mathematical consequences, historically known as "Newton's Second Law":

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \frac{\mathrm{d}(m\vec{v})}{\mathrm{d}t} = m\vec{a}$$

The quantity *m***v** is called the (canonical) momentum. The net force on a particle is thus equal to rate of change of momentum of the particle with time.

So long as the force acting on a particle is known, Newton's second law is sufficient to

describe the motion of a particle. Once independent relations for each force acting on a particle are available, they can be substituted into Newton's second law to obtain an ordinary differential equation, which is called the *equation of motion*.

Important forces include the gravitational force and the Lorentz force for electromagnetism.

In addition, Newton's third law can sometimes be used to deduce the forces acting on a particle: if it is known that particle A exerts a force **F** on another particle B, it follows that B must exert an equal and opposite *reaction force*, −**F**, on A. The strong form of Newton's third law requires that **F** and −**F** act along the line connecting A and B, while the weak form does not. Illustrations of the weak form of Newton's third law are often found for magnetic forces.

Work and energy

If a constant force **F** is applied to a particle that achieves a displacement Δ**r**, the *work* done by the force is defined as the scalar product of the force and displacement vectors.

More generally, if the force varies as a function of position as the particle moves from r_1 to r_2 along a path C, the work done on the particle is given by the line integral

$$W = \int_C \vec{F}(\vec{r}) \cdot \mathrm{d}\vec{r}$$

If the work done in moving the particle from r_1 to r_2 is the same no matter what path is taken, the force is said to be conservative. Gravity is a conservative force, as is the force due to an idealized spring, as given by Hooke's law. The force due to friction is non-conservative.

The kinetic energy E_k of a particle of mass m travelling at speed v is given by

$$E_K = \frac{1}{2}mv^2$$

For extended objects composed of many particles, the kinetic energy of the composite body is the sum of the kinetic energies of the particles.

The work–energy theorem states that for a particle of constant mass m the total work W done on the particle from position r_1 to r_2 is equal to the change in kinetic energy E_k of the particle.

Conservative forces can be expressed as the gradient of a scalar function, known as the potential energy and denoted E_p

$$\vec{F} = -\nabla E_P$$

If all the forces acting on a particle are conservative, and E_p is the total potential energy (which is defined as a work of involved forces to rearrange mutual positions of bodies), obtained by summing the potential energies corresponding to each force, then the total energy is constant in time. This result is known as *conservation of energy*.

It is often useful, because many commonly encountered forces are conservative.

Momentum and collisions

Momentum

In classical mechanics, **linear momentum** or **translational momentum** (*pl.* momenta; SI unit kg m/s, or equivalently, N s) is the product of the mass and velocity of an object. For example, a heavy truck moving fast has a large momentum—it takes a large and prolonged force to get the truck up to this speed, and it takes a large and prolonged force to bring it to a stop afterwards. If the truck were lighter, or moving more slowly, then it would have less momentum.

Like velocity, linear momentum is a vector quantity, possessing a direction as well as a magnitude:

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

Linear momentum is also a conserved quantity, meaning that if a closed system is not affected by external forces, its total linear momentum cannot change. In classical mechanics, conservation of linear momentum is implied by Newton's laws; but it also holds in special relativity (with a modified formula) and, with appropriate definitions, a (generalized) linear momentum conservation law holds in electrodynamics, quantum mechanics, quantum field theory, and general relativity.

The momentum of a system of particles is the vector sum of their momenta.

A system of particles has a center of mass, a point determined by the weighted sum of their positions:

$$r_{\text{cm}} = \frac{m_1 r_1 + m_2 r_2 + \cdots}{m_1 + m_2 + \cdots}.$$

If all the particles are moving, the center of mass will generally be moving as well. If the center of mass is moving at velocity v_{cm}, the momentum is:

$$\mathbf{p} = m\mathbf{v}_{\text{cm}}$$

This is known as Euler's first law.

Application to collisions

By itself, the law of conservation of momentum is not enough to determine the motion of particles after a collision. Another property of the motion, kinetic energy, must be known. This is not necessarily conserved. If it is conserved, the collision is called an *elastic collision*; if not, it is an *inelastic collision*.

An elastic collision is one in which no kinetic energy is lost. Perfectly elastic "collisions" can occur when the objects do not touch each other, as for example in atomic or nuclear scattering where electric repulsion keeps them apart. A slingshot maneuver of a satellite around a planet can

also be viewed as a perfectly elastic collision from a distance. A collision between two pool balls is a good example of an *almost* totally elastic collision, due to their high rigidity; but when bodies come in contact there is always some dissipation.

In an inelastic collision, some of the kinetic energy of the colliding bodies is converted into other forms of energy such as heat or sound. Examples include traffic collisions, in which the effect of lost kinetic energy can be seen in the damage to the vehicles; electrons losing some of their energy to atoms; and particle accelerators in which the kinetic energy is converted into mass in the form of new particles.

In a perfectly inelastic collision (such as a bug hitting a windshield), both bodies have the same motion afterwards.

Angular momentum

In physics, **angular momentum**, **moment of momentum**, or **rotational momentum** is a vector quantity that represents the product of a body's rotational inertia and rotational velocity about a particular axis. The angular momentum of a system of particles (e.g. a rigid body) is the sum of angular momenta of the individual particles. For a rigid body rotating around an axis of symmetry (e.g. the blades of a ceiling fan), the angular momentum can be expressed as the product of the body's moment of inertia, I, (i.e., a measure of an object's resistance to changes in its rotation velocity) and its angular velocity $\boldsymbol{\omega}$:

$$\mathbf{L} = I\boldsymbol{\omega}.$$

In this way, angular momentum is sometimes described as the rotational analog of linear momentum.

For the case of an object that is small compared with the radial distance to its axis of rotation, such as a tin can swinging from a long string or a planet orbiting in a circle around the Sun, the angular momentum can be expressed as its linear momentum, $m\mathbf{v}$, crossed by its position from the origin, $\boldsymbol{r}$. Thus, the angular momentum $\mathbf{L}$ of a particle with respect to some point of origin is

$$\mathbf{L} = \mathbf{r} \times m\mathbf{v}.$$

Because of the cross product, $\mathbf{L}$ is a pseudo-vector perpendicular to both the radial vector $\boldsymbol{r}$ and the momentum vector $\boldsymbol{p}$ and it is assigned a sign by the right-hand rule.

Angular momentum is conserved in a system where there is no net external torque, and its conservation helps explain many diverse phenomena. For example, the increase in rotational speed of a spinning figure skater as the skater's arms are contracted is a consequence of conservation of angular momentum. The very high rotational rates of neutron stars can also be explained in terms of angular momentum conservation. Moreover, angular momentum conservation has numerous

applications in physics and engineering (e.g., the gyrocompass).

Conservation of angular momentum

The **law of conservation of angular momentum** states that when no external torque acts on an object or a closed system of objects, no change of angular momentum can occur. Hence, the angular momentum before an event involving only internal torques or no torques is equal to the angular momentum after the event. This conservation law mathematically follows from isotropy, or continuous directional symmetry of space (no direction in space is any different from any other direction).

The time derivative of angular momentum is called torque:

$$\tau = \frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} \times \mathbf{p} + \mathbf{r} \times \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = 0 + \mathbf{r} \times \mathbf{F} = \mathbf{r} \times \mathbf{F}$$

So requiring the system to be "closed" here is mathematically equivalent to zero external torque acting on the system:

$$\mathbf{L}_{\text{system}} = \text{constant} \leftrightarrow \sum \tau_{\text{ext}} = 0$$

The conservation of angular momentum is used extensively in analyzing what is called *central force motion*. If the net force on some body is directed always toward some fixed point, the *center*, then there is no torque on the body with respect to the center, and so the angular momentum of the body about the center is constant. Constant angular momentum is extremely useful when dealing with the orbits of planets and satellites, and also when analyzing the Bohr model of the atom.

The conservation of angular momentum explains the angular acceleration of an ice skater as she brings her arms and legs close to the vertical axis of rotation. By bringing part of mass of her body closer to the axis she decreases her body's moment of inertia. Because angular momentum is constant in the absence of external torques, the angular velocity (rotational speed) of the skater has to increase.

The same phenomenon results in extremely fast spin of compact stars (like white dwarfs, neutron stars and black holes) when they are formed out of much larger and slower rotating stars (indeed, decreasing the size of object 10^4 times results in increase of its angular velocity by the factor 10^8).

Vocabulary

classical mechanics 经典力学　　　　　　reconcile 调整，使和谐

projectiles 抛体　　　　　　　　　　　wave–particle duality 波粒二象性

quantum mechanics 量子力学　　　　　　Newtonian mechanics 牛顿力学

Lagrangian mechanics 拉格朗日力学

Hamiltonian mechanics 哈密顿力学

Substantially 实质上地

analytical mechanics 分析力学

point particles 质点

degrees of freedom 自由度

assumes 假定

★ with respect to 相对于，关于，考虑到

★ arbitrary 任意的

reference point 参考点

★ coordinate system 坐标系

★ vector 矢量

Euclidean geometry 欧几里德几何

★ Velocity 速度

★ derivative 导数

★ acceleration 加速度

★ magnitude 强度

deceleration 减速度

reference frames 参照系

inertial frames 惯性系

fictitious forces 虚拟力

★ momentum 动量 （复数：momenta）

postulate 先决条件，基本原理，假定

Interpretation 阐释

★ canonical 正则的，典型的

ordinary differential equation 常微分方程

Lorentz force 洛仑兹力

★ exerts 施加

★ Illustrations 解说

Work 功

scalar product 标积

line integral 线积分

★ conservative 保守的

★ kinetic energy 内能

★ theorem 原理

★ State 状态，说明，规定

Gradient 梯度，斜率

 conservation of energy.能量守恒

translational momentum 平动动量

★ Imply 意味着，隐含，暗示

Euler's first law 尤拉第一定律

elastic collision 弹性碰撞

scattering 散射

Repulsion 排斥

slingshot maneuver 弹弓机动

dissipation 耗散，浪费，损耗

windshield 挡风玻璃

★ angular momentum 角动量

moment of momentum 动量矩

rotational momentum 转动动量

tin 罐头

crossed 叉乘

★ Pseudo- 伪的，假的

Torque 转矩

gyrocompass 回转罗盘

★ Isotropy 各向同性

central force motion 向心力运动

★ results in 导致结果是

3 Thermodynamics 热力学

Introduction

Thermodynamics is a branch of natural science concerned with heat and its relation to energy and work. It defines macroscopic variables (such as temperature, internal energy, entropy, and pressure) that characterize materials and radiation, and explains how they are related and by what laws they change with time. Thermodynamics describes the average behavior of very large numbers of microscopic constituents, and its laws can be derived from statistical mechanics.

Thermodynamics applies to a wide variety of topics in science and engineering—such as engines, phase transitions, chemical reactions, transport phenomena, and even black holes. Results of thermodynamic calculations are essential for other fields of physics and for chemistry, chemical engineering, aerospace engineering, mechanical engineering, cell biology, biomedical engineering, and materials science—and useful in other fields such as economics.

Much of the empirical content of thermodynamics is contained in the four laws.

The first law asserts the existence of a quantity called the internal energy of a system, which is distinguishable from the kinetic energy of bulk movement of the system and from its potential energy with respect to its surroundings. The first law distinguishes transfers of energy between closed systems as heat and as work.

The second law concerns two quantities called temperature and entropy. Entropy expresses the limitations, arising from what is known as irreversibility, on the amount of thermodynamic work that can be delivered to an external system by a thermodynamic process. Temperature, whose properties are also partially described by the zeroth law of thermodynamics, quantifies the direction of energy flow as heat between two systems in thermal contact and quantifies the common-sense notions of "hot" and "cold".

Historically, thermodynamics developed out of a desire to increase the efficiency of early steam engines, particularly through the work of French physicist Nicolas Léonard Sadi Carnot (1824)【卡诺】. Irish-born British physicist Lord Kelvin【开尔文勋爵】 was the first to formulate a concise definition of thermodynamics in 1854:

> *Thermo-dynamics is the subject of the relation of heat to forces acting between*
> *contiguous parts of bodies, and the relation of heat to electrical agency.*

Initially, the thermodynamics of heat engines concerned mainly the thermal properties of their 'working materials', such as steam. This concern was then linked to the study of energy transfers in chemical processes, for example to the investigation, published in 1840, of the heats of chemical reactions by Germain Hess, which was not originally explicitly concerned with the relation between energy exchanges by heat and work. Chemical thermodynamics studies the role of entropy in chemical reactions. Also, statistical thermodynamics, or statistical mechanics, gave explanations of macroscopic thermodynamics by statistical predictions of the collective motion of particles based on the mechanics of their microscopic behavior.

The plain term 'thermodynamics' refers to macroscopic description of bodies and processes. "Any reference to atomic constitution is foreign to classical thermodynamics." The qualified term 'statistical thermodynamics' refers to descriptions of bodies and processes in terms of the atomic constitution of matter, mainly described by sets of items all alike, so as to have equal probabilities.

Thermodynamics arose from the study of energy transfers that can be strictly resolved into two distinct components, heat and work, specified by macroscopic variables.

Thermodynamic equilibrium is one of the most important concepts for thermodynamics. The temperature of a system in thermodynamic equilibrium is well defined, and is perhaps the most characteristic quantity of thermodynamics. As the systems and processes of interest are taken further from thermodynamic equilibrium, their exact thermodynamical study becomes more difficult. Relatively simple approximate calculations, however, using the variables of equilibrium thermodynamics, are of much practical value in engineering. In many important practical cases, such as heat engines or refrigerators, the systems consist of many subsystems at different temperatures and pressures. In practice, thermodynamic calculations deal effectively with these complicated dynamic systems provided the equilibrium thermodynamic variables are nearly enough well-defined.

Basic for thermodynamics are the concepts of *system* and *surroundings*. The surroundings of a thermodynamic system consist of physical devices and of other thermodynamic systems that can interact with it. An example of a thermodynamic surrounding is a heat bath, which is considered to be held at a prescribed temperature, regardless of the interactions it might have with the system.

There are two fundamental kinds of physical entity in thermodynamics, states of a system, and thermodynamic processes of a systems. This allows two fundamental approaches to thermodynamic reasoning, that in terms of states of a system, and that in terms of cyclic processes of a system.

A thermodynamic system can be defined in terms of its states. In this way, a thermodynamic system is a macroscopic physical object, explicitly specified in terms of macroscopic physical

and chemical variables that describe its macroscopic properties. The macroscopic state variables of thermodynamics have been recognized in the course of empirical work in physics and chemistry.

A thermodynamic system can also be defined in terms of the processes it can undergo. Of particular interest are cyclic processes. This was the way of the founders of thermodynamics in the first three quarters of the nineteenth century.

For thermodynamics and statistical thermodynamics to apply to a process in a body, it is necessary that the atomic mechanisms of the process fall into just two classes:

- those so rapid that, in the time frame of the process of interest, the atomic states effectively visit all of their accessible range, bringing the system to its state of internal thermodynamic equilibrium; and
- those so slow that their progress can be neglected in the time frame of the process of interest.

The rapid atomic mechanisms mediate the macroscopic changes that are of interest for thermodynamics and statistical thermodynamics, because they quickly bring the system near enough to thermodynamic equilibrium. "When intermediate rates are present, thermodynamics and statistical mechanics cannot be applied." Such intermediate rate atomic processes do not bring the system near enough to thermodynamic equilibrium in the time frame of the macroscopic process of interest. This separation of time scales of atomic processes is a theme that recurs throughout the subject.

For example, classical thermodynamics is characterized by its study of materials that have equations of state or characteristic equations. They express relations between macroscopic mechanical variables and temperature that are reached much more rapidly than the progress of any imposed changes in the surroundings, and are in effect variables of state for thermodynamic equilibrium. They express the constitutive peculiarities of the material of the system. A classical material can usually be described by a function that makes pressure dependent on volume and temperature, the resulting pressure being established much more rapidly than any imposed change of volume or temperature.

Thermodynamic facts can often be explained by viewing macroscopic objects as assemblies of very many microscopic or atomic objects that obey Hamiltonian dynamics. The microscopic or atomic objects exist in species, the objects of each species being all alike. Because of this likeness, statistical methods can be used to account for the macroscopic properties of the thermodynamic system in terms of the properties of the microscopic species. Such explanation is called statistical thermodynamics; also often it is also referred to by the term 'statistical mechanics', though this term can have a wider meaning, referring to 'microscopic objects', such as

economic quantities, that do not obey Hamiltonian dynamics.

Laws of thermodynamics

Thermodynamics <u>states</u> a set of four laws that are valid for all systems that fall within the <u>constraints</u> implied by each. In the various theoretical descriptions of thermodynamics these laws may be expressed in seemingly differing forms, but the most <u>prominent</u> formulations are the following:

- **Zeroth law of thermodynamics**: If two systems are each in thermal equilibrium with a third, they are also in thermal equilibrium with each other.
- **First law of thermodynamics**: The increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by it: ΔU=Q–W.
- **Second law of thermodynamics**: Heat cannot <u>spontaneously</u> <u>flow</u> from a colder location to a hotter location.
- **Third law of thermodynamics**: As a system approaches absolute zero the entropy of the system approaches a minimum value.

Zeroth law of thermodynamics

The zeroth law implies that thermal equilibrium is an equivalence relation on the set of thermodynamic systems under consideration.

Systems are said to be in thermal equilibrium with each other if spontaneous molecular thermal energy exchanges between them do not lead to a net exchange of energy.

This law is <u>tacitly</u> assumed in every measurement of temperature. For two bodies known to be at the same temperature, deciding if they are in thermal equilibrium when put into thermal contact does not require actually bringing them into contact and measuring any changes of their observable properties in time.

In traditional statements, the law provides an empirical definition of temperature and justification for the construction of practical thermometers. In contrast to absolute thermodynamic temperatures, empirical temperatures are measured just by the mechanical properties of bodies, such as their volumes, without <u>reliance</u> on the concepts of energy, entropy or the first, second, or third laws of thermodynamics. Empirical temperatures lead to calorimetry for heat transfer in terms of the mechanical properties of bodies, without reliance on mechanical concepts of energy.

The first law of thermodynamics

The first law of thermodynamics <u>asserts</u> the existence of a state variable for a system, the internal energy, and tells how it changes in thermodynamic processes. The law allows a given internal energy of a system to be reached by any combination of heat and work. It is important that internal energy is a variable of state of the system whereas heat and work are variables that describe processes or changes of the state of systems.

The first law observes that the internal energy of an <u>isolated system</u> obeys the principle of conservation of energy, which states that energy can be transformed (changed from one form to another), but cannot be created or destroyed.

The second law of thermodynamics

The second law of thermodynamics is an expression of the universal principle of dissipation of kinetic and potential energy observable in nature. The second law is an observation of the fact that over time, differences in temperature, pressure, and chemical potential tend to <u>even out</u> in a physical system that is isolated from the outside world. Entropy is a measure of how much this process has progressed. The entropy of an isolated system that is not in equilibrium tends to increase over time, approaching a maximum value at equilibrium.

In classical thermodynamics, the second law is a basic <u>postulate</u> applicable to any system involving heat energy transfer; in statistical thermodynamics, the second law is a consequence of the assumed randomness of molecular chaos. There are many versions of the second law, but they all have the same effect, which is to explain the phenomenon of irreversibility in nature.

The third law of thermodynamics

The third law of thermodynamics is a statistical law of nature regarding entropy and the impossibility of reaching absolute zero of temperature. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is the absolute entropy. Alternate definitions are, "the entropy of all systems and of all states of a system is smallest at absolute zero," or equivalently "it is impossible to reach the absolute zero of temperature by any finite number of processes".

Absolute zero is −273.15 ° C (degrees Celsius), or −459.67 ° F (degrees Fahrenheit) or 0 K (kelvin).

System models

An important concept in thermodynamics is the thermodynamic system, a precisely defined region of the universe under study. Everything in the universe except the system is known as the

surroundings. A system is separated from the remainder of the universe by a *boundary*, which may be notional or not, but by convention delimits a finite volume. Exchanges of work, heat, or matter between the system and the surroundings take place across this boundary.

The boundary is simply a surface around the volume of interest. Anything that passes across the boundary that effects a change in the internal energy needs to be accounted for in the energy balance equation. The volume can be the region surrounding a single atom resonating energy,   a body of steam or air in a steam engine, the body of a tropical cyclone in the field of atmospheric thermodynamics, or just one nuclide (i.e. a system of quarks) as hypothesized in quantum thermodynamics.

Boundaries are of four types: fixed, moveable, real, and imaginary. For example, in an engine, a fixed boundary means the piston is locked at its position; then a constant volume process occurs, no work being permitted. In that same engine, a moveable boundary allows the piston to move in and out, permitting work. For closed systems, boundaries are real, while open system boundaries are often imaginary.

Thermodynamics sometimes distinguishes five classes of systems, defined in terms of what is allowed to cross their boundaries.

- *Isolated systems* are completely isolated from their environment. They do not exchange energy or matter with their environment. In practice, a system can never be absolutely isolated from its environment, because there is always at least some slight coupling, such as gravitational attraction.

- *Closed systems* are able to exchange energy (heat and work) but not matter with their environment. A greenhouse is an example of a closed system exchanging heat but not work with its environment. Whether a system exchanges heat, work or both is usually thought of as a property of its boundary.

- An *open system* has a part of its boundary that allows transfer of energy as well as matter between it and its surroundings. A boundary part that allows matter transfer is called permeable.

States and processes

There are two fundamental kinds of entity in thermodynamics, states of a system, and processes of a system. This allows three fundamental approaches to thermodynamic reasoning, that in terms of states of thermodynamic equilibrium of a system, and that in terms of time-invariant processes of a system, and that in terms of cyclic processes of a system.

The approach through states of thermodynamic equilibrium of a system requires a full account of the state of the system as well as a notion of process from one state to another of a system, but may require only an idealized or partial account of the state of the surroundings of the

system or of other systems.

The method of description in terms of states of thermodynamic equilibrium has limitations. For example, processes in a region of turbulent flow, or in a burning gas mixture, or in a Knudsen gas may be beyond "the province of thermodynamics". (A Knudsen gas is a gas in a state of such low density that the mean free path of molecules is greater than the diameter of receptacle that contains it. The molecular dynamical regime is then dominated by the collisions of the gas molecules with the walls of the receptacle rather than with each other.) This problem can sometimes be circumvented through the method of description in terms of cyclic or of time-invariant flow processes. This is part of the reason why the founders of thermodynamics often preferred the cyclic process description.

Approaches through processes of time-invariant flow of a system are used for some studies. Some processes, for example Joule-Thomson expansion, are studied through steady-flow experiments, but can be accounted for by distinguishing the steady bulk flow kinetic energy from the internal energy, and thus can be regarded as within the scope of classical thermodynamics defined in terms of equilibrium states or of cyclic processes. (**Joule–Thomson expansion** describes the temperature change of a gas or liquid when it is forced through a valve or porous plug while kept insulated so that no heat is exchanged with the environment.) Other flow processes, for example thermoelectric effects, are essentially defined by the presence of differential flows or diffusion so that they cannot be adequately accounted for in terms of equilibrium states or classical cyclic processes.

The notion of a cyclic process does not require a full account of the state of the system, but does require a full account of how the process occasions transfers of matter and energy between the principal system (which is often called the *working body*) and its surroundings, which must include at least two heat reservoirs at different known and fixed temperatures, one hotter than the principal system and the other colder than it, as well as a reservoir that can receive energy from the system as work and can do work on the system. The reservoirs can alternatively be regarded as auxiliary idealized component systems, alongside the principal system. Thus an account in terms of cyclic processes requires at least four contributory component systems. The independent variables of this account are the amounts of energy that enter and leave the idealized auxiliary systems. In this kind of account, the working body is often regarded as a "black box", and its own state is not specified. In this approach, the notion of a properly numerical scale of empirical temperature is a presupposition of thermodynamics, not a notion constructed by or derived from it.

Account in terms of states of thermodynamic equilibrium

When a system is at thermodynamic equilibrium under a given set of conditions of its surroundings, it is said to be in a definite thermodynamic state, which is fully described by its

state variables.

If a system is simple as defined above, and is in thermodynamic equilibrium, and is not subject to an externally imposed force field, such as gravity, electricity, or magnetism, then it is homogeneous, that is say, spatially uniform in all respects.

In a sense, a homogeneous system can be regarded as spatially zero-dimensional, because it has no spatial variation.

If a system in thermodynamic equilibrium is homogeneous, then its state can be described by a few physical variables, which are mostly classifiable as intensive variables and extensive variables.

Examples of extensive thermodynamic variables are total mass and total volume. Examples of intensive thermodynamic variables are temperature, pressure, and chemical concentration; intensive thermodynamic variables are defined at each spatial point and each instant of time in a system.

Intensive variables are defined by the property that if any number of systems, each in its own separate homogeneous thermodynamic equilibrium state, all with the same respective values of all of their intensive variables, regardless of the values of their extensive variables, are laid contiguously with no partition between them, so as to form a new system, then the values of the intensive variables of the new system are the same as those of the separate constituent systems. Such a composite system is in a homogeneous thermodynamic equilibrium. Examples of intensive variables are temperature, chemical concentration, pressure, density of mass, density of internal energy, and, when it can be properly defined, density of entropy.

Extensive variables are defined by the property that if any number of systems, regardless of their possible separate thermodynamic equilibrium or non-equilibrium states or intensive variables, are laid side by side with no partition between them so as to form a new system, then the values of the extensive variables of the new system are the sums of the values of the respective extensive variables of the individual separate constituent systems. Obviously, there is no reason to expect such a composite system to be in a homogeneous thermodynamic equilibrium.

Though, when it can be properly defined, density of entropy is an intensive variable, for inhomogeneous systems, entropy itself does not fit into this classification of state variables. The reason is that entropy is a property of a system as a whole, and not necessarily related simply to its constituents separately.

It is true that for any number of systems each in its own separate homogeneous thermodynamic equilibrium, all with the same values of intensive variables, removal of the partitions between the separate systems results in a composite homogeneous system in thermodynamic equilibrium, with all the values of its intensive variables the same as those of the constituent systems, and it is

reservedly or conditionally true that the entropy of such a restrictively defined composite system is the sum of the entropies of the constituent systems. But if the constituent systems do not satisfy these restrictive conditions, the entropy of a composite system cannot be expected to be the sum of the entropies of the constituent systems, because the entropy is a property of the composite system as a whole.

Therefore, though under these restrictive reservations, entropy satisfies some requirements for extensivity defined just above, entropy in general does not fit the above definition of an extensive variable.

Being neither an intensive variable nor an extensive variable according to the above definition, entropy is thus a stand-out variable, because it is a state variable of a system as a whole. A non-equilibrium system can have a very inhomogeneous dynamical structure. This is one reason for distinguishing the study of equilibrium thermodynamics from the study of non-equilibrium thermodynamics.

The physical reason for the existence of extensive variables is the time-invariance of volume in a given inertial reference frame, and the strictly local conservation of mass, momentum, angular momentum, and energy. As noted by Gibbs, entropy is unlike energy and mass, because it is not locally conserved. The stand-out quantity entropy is never conserved in real physical processes; all real physical processes are irreversible. The motion of planets seems reversible on a short time scale (millions of years), but their motion, according to Newton's laws, is mathematically an example of deterministic chaos. Eventually a planet suffers an unpredictable collision with an object from its surroundings, outer space in this case, and consequently its future course is radically unpredictable. Theoretically this can be expressed by saying that every natural process dissipates some information from the predictable part of its activity into the unpredictable part. The predictable part is expressed in the generalized mechanical variables, and the unpredictable part in heat.

Other state variables can be regarded as conditionally 'extensive' subject to reservation as above, but not extensive as defined above. Examples are the Gibbs free energy, the Helmholtz free energy, and the enthalpy. Consequently, just because for some systems under particular conditions of their surroundings such state variables are conditionally conjugate to intensive variables, such conjugacy does not make such state variables extensive as defined above. This is another reason for distinguishing the study of equilibrium thermodynamics from the study of non-equilibrium thermodynamics. In another way of thinking, this explains why heat is to be regarded as a quantity that refers to a process and not to a state of a system.

A system with no internal partitions, and in thermodynamic equilibrium, can be inhomogeneous in the following respect: it can consist of several so-called 'phases', each

homogeneous in itself, in immediate contiguity with other phases of the system, but distinguishable by their having various respectively different physical characters, with discontinuity of intensive variables at the boundaries between the phases; a mixture of different chemical species is considered homogeneous for this purpose if it is physically homogeneous. For example, a vessel can contain a system consisting of water vapour overlying liquid water; then there is a vapour phase and a liquid phase, each homogeneous in itself, but still in thermodynamic equilibrium with the other phase.

Equation of state

The macroscopic variables of a thermodynamic system in thermodynamic equilibrium, in which temperature is well defined, can be related to one another through equations of state or characteristic equations. They express the constitutive peculiarities of the material of the system. The equation of state must comply with some thermodynamic constraints, but cannot be derived from the general principles of thermodynamics alone.

Thermodynamic processes

A thermodynamic process is defined by changes of state internal to the system of interest, combined with transfers of matter and energy to and from the surroundings of the system or to and from other systems. A system is demarcated from its surroundings or from other systems by partitions that more or less separate them, and may move as a piston to change the volume of the system and thus transfer work.

Dependent and independent variables for a process

A process is described by changes in values of state variables of systems or by quantities of exchange of matter and energy between systems and surroundings. The change must be specified in terms of prescribed variables. The choice of which variables are to be used is made in advance of consideration of the course of the process, and cannot be changed. Certain of the variables chosen in advance are called the independent variables. From changes in independent variables may be derived changes in other variables called dependent variables. For example a process may occur at constant pressure with pressure prescribed as an independent variable, and temperature changed as another independent variable, and then changes in volume are considered as dependent. Careful attention to this principle is necessary in thermodynamics.

Changes of state of a system

In the approach through equilibrium states of the system, a process can be described in two main ways.

In one way, the system is considered to be connected to the surroundings by some kind of more or less separating partition, and allowed to reach equilibrium with the surroundings with that partition in place. Then, while the separative character of the partition is kept unchanged, the conditions of the surroundings are changed, and exert their influence on the system again through the separating partition, or the partition is moved so as to change the volume of the system; and a new equilibrium is reached. For example, a system is allowed to reach equilibrium with a heat bath at one temperature; then the temperature of the heat bath is changed and the system is allowed to reach a new equilibrium; if the partition allows conduction of heat, the new equilibrium is different from the old equilibrium.

In the other way, several systems are connected to one another by various kinds of more or less separating partitions, and to reach equilibrium with each other, with those partitions in place. In this way, one may speak of a 'compound system'. Then one or more partitions is removed or changed in its separative properties or moved, and a new equilibrium is reached. The Joule-Thomson experiment is an example of this; a tube of gas is separated from another tube by a porous partition; the volume available in each of the tubes is determined by respective pistons; equilibrium is established with an initial set of volumes; the volumes are changed and a new equilibrium is established.

Commonly considered thermodynamic processes

It is often convenient to study a thermodynamic process in which a single variable, such as temperature, pressure, or volume, etc., is held fixed. Furthermore, it is useful to group these processes into pairs, in which each variable held constant is one member of a conjugate pair.

Several commonly studied thermodynamic processes are:

- Isobaric process: occurs at constant pressure
- Isochoric process: occurs at constant volume (also called isometric/isovolumetric)
- Isothermal process: occurs at a constant temperature
- Adiabatic process: occurs without loss or gain of energy as heat
- Isentropic process: a reversible adiabatic process occurs at a constant entropy, but is a fictional idealization. Conceptually it is possible to actually physically conduct a process that keeps the entropy of the system constant, allowing systematically controlled removal of heat, by conduction to a cooler body, to compensate for entropy produced within the system by irreversible work done on the system.
- Isenthalpic process: occurs at a constant enthalpy
- Isolated process: no matter or energy (neither as work nor as heat) is transferred into or out of the system

Conjugate variables

A central concept of thermodynamics is that of energy. By the First Law, the total energy of a system and its surroundings is conserved. Energy may be transferred into a system by heating, compression, or addition of matter, and extracted from a system by cooling, expansion, or extraction of matter. In mechanics, for example, energy transfer equals the product of the force applied to a body and the resulting displacement.

Conjugate variables are pairs of thermodynamic concepts, with the first being akin to a "force" applied to some thermodynamic system, the second being akin to the resulting "displacement," and the product of the two equalling the amount of energy transferred. The common conjugate variables are:

- Pressure-volume (the mechanical parameters);
- Temperature-entropy (thermal parameters);
- Chemical potential-particle number (material parameters).

Potentials

Thermodynamic potentials are different quantitative measures of the stored energy in a system. Potentials are used to measure energy changes in systems as they evolve from an initial state to a final state. The potential used depends on the constraints of the system, such as constant temperature or pressure. For example, the Helmholtz and Gibbs energies are the energies available in a system to do useful work when the temperature and volume or the pressure and temperature are fixed, respectively.

The five most well known potentials are:

- Internal energy: U
- Helmholtz free energy: $E=U\text{-}TS$
- Enthalpy: $H=U+pV$
- Gribbs free energy: $G=H\text{-}TS$
- Landau potential (Grand potential): $\Omega=U\text{-}TS\text{-}\mu N$

Scope of thermodynamics

Originally thermodynamics concerned material and radiative phenomena that are experimentally reproducible. For example, a state of thermodynamic equilibrium is a steady state reached after a system has aged so that it no longer changes with the passage of time.

But more than that, for thermodynamics, a system, defined by its being prepared in a certain way must, consequent on every particular occasion of preparation, upon aging, reach one and the same eventual state of thermodynamic equilibrium, entirely determined by the way of preparation.

Such reproducibility is because the systems consist of so many molecules that the molecular variations between particular occasions of preparation have negligible or scarcely discernable effects on the macroscopic variables that are used in thermodynamic descriptions.

This led to Boltzmann's discovery that entropy had a statistical or probabilistic nature. Probabilistic and statistical explanations arise from the experimental reproducibility of the phenomena.

Gradually, the laws of thermodynamics came to be used to explain phenomena that occur outside the experimental laboratory. For example, phenomena on the scale of the earth's atmosphere cannot be reproduced in a laboratory experiment. But processes in the atmosphere can be modeled by use of thermodynamic ideas, extended well beyond the scope of laboratory equilibrium thermodynamics. A parcel of air can, near enough for many studies, be considered as a closed thermodynamic system, one that is allowed to move over significant distances. The pressure exerted by the surrounding air on the lower face of a parcel of air may differ from that on its upper face. If this results in rising of the parcel of air, it can be considered to have gained potential energy as a result of work being done on it by the combined surrounding air below and above it. As it rises, such a parcel usually expands because the pressure is lower at the higher altitudes that it reaches. In that way, the rising parcel also does work on the surrounding atmosphere.

For many studies, such a parcel can be considered nearly to neither gain nor lose energy by heat conduction to its surrounding atmosphere, and its rise is rapid enough to leave negligible time for it to gain or lose heat by radiation; consequently the rising of the parcel is near enough adiabatic. Thus the adiabatic gas law accounts for its internal state variables, provided that there is no precipitation into water droplets, no evaporation of water droplets, and no sublimation in the process.

More precisely, the rising of the parcel is likely to occasion friction and turbulence, so that some potential and some kinetic energy of bulk converts into internal energy of air considered as effectively stationary. Friction and turbulence thus oppose the rising of the parcel.

Vocabulary

★ **thermodynamics** 热力学   ★ entropy 熵

macroscopic variables 宏观变量   microscopic constituents 微观组分

statistical mechanics 统计力学

phase transitions 相变

transport phenomena 输运现象

★ essential 极其重要的，本质的

economics 经济学

★ empirical 经验主义的

★ asserts 声称，断言

distinguishable 无法区分

bulk 大部分，主体，大量

concerns 关注

★ irreversibility 不可逆性

steam engines 蒸汽机

concise definition 简明的定义

contiguous 邻近的

★ collective 协同的

★ refers to 涉及到，引用

★ in terms of 用...的话，根据，按照，在...方面

★ so as to 以便，为的是

energy transfers 能量转化

★ equilibrium 平衡

heat bath 热浴，热库

★ entity 实体，对象

cyclic processes 循环过程

★ state n. 状态; vt. 说明，规定

mediate 调解

intermediate rates 中间速率

★ impose 施加的，使负担

constitutive 组成的，本质的，基本的

peculiarities 特征，特点

★ assemblies 集合，组装

★ species 种类

★ constraints 约束

★ prominent 主要的

★ spontaneously 自发地

flow 流动

tacitly 默认的，心照不宣地

★ reliance 依赖，依靠，信任，信赖

calorimetry 量热计

★ asserts 声称，断言

★ isolated system 孤立系统

even out 平摊，使平坦

★ postulate 假设，基本条件

delimits 划定边界

★ be accounted for 计算在内，占比例，解释

tropical cyclone 热带旋风；飓风

nuclide 核素

piston 活塞

★ permeable 可渗透的

time-invariant 不随时间变化

partial 部分地

turbulent flow 涡流，紊流，乱流

receptacle 容器，插座

circumvente 绕行，规避，巧取

notion 观念，概念

★ principal 主要的（注意区别：principle 原理）

heat reservoirs 热库

★ auxiliary 辅助的

presupposition 预想，假定

★ subject to 服从，受到

★ homogeneous 同质的，均匀的

spatially uniform 空间均匀的

intensive variables 强度变量

extensive variables 外延变数，广延量

deterministic chaos 决定性混沌

radically 根本地，完全地

dissipates 散失，消散

★ enthalpy 焓

★ conjugate 共轭，配合，耦合

★ respect 方面，尊重，问候

vessel 容器，船，脉管

comply with 遵守，符合，依从

★ relate **相关联**，符合，讲述

demarcated 划界，区分

prescribed 规定，指定，开处方

in place 在适当的位置，适当地

porous 多孔的

adiabatic 绝热

isentropic 等熵的

compensate 补偿

akin 同类的，同源的

parcel 局部，小包

evaporation 蒸发

sublimation 升华

4　Electromagnetism　电磁学

Introduction

The electromagnetic force is one of the four fundamental interactions in nature, the other three being the strong interaction, the weak interaction, and gravitation. This force is described by electromagnetic fields, and has innumerable physical instances including the interaction of electrically charged particles and the interaction of uncharged magnetic force fields with electrical conductors.

The science of electromagnetic phenomena is defined in terms of the electromagnetic force, sometimes called the Lorentz force, which includes both electricity and magnetism as elements of one phenomenon.

The electromagnetic force is the interaction responsible for almost all the phenomena encountered in daily life, with the exception of gravity. Ordinary matter takes its form as a result of intermolecular forces between individual molecules in matter. Electrons are bound by electromagnetic wave mechanics into orbitals around atomic nuclei to form atoms, which are the building blocks of molecules. This governs the processes involved in chemistry, which arise from interactions between the electrons of neighboring atoms, which are in turn determined by the interaction between electromagnetic force and the momentum of the electrons.

There are numerous mathematical descriptions of the electromagnetic field. In classical electrodynamics, electric fields are described as electric potential and electric current in Ohm's law, magnetic fields are associated with electromagnetic induction and magnetism, and Maxwell's equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents.

The theoretical implications of electromagnetism, in particular the establishment of the speed of light based on properties of the "medium" of propagation (permeability and permittivity), led to the development of special relativity by Albert Einstein in 1905.

Electrostatics

Electrostatics is the branch of physics that deals with the phenomena and properties of stationary or slow-moving electric charges with no acceleration.

Since classical antiquity, it has been known that some materials such as amber attract lightweight particles after rubbing. The Greek word for amber, $\nu o \rho \tau \kappa \varepsilon \lambda \eta$ electron, was the source of the word 'electricity'. Electrostatic phenomena arise from the forces that electric charges exert on each other. Such forces are described by Coulomb's law. Even though electrostatically induced forces seem to be rather weak, the electrostatic force between e.g. an electron and a proton, that together make up a hydrogen atom, is about 40 orders of magnitude stronger than the gravitational force acting between them.

There are many examples of electrostatic phenomena, from those as simple as the attraction of the plastic wrap to your hand after you remove it from a package, to damage of electronic components during manufacturing, to the operation of photocopiers. Electrostatics involves the buildup of charge on the surface of objects due to contact with other surfaces. Although charge exchange happens whenever any two surfaces contact and separate, the effects of charge exchange are usually only noticed when at least one of the surfaces has a high resistance to electrical flow. This is because the charges that transfer to or from the highly resistive surface are more or less trapped there for a long enough time for their effects to be observed. These charges then remain on the object until they either bleed off to ground or are quickly neutralized by a discharge: e.g., the familiar phenomenon of a static 'shock' is caused by the neutralization of charge built up in the body from contact with nonconductive surfaces.

Coulomb's law

The fundamental equation of electrostatics is Coulomb's law, which describes the force between two point charges. The magnitude of the electrostatic force between two point electric charges Q_1 and Q_2 is directly proportional to the product of the magnitudes of each charge and inversely proportional to the surface area of a sphere whose radius is equal to the distance between the charges:

$$F = \frac{Q_1 Q_2}{4\pi r^2 \varepsilon_0} \ ,$$

where ε_0 is a constant called the vacuum permittivity or permittivity of free space.

Electric field

An **electric field** is generated by electrically charged particles and time-varying magnetic fields. The electric field depicts the force experienced by a motionless electrically charged test particle at any point in space.

The electric field is a vector field with SI units of newtons per coulomb (N C^{-1}) or, equivalently, volts per meter (V m^{-1}). The SI base units of the electric field are kgm·s^{-3}·A^{-1}. The strength or magnitude of the field at a given point is defined as the force that would be exerted on

a positive test charge of 1 coulomb placed at that point; the direction of the field is given by the direction of that force. Electric fields contain electrical energy with energy density proportional to the square of the field amplitude. The electric field is to charge as gravitational acceleration is to mass.

An electric field that changes with time, such as due to the motion of charged particles in the field, influences the local magnetic field. That is, the electric and magnetic fields are not completely separate phenomena; what one observer perceives as an electric field, another observer in a different frame of reference perceives as a mixture of electric and magnetic fields. For this reason, one speaks of "electromagnetism" or "electromagnetic fields". In quantum electrodynamics, disturbances in the electromagnetic fields are called photons, and the energy of photons is quantized.

Gauss's law

Gauss's law states that "the total electric flux through any closed hypothetical surface of any shape drawn in an electric field is proportional to the total electric charge enclosed within the surface".

Mathematically, Gauss's law takes the form of an integral equation:

$$\oint_S \vec{E} \cdot \mathrm{d}\vec{A} = \int_V \frac{\rho}{\varepsilon_0} \cdot \mathrm{d}V.$$

Alternatively, in differential form, the equation becomes

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}.$$

where $\vec{\nabla} \cdot$ is the divergence operator.

Electrostatic potential

Because the electric field is irrotational, it is possible to express the electric field as the gradient of a scalar function, called the electrostatic potential (also known as the voltage). An electric field, points from regions of high potential, Φ, to regions of low potential, expressed mathematically as

$$\vec{E} = -\vec{\nabla}\phi.$$

The electrostatic potential at a point can be defined as the amount of work per unit charge required to move a charge from infinity to the given point.

Magnetostatics

Magnetostatics is the study of magnetic fields in systems where the currents are steady (not

changing with time). It is the magnetic analogue of electrostatics, where the charges are stationary. The magnetization need not be static; the equations of magnetostatics can be used to predict fast magnetic switching events that occur on time scales of nanoseconds or less. Magnetostatics is even a good approximation when the currents are not static — as long as the currents do not alternate rapidly. Magnetostatics is widely used in applications of micromagnetics such as models of magnetic recording devices.

Biot-Savart law

In electromagnetism, the **Biot–Savart**(毕奥-萨伐尔) **law** is an equation that describes the magnetic field generated by an electric current. It relates the magnetic field to the magnitude, direction, length, and proximity of the electric current. The law is valid in the magnetostatic approximation, and is consistent with both Ampère's circuital law and Gauss's law for magnetism. It is named for Jean-Baptiste Biot and Felix Savart who discovered this relationship in 1820.

The Biot–Savart law is used for computing the resultant magnetic field **B** at position **r** generated by a *steady* current I : a continual flow of charges which is constant in time and the charge neither accumulates nor depletes at any point. The law is a physical example of a line integral: evaluated over the path C the electric currents flow. The equation in SI units is

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int_C \frac{Id\mathbf{l} \times \hat{\mathbf{r}}}{|\mathbf{r}|^2}$$

where *r* is the full displacement vector from the wire element to the point at which the field is being computed , $\hat{\mathbf{r}}$ is the unit vector of *r, dl* is a vector whose magnitude is the length of the differential element of the wire, in the direction of conventional current, and μ$_0$ is the magnetic constant.

The integral is usually around a closed curve, since electric currents can only flow around closed paths. An infinitely long wire is a counter-example.

To apply the equation, the point in space where the magnetic field is to be calculated is arbitrarily chosen. Holding that point fixed, the line integral over the path of the electric currents is calculated to find the total magnetic field at that point. The application of this law implicitly relies on the superposition principle for magnetic fields, i.e. the fact that the magnetic field is a vector sum of the field created by each infinitesimal section of the wire individually.

Ampère's circuital law

It relates magnetic fields to electric currents that produce them. Using Ampere's law, one can determine the magnetic field associated with a given current or current associated with a given magnetic field, providing there is no time changing electric field present. In its historically original

form, Ampère's circuital law relates the magnetic field to its electric current source. The law can be written in two forms, the "integral form" and the "differential form". The forms are equivalent, and related by the Kelvin–Stokes theorem. It can also be written in terms of either the $\boldsymbol{B}$ or $\boldsymbol{H}$ magnetic fields.

Ampère's circuital law is now known to be a correct law of physics in a magnetostatic situation: The system is static except possibly for continuous steady currents within closed loops. In all other cases the law is incorrect unless Maxwell's correction is included.

Integral form

In SI units, the "integral form" of the original Ampère's circuital law is a line integral of the magnetic field around some closed curve C (arbitrary but must be closed). The curve C in turn bounds both a surface S which the electric current passes through (again arbitrary but not closed—since no three-dimensional volume is enclosed by S), and encloses the current. The mathematical statement of the law is a relation between the total amount of magnetic field around some path (line integral) due to the current which passes through that enclosed path (surface integral). It can be written in a number of forms.

In terms of **total** current, which includes both free and bound current, the line integral of the magnetic $\boldsymbol{B}$-field (in tesla, T) around closed curve C is proportional to the total current I_{enc} passing through a surface S (enclosed by C):

$$\oint_C \mathbf{B} \cdot \mathrm{d}\boldsymbol{\ell} = \mu_0 \iint_S \mathbf{J} \cdot \mathrm{d}\mathbf{S} = \mu_0 I_{\text{enc}}$$

where $\boldsymbol{J}$ is the total current density (in ampere per square metre, Am^{-2}).

There are a number of ambiguities in the above definitions that require clarification and a choice of convention.

First, three of these terms are associated with sign ambiguities: the line integral could go around the loop in either direction (clockwise or counterclockwise); the vector area dS could point in either of the two directions normal to the surface; and I_{enc} is the net current passing through the surface S, meaning the current passing through in one direction, minus the current in the other direction—but either direction could be chosen as positive. These ambiguities are resolved by the right-hand rule: With the palm of the right-hand toward the area of integration, and the index-finger pointing along the direction of line-integration, the outstretched thumb points in the direction that must be chosen for the vector area dS. Also the current passing in the same direction as dS must be counted as positive. The right hand grip rule can also be used to determine the signs.

Second, there are infinitely many possible surfaces S that have the curve C as their border. Which of those surfaces is to be chosen? If the loop does not lie in a single plane, for example, there

is no one obvious choice. The answer is that it does not matter; it can be proven that any surface with boundary *C* can be chosen.

Differential form

By the Stokes' theorem, this equation can also be written in a "differential form". Again, this equation only applies in the case where the electric field is constant in time, meaning the currents are steady (time-independent), else the magnetic field would change with time. In SI units, the equation states for total current:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

where $\nabla \times$ is the curl operator.

Free current versus bound current

The electric current that arises in the simplest textbook situations would be classified as "free current"—for example, the current that passes through a wire or battery. In contrast, "bound current" arises in the context of bulk materials that can be magnetized and/or polarized.

When a material is magnetized (for example, by placing it in an external magnetic field), the electrons remain bound to their respective atoms, but behave as if they were orbiting the nucleus in a particular direction, creating a microscopic current. When the currents from all these atoms are put together, they create the same effect as a macroscopic current, circulating perpetually around the magnetized object. This magnetization current $\mathbf{J}_\mathrm{M}$ is one contribution to "bound current".

The other source of bound current is bound charge. When an electric field is applied, the positive and negative bound charges can separate over atomic distances in polarizable materials, and when the bound charges move, the polarization changes, creating another contribution to the "bound current", the polarization current $\mathbf{J}_\mathrm{P}$.

Displacement current

In free space, the displacement current is related to the time rate of change of electric field.

In a dielectric the above contribution to displacement current is present too, but a major contribution to the displacement current is related to the polarization of the individual molecules of the dielectric material. Even though charges cannot flow freely in a dielectric, the charges in molecules can move a little under the influence of an electric field. The positive and negative charges in molecules separate under the applied field, causing an increase in the state of polarization, expressed as the polarization density $\boldsymbol{P}$. A changing state of polarization is equivalent to a current.

Both contributions to the displacement current are combined by defining the displacement current as:

$$\mathbf{J}_\mathrm{D} = \frac{\partial}{\partial t} \mathbf{D}(\mathbf{r},\ t)\ ,$$

where the electric displacement field is defined as:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 \varepsilon_{\mathrm{r}} \mathbf{E} \ ,$$

where ε_0 is the electric constant, ε_r the relative static permittivity, and *P* is the polarization density. Substituting this form for *D* in the expression for displacement current, it has two components:

$$\mathbf{J}_{\mathrm{D}} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t}.$$

The first term on the right hand side is present everywhere, even in a vacuum. It doesn't involve any actual movement of charge, but it nevertheless has an associated magnetic field, as if it were an actual current. Some authors apply the name *displacement current* to only this contribution.

The second term on the right hand side is the displacement current as originally conceived by Maxwell, associated with the polarization of the individual molecules of the dielectric material.

Extending the original law: the Maxwell-Ampère equation

Next Ampère's equation is extended by including the polarization current, thereby remedying the limited applicability of the original Ampère's circuital law.

Treating free charges separately from bound charges, Ampère's equation including Maxwell's correction in terms of the *H*-field is (the *H*-field is used because it includes the magnetization currents, so *J*$_\mathrm{M}$ does not appear explicitly):

$$\oint_C \mathbf{H} \cdot \mathrm{d}\boldsymbol{\ell} = \iint_S \left(\mathbf{J}_{\mathrm{f}} + \frac{\partial}{\partial t} \mathbf{D} \right) \cdot \mathrm{d}\mathbf{S}$$

where *H* is the magnetic H field (also called "auxiliary magnetic field", "magnetic field intensity", or just "magnetic field"), *D* is the electric displacement field, and *J*$_\mathrm{f}$ is the enclosed conduction current or free current density. In differential form,

$$\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{f}} + \frac{\partial}{\partial t} \mathbf{D} \ .$$

Gauss's law for magnetism

In physics, **Gauss's law for magnetism** is one of Maxwell's equations—the four equations that underlie classical electrodynamics. It states that the magnetic field **B** has divergence equal to zero, in other words, that it is a solenoidal vector field. It is equivalent to the statement that magnetic monopoles do not exist. Rather than "magnetic charges", the basic entity for magnetism is the magnetic dipole. (Of course, if monopoles were ever found, the law would have to be modified.)

Gauss's law for magnetism can be written in two forms, a *differential form* and an *integral form*. These forms are equivalent due to the divergence theorem.

The name "Gauss's law for magnetism" is not universally used. The law is also called

"Absence of free magnetic poles". It is also referred to as the "transversality requirement" because for plane waves it requires that the polarization be transverse to the direction of propagation.

Differential form

The differential form for Gauss's law for magnetism is:

$$\nabla \cdot \mathbf{B} = 0$$

where $\nabla \cdot$ denotes divergence, and B is the magnetic field.

Integral form

The integral form of Gauss's law for magnetism states:

$$\oiint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

where S is any closed surface, and dA is a vector, whose magnitude is the area of an infinitesimal piece of the surface S, and whose direction is the outward-pointing surface normal.

The left-hand side of this equation is called the net flux of the magnetic field out of the surface, and Gauss's law for magnetism states that it is always zero.

The integral and differential forms of Gauss's law for magnetism are mathematically equivalent, due to the divergence theorem. That said, one or the other might be more convenient to use in a particular computation.

The law in this form states that for each volume element in space, there are exactly the same number of "magnetic field lines" entering and exiting the volume. No total "magnetic charge" can build up in any point in space. For example, the south pole of the magnet is exactly as strong as the north pole, and free-floating south poles without accompanying north poles (magnetic monopoles) are not allowed. In contrast, this is not true for other fields such as electric fields or gravitational fields, where total electric charge or mass can build up in a volume of space.

Electromagnetic induction

Electromagnetic induction is the production of a potential difference (voltage) across a conductor when it is exposed to a varying magnetic field.

Faraday's law of induction is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF). It is the fundamental operating principle of transformers, inductors, and many types of electrical motors, generators and solenoids.

The **Maxwell–Faraday equation** is a generalisation of Faraday's law, and forms one of Maxwell's equations.

Faraday's Law

Faraday's law of induction makes use of the magnetic flux Φ_B through a hypothetical surface Σ whose boundary is a wire loop. Since the wire loop may be moving, we write $\Sigma(t)$ for the surface. The magnetic flux is defined by a surface integral:

$$\Phi_B = \iint_{\Sigma(t)} \mathbf{B}(\mathbf{r}, t) \cdot d\mathbf{A} \, ,$$

where dA is an element of surface area of the moving surface $\Sigma(t)$, $\boldsymbol{B}$ is the magnetic field, and $\boldsymbol{B}\cdot d\boldsymbol{A}$ is a vector dot product (the infinitesimal amount of magnetic flux). In more visual terms, the magnetic flux through the wire loop is proportional to the number of magnetic flux lines that pass through the loop.

When the flux changes—because $\boldsymbol{B}$ changes, or because the wire loop is moved or deformed, or both—Faraday's law of induction says that the wire loop acquires an EMF is ε, defined the energy available per unit charge which travels once around the wire loop (the unit of EMF is the volt). Equivalently, it is the voltage that would be measured by cutting the wire to create an open circuit, and attaching a voltmeter to the leads. According to the Lorentz force law (in SI units),

$$\mathbf{F} = q \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right)$$

the EMF on a wire loop is:

$$\mathcal{E} = \frac{1}{q} \oint_{\text{wire}} \mathbf{F} \cdot d\boldsymbol{\ell} = \oint_{\text{wire}} \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \cdot d\boldsymbol{\ell}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field (aka magnetic flux density, magnetic induction), $d\boldsymbol{l}$ is an infinitesimal arc length along the wire, and the line integral is evaluated along the wire (along the curve the coincident with the shape of the wire).

The EMF is also given by the rate of change of the magnetic flux:

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \, ,$$

where ε is the electromotive force (EMF) in volts and Φ_B is the magnetic flux in webers. The direction of the electromotive force is given by Lenz's law.

For a tightly wound coil of wire, composed of N identical loops, each with the same Φ_B, Faraday's law of induction states that

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

where N is the number of turns of wire and Φ_B is the magnetic flux in webers through a *single* loop.

Maxwell‑Faraday equation

The Maxwell–Faraday equation is a generalisation of Faraday's law that states that a time-varying magnetic field is always accompanied by a spatially-varying, non-conservative

electric field, and vice-versa. The Maxwell–Faraday equation is

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

where $\nabla\times$ is the curl operator and again $\mathbf{E}(\mathbf{r}, t)$ is the electric field and $\mathbf{B}(\mathbf{r}, t)$ is the magnetic field. These fields can generally be functions of position $\mathbf{r}$ and time t.

The Maxwell–Faraday equation is one of the four Maxwell's equations, and therefore plays a fundamental role in the theory of classical electromagnetism. It can also be written in an **integral form** by the Kelvin-Stokes theorem:

$$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\int_{\Sigma} \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{A}$$

where Σ is a surface bounded by the closed contour $\partial\Sigma$, $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field. $d\boldsymbol{l}$ is an infinitesimal vector element of the contour $\partial\Sigma$, $d\boldsymbol{A}$ is an infinitesimal vector element of surface Σ.

Maxwell's equations

Maxwell's equations are a set of partial differential equations that, together with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits. These fields in turn underlie modern electrical and communications technologies. Maxwell's equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents.

The equations have two major variants. The "microscopic" set of Maxwell's equations uses total charge and total current, including the complicated charges and currents in materials at the atomic scale; it has universal applicability, but may be unfeasible to calculate. The "macroscopic" set of Maxwell's equations defines two new auxiliary fields that describe large-scale behavior without having to consider these atomic scale details, but it requires the use of parameters characterizing the electromagnetic properties of the relevant materials.

The term "Maxwell's equations" is often used for other forms of Maxwell's equations. For example, space-time formulations are commonly used in high energy and gravitational physics. These formulations defined on space-time, rather than space and time separately are manifestly compatible with special and general relativity. In quantum mechanics, versions of Maxwell's equations based on the electric and magnetic potentials are preferred.

Since the mid-20th century, it has been understood that Maxwell's equations are not exact laws of the universe, but are a classical approximation to the more accurate and fundamental theory of quantum electrodynamics. In most cases, though, quantum deviations from Maxwell's equations are immeasurably small. Exceptions occur when the particle nature of light is important or for very

strong electric fields.

    To describe electromagnetism in the powerful language of vector calculus, the Lorentz force law defines the electric field E, a vector field, and the magnetic field B, a pseudovector field, where each generally have time-dependence. The sources of these fields are electric charges and electric currents, which can be expressed as the total amounts of electric charge Q and current I within a region of space, or as local densities of these - namely charge density ρ and current density J.

    In this language there are four equations. Two of them describe how the fields vary in space due to sources, if any; electric fields <u>emanating</u> from electric charges in Gauss's law, and magnetic fields as closed field lines *not due to magnetic monopoles* in Gauss's law for magnetism. The other two describe how the fields "circulate" around their respective sources; the magnetic field "circulates" around electric currents and time varying electric fields in Ampère's law with Maxwell's correction, while the electric field "circulates" around time varying magnetic fields in Faraday's law.

Vocabulary

electromagnetism　电磁学

electric 电的

magnetic 磁的

electromagnetic 电磁的

★ fundamental interactions 基本相互作用

conductors 导体

electrons 电子

electrodynamics 电动力学

electromagnetic induction 电磁感应

alter 改变

propagation 传播，繁殖

permeability 渗透性，磁导率

permittivity 介电常数，电容率

electrostatics 静电学

antiquity 古代人，古董

amber 琥珀

resistance 阻抗

bleed off 排放，放出

proportional 正比于

product 产品, 结果, **乘积**

perceive 　感觉, 认知, 理解, 意识到

electric flux 电通量

divergence 发散，散度

irrotational 无旋的

gradient 梯度

magnetostatics 静磁学

steady 稳恒的

accumulates 积累

depletes 损耗，衰竭

conventional current 常规电流

implicitly 隐含地，无疑

superposition principle 叠加原理

infinitesimal 极微量的，无限小的

bound 束缚的

ambiguities 含糊，多义性

clarification 澄清

normal 普通，常规，法向，垂直

curl operator 旋度算子

perpetually 持续不断地，永久地

dielectric 电介质

remedy 修补

solenoidal vector field 无散度矢量场

transversality 横截性

net flux 净通量

electromotive force 电源电动势

aka 又称为(as known as)

vice-versa 反过来；反之亦然

partial differential equations 差分方程

manifestly 明白地

emanate 产生，表现，显示

5 Optics 光学

Introduction

Optics is the branch of physics which involves the behaviour and properties of light, including its interactions with matter and the construction of instruments that use or detect it. Optics usually describes the behaviour of visible, ultraviolet, and infrared light. Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.

Most optical phenomena can be accounted for using the classical electromagnetic description of light. Complete electromagnetic descriptions of light are, however, often difficult to apply in practice. Practical optics is usually done using simplified models. The most common of these, geometric optics, treats light as a collection of rays that travel in straight lines and bend when they pass through or reflect from surfaces. Physical optics is a more comprehensive model of light, which includes wave effects such as diffraction and interference that cannot be accounted for in geometric optics. Historically, the ray-based model of light was developed first, followed by the wave model of light. Progress in electromagnetic theory in the 19th century led to the discovery that light waves were in fact electromagnetic radiation.

Classical optics

Classical optics is divided into two main branches: geometrical optics and physical optics. In geometrical, or ray optics, light is considered to travel in straight lines, and in physical, or wave optics, light is considered to be an electromagnetic wave.

Geometrical optics can be viewed as an approximation of physical optics which can be applied when the wavelength of the light used is much smaller than the size of the optical elements or system being modeled.

Geometrical optics

Geometrical optics, or *ray optics*, describes the propagation of light in terms of "rays" which travel in straight lines, and whose paths are governed by the laws of reflection and refraction at interfaces between different media. They can be summarized as follows:

- When a ray of light hits the boundary between two transparent materials, it is divided into

a reflected and a refracted ray.

- The law of <u>reflection</u> says that the reflected ray lies in the plane of incidence, and the angle of reflection equals the angle of incidence.
- The law of <u>refraction</u> says that the refracted ray lies in the plane of incidence, and the sine of the angle of refraction divided by the sine of the angle of incidence is a constant.

The laws of reflection and refraction can be derived from Fermat's principle which states that the path taken between two points by a ray of light is the path that can be traversed in the least time.

Refractions

Refraction occurs when light travels through an area of space that has a changing index of refraction; this principle allows for lenses and the focusing of light. The simplest case of refraction occurs when there is an interface between a uniform medium with index of refraction and another medium with another index of refraction . In such situations, Snell's Law describes the resulting deflection of the light ray:

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

where θ_1 and θ_2 are the angles between the normal (to the interface) and the <u>incident</u> and refracted waves, respectively. This phenomenon is also associated with a changing speed of light as seen from the definition of index of refraction which implies

$$v_1 \sin \theta_2 = v_2 \sin \theta_1$$

where v_1 and v_2 are the wave velocities through the respective media.

Various consequences of Snell's Law include the fact that for light rays travelling from a material with a high index of refraction to a material with a low index of refraction, it is possible for the interaction with the interface to result in zero transmission. This phenomenon is called total internal reflection and allows for <u>fibre optics</u> technology. It is also possible to produce polarized light rays using a combination of reflection and refraction: When a refracted ray and the reflected ray form a right angle, the reflected ray has the property of "plane polarization". The angle of incidence required for such a <u>scenario</u> is known as Brewster's angle.

A device which produces converging or diverging light rays due to refraction is known as a <u>lens</u>. Thin lenses produce focal points on either side that can be modelled using the lensmaker's equation. In general, two types of lenses exist: <u>convex lenses</u>, which cause parallel light rays to <u>converge</u>, and <u>concave lenses</u>, which cause parallel light rays to <u>diverge</u>. Similarly to curved mirrors, thin lenses follow a simple equation that determines the location of the images given a particular <u>focal length</u> (*f*) and object distance (S_1):

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$$

where S_2 is the distance associated with the image and is considered by convention to be negative if

on the same side of the lens as the object and positive if on the opposite side of the lens. The focal length *f* is considered negative for concave lenses.

Physical optics

In physical optics, light is considered to propagate as a wave. This model predicts phenomena such as interference and diffraction, which are not explained by geometric optics. The speed of light waves in air is approximately 3.0×10^8 m/s (exactly 299,792,458 m/s in vacuum). The wavelength of visible light waves varies between 400 and 700 nm, but the term "light" is also often applied to infrared (0.7 – 300 μm) and ultraviolet radiation (10–400 nm).

The wave model can be used to make predictions about how an optical system will behave. The existence of electromagnetic waves was predicted in 1865 by Maxwell's equations. These waves propagate at the speed of light and have varying electric and magnetic fields which are orthogonal to one another, and also to the direction of propagation of the waves. Light waves are now generally treated as electromagnetic waves except when quantum mechanical effects have to be considered.

Modeling and design of optical systems using physical optics

Many simplified approximations are available for analyzing and designing optical systems. Most of these use a single scalar quantity to represent the electric field of the light wave, rather than using a vector model with orthogonal electric and magnetic vectors. The Huygens–Fresnel equation is one such model. This was derived empirically by Fresnel in 1815, based on Huygen's hypothesis that each point on a wavefront generates a secondary spherical wavefront, which Fresnel combined with the principle of superposition of waves. The Kirchhoff diffraction equation, which is derived using Maxwell's equations, puts the Huygens-Fresnel equation on a firmer physical foundation.

More rigorous models, involving the modeling of both electric and magnetic fields of the light wave, are required when dealing with the detailed interaction of light with materials where the interaction depends on their electric and magnetic properties. For instance, the behavior of a light wave interacting with a metal surface is quite different from what happens when it interacts with a dielectric material. A vector model must also be used to model polarized light.

Superposition and interference

In the absence of nonlinear effects, the superposition principle can be used to predict the shape of interacting waveforms through the simple addition of the disturbances. This interaction of waves to produce a resulting pattern is generally termed "interference" and can result in a variety

of outcomes. If two waves of the same wavelength and frequency are *in phase*, both the wave crests and wave troughs align. This results in constructive interference and an increase in the amplitude of the wave, which for light is associated with a brightening of the waveform in that location. Alternatively, if the two waves of the same wavelength and frequency are out of phase, then the wave crests will align with wave troughs and vice-versa. This results in destructive interference and a decrease in the amplitude of the wave, which for light is associated with a dimming of the waveform at that location.

Since the Huygens–Fresnel principle states that every point of a wavefront is associated with the production of a new disturbance, it is possible for a wavefront to interfere with itself constructively or destructively at different locations producing bright and dark fringes in regular and predictable patterns. Interferometry is the science of measuring these patterns, usually as a means of making precise determinations of distances or angular resolutions. The Michelson interferometer was a famous instrument which used interference effects to accurately measure the speed of light.

Constructive interference in thin films can create strong reflection of light in a range of wavelengths, which can be narrow or broad depending on the design of the coating. These films are used to make dielectric mirrors, interference filters, heat reflectors, and filters for color separation in color television cameras. This interference effect is also what causes the colorful rainbow patterns seen in oil slicks.

Diffraction and optical resolution

Diffraction is the process by which light interference is most commonly observed.

The first physical optics model of diffraction that relied on the Huygens–Fresnel principle was developed in 1803 by Thomas Young in his interference experiments with the interference patterns of two closely spaced slits. Young showed that his results could only be explained if the two slits acted as two unique sources of waves rather than corpuscles. In 1815 and 1818, Augustin-Jean Fresnel firmly established the mathematics of how wave interference can account for diffraction.

The simplest physical models of diffraction use equations that describe the angular separation of light and dark fringes due to light of a particular wavelength (λ). In general, the equation takes the form

$$m\lambda = d\sin\theta$$

where d is the separation between two wavefront sources (in the case of Young's experiments, it was two slits), θ is the angular separation between the central fringe and the mth order fringe, where the central maximum is $m=0$.

This equation is modified slightly to take into account a variety of situations such as diffraction

through a single gap, diffraction through multiple slits, or diffraction through a diffraction grating that contains a large number of slits at equal spacing. More complicated models of diffraction require working with the mathematics of Fresnel or Fraunhofer diffraction.

X-ray diffraction makes use of the fact that atoms in a crystal have regular spacing at distances that are on the order of one angstrom. To see diffraction patterns, x-rays with similar wavelengths to that spacing are passed through the crystal. Since crystals are three-dimensional objects rather than two-dimensional gratings, the associated diffraction pattern varies in two directions according to Bragg reflection, with the associated bright spots occurring in unique patterns.

Diffraction effects limit the ability for an optical detector to optically resolve separate light sources. In general, light that is passing through an aperture will experience diffraction and the best images that can be created appear as a central spot with surrounding bright rings, separated by dark nulls; this pattern is known as an Airy pattern, and the central bright lobe as an Airy disk.

The size of such an Airy disk is given by

$$\sin \theta = 1.22 \frac{\lambda}{D}$$

where θ is the angular resolution, λ is the wavelength of the light, and D is the diameter of the lens aperture. If the angular separation of the two points is significantly less than the Airy disk angular radius, then the two points cannot be resolved in the image, but if their angular separation is much greater than this, distinct images of the two points are formed and they can therefore be resolved. Rayleigh defined the somewhat arbitrary "Rayleigh criterion" that two points whose angular separation is equal to the Airy disk radius (measured to first null, that is, to the first place where no light is seen) can be considered to be resolved. It can be seen that the greater the diameter of the lens or its aperture, the finer the resolution. Interferometry, with its ability to mimic extremely large baseline apertures, allows for the greatest angular resolution possible.

Dispersion and scattering

Refractive processes take place in the physical optics limit, where the wavelength of light is similar to other distances, as a kind of scattering. The simplest type of scattering is Thomson scattering which occurs when electromagnetic waves are deflected by single particles. In the limit of Thompson scattering, in which the wavelike nature of light is evident, light is dispersed independent of the frequency, in contrast to Compton scattering which is frequency-dependent and strictly a quantum mechanical process, involving the nature of light as particles. In a statistical sense, elastic scattering of light by numerous particles much smaller than the wavelength of the light is a process known as Rayleigh scattering.

Dispersion occurs when different frequencies of light have different phase velocities, due

either to material properties (*material dispersion*) or to the geometry of an optical waveguide (*waveguide dispersion*). The most familiar form of dispersion is a decrease in index of refraction with increasing wavelength, which is seen in most transparent materials. This is called "normal dispersion". It occurs in all dielectric materials, in wavelength ranges where the material does not absorb light. In wavelength ranges where a medium has significant absorption, the index of refraction can increase with wavelength. This is called "anomalous dispersion".

The separation of colors by a prism is an example of normal dispersion. At the surfaces of the prism, Snell's law predicts that light incident at an angle θ to the normal will be refracted at an angle arcsin($\sin\theta/n$). Thus, blue light, with its higher refractive index, is <u>bent</u> more strongly than red light, resulting in the well-known rainbow pattern.

Polarization

<u>Polarization</u> is a general property of waves that describes the <u>orientation</u> of their <u>oscillations</u>. For transverse waves such as many electromagnetic waves, it describes the orientation of the oscillations in the plane <u>perpendicular</u> to the wave's direction of travel. The oscillations may be oriented in a single direction (linear polarization), or the oscillation direction may rotate as the wave travels (circular or elliptical polarization). Circularly polarized waves can rotate rightward or leftward in the direction of travel, and which of those two rotations is present in a wave is called the wave's <u>chirality</u>.

The typical way to consider polarization is to keep track of the orientation of the electric field vector as the electromagnetic wave propagates. The electric field vector of a plane wave may be arbitrarily divided into two perpendicular components labeled *x* and *y* (with **z** indicating the direction of travel). The shape traced out in the x-y plane by the electric field vector is a Lissajous figure that describes the *polarization state*.

Media that reduce the amplitude of certain polarization modes are called *<u>dichroic</u>* with devices that block nearly all of the radiation in one mode known as *polarizing filters* or simply "polarizers". Malus' law says that when a perfect polarizer is placed in a linear polarized beam of light, the intensity, *I*, of the light that passes through is given by

$$I = I_0 \cos^2 \theta_i \quad ,$$

where I_0 is the initial intensity, and θ_i is the angle between the light's initial polarization direction and the axis of the polarizer.

Vocabulary

★ optics 光学

ultraviolet 紫外的

infrared 红外的

★ account for 说明，解释

diffraction 衍射

★ interference 干涉

reflection 反射

refraction 折射

Fermat's principle 费马原理

index of refraction 折射率；折光率；折射系数

incident 事件，入射的, 传入的

fibre optics 纤维光学；光学纤维，光纤

★ scenario 场景；剧本；情节

★ lens 透镜

convex lenses 凸透镜

★ converge 会聚

concave lenses 凹透镜

★ diverge 发散

focal length 焦距

★ orthogonal 正交

★ scalar 标量

in phase 同相

wave crests 波峰

wave troughs 波谷

constructive interference 相长干涉

destructive interference 相消干涉

★ fringes 条纹

interferometry 干涉仪

slit 狭缝

diffraction grating 衍射光栅

★ angstrom 埃，å

★ resolve 解决，分解，解析

aperture 小孔，缝隙

Rayleigh criterion 瑞利判据

interferometry 干涉测量法

scatter 散射

deflect 偏转，偏离

disperse 消散，弥散，散射

phase velocities 相速度

waveguide 波导

normal dispersion 正常色散

anomalous dispersion 反常色散

★ prism 棱镜

bend 弯曲，弯折

★ polarization 偏振，极化

★ orientation 朝向

★ oscillation 振动，振荡

★ perpendicular 垂直，正交

★ chirality 手性，偏光性

dichroic 二向色性

6   Atomic physics   原子物理

Introduction

Atomic physics is the field of physics that studies atoms as an <u>isolated</u> system of electrons and an atomic nucleus. It is primarily concerned with the arrangement of electrons around the nucleus and the processes by which these arrangements change. This includes ions as well as neutral atoms and, unless otherwise stated, for the purposes of this discussion it should be assumed that the term *atom* includes ions.

The term *atomic physics* is often associated with nuclear power and nuclear bombs, due to the <u>synonymous</u> use of *atomic* and *nuclear* in standard English. However, physicists distinguish between atomic physics — which deals with the atom as a system consisting of a nucleus and electrons — and nuclear physics, which considers atomic nuclei alone.

Isolated atoms

Atomic physics always considers atoms in isolation. Atomic models will consist of a single nucleus that may be surrounded by one or more bound electrons. It is not concerned with the formation of molecules (although much of the physics is identical), nor does it examine atoms in a solid state as condensed matter. It is concerned with processes such as <u>ionization</u> and <u>excitation</u> by photons or collisions with atomic particles.

While modelling atoms in isolation may not seem realistic, if one considers atoms in a gas or <u>plasma</u> then the time-scales for atom-atom interactions are huge in comparison to the atomic processes that are generally considered. This means that the individual atoms can be treated as if each were in isolation, as the vast majority of the time they are. By this consideration atomic physics provides the underlying theory in plasma physics and atmospheric physics, even though both deal with very large numbers of atoms.

Electronic configuration

Electrons form notional shells around the nucleus. These are naturally in a ground state but can be excited by the absorption of energy from light (photons), magnetic fields, or interaction with a colliding particle (typically other electrons).

Electrons that <u>populate</u> a shell are said to be in a <u>bound state</u>. The energy necessary to

remove an electron from its shell (taking it to infinity) is called the <u>binding energy</u>. Any quantity of energy absorbed by the electron in excess of this amount is converted to kinetic energy according to the conservation of energy. The atom is said to have undergone the process of ionization.

In the event the electron absorbs a quantity of energy less than the binding energy, it will <u>transition</u> to an excited state. After a statistically sufficient quantity of time, an electron in an excited state will undergo a transition to a lower state. The change in energy between the two energy levels must be accounted for (conservation of energy). In a <u>neutral</u> atom, the system will emit a photon of the difference in energy. However, if the excited atom has been previously ionized, in particular if one of its inner shell electrons has been removed, a phenomenon known as the <u>Auger effect</u> may take place where the quantity of energy is transferred to one of the bound electrons causing it to go into the <u>continuum</u>. This allows one to multiply ionize an atom with a single photon.

There are rather strict selection rules as to the electronic configurations that can be reached by excitation by light—however there are no such rules for excitation by collision processes.

Electron shell

In chemistry and atomic physics, an **electron shell**, also called a <u>principal energy level</u> may be thought of as an orbit followed by electrons around an atom's nucleus. The closest shell to the nucleus is called the "1 shell" (also called "K shell"), followed by the "2 shell" (or "L shell"), then the "3 shell" (or "M shell"), and so on farther and farther from the nucleus. The shells correspond with the principal quantum numbers (1, 2, 3, 4...) or are labeled alphabetically with letters used in the X-ray notation (K, L, M, …).

Each shell can contain only a fixed number of electrons: The 1st shell can hold <u>up to</u> two electrons, the 2nd shell can hold up to eight electrons, the 3rd shell can hold up to 18, and 4th shell can hold up to 32 and so on. Since electrons are electrically attracted to the nucleus, an atom's electrons will generally occupy outer shells only if the more inner shells have already been completely filled by other electrons. However, this is not a strict requirement: Atoms may have two or even three incomplete outer shells.

The electrons in the outermost occupied shell (or shells) determine the chemical properties of the atom; it is called the *valence shell*.

Each shell consists of one or more *subshells*, and each subshell consists of one or more atomic orbitals.

Shell

The electron shells are labeled *K*, *L*, *M*, *N*, *O*, *P*, and Q; or 1, 2, 3, 4, 5, 6, and 7; going from

innermost shell outwards. Electrons in outer shells have higher average energy and travel farther from the nucleus than those in inner shells. This makes them more important in determining how the atom reacts chemically and behaves as a conductor, because the pull of the atom's nucleus upon them is weaker and more easily broken. In this way, a given element's reactivity is highly dependent upon its electronic configuration.

Subshells

Each shell is composed of one or more subshells, which are themselves composed of atomic orbitals. For example, the first (K) shell has one subshell, called "1s"; the second (L) shell has two subshells, called "2s" and "2p"; the third shell has "3s", "3p", and "3d"; the fourth shell has "4s", "4p", "4d" and "4f"; the fifth shell has "5s", "5p", "5d", and "5f" and can theoretically hold more but the "5f" subshell, although occupied in actinides, is not filled in any element occurring naturally.

Although it is commonly stated that all the electrons in a shell have the same energy, this is an approximation. However, the electrons in one *subshell* do have exactly the same level of energy, with later subshells having more energy per electron than earlier ones. This effect is great enough that the energy ranges associated with shells can overlap.

Number of electrons in each shell

An atom's electron shells are filled according to the following theoretical constraints:

- Each *s* subshell holds at most 2 electrons
- Each *p* subshell holds at most 6 electrons
- Each *d* subshell holds at most 10 electrons
- Each *f* subshell holds at most 14 electrons
- Each *g* subshell holds at most 18 electrons

Therefore, the *K* shell, which contains only an *s* subshell, can hold up to 2 electrons; the *L* shell, which contains an *s* and a *p*, can hold up to 2 + 6 = 8 electrons; and so forth. The general formula is that the *n*th shell can in principle hold up to $2n^2$ electrons.

Although that formula gives the maximum in principle, in fact that maximum is only *achieved* (by known elements) for the first four shells (K,L,M,N). No known element has more than 32 electrons in any one shell. This is because the subshells are filled according to the Aufbau principle.

Aufbau principle

The **Aufbau principle** (from the German *Aufbau* meaning "building up, construction": also **Aufbau rule** or **building-up principle**) postulates a hypothetical process in which an atom is "built up" by progressively adding electrons.

According to the principle, electrons fill orbitals starting at the lowest available (possible) energy levels before filling higher levels (e.g. 1*s* before 2*s*). The number of electrons that can occupy each orbital is limited by the Pauli exclusion principle. If multiple orbitals of the same energy are available, Hund's rule states that unoccupied orbitals will be filled before occupied orbitals are reused (by electrons having different spins).

The Madelung energy ordering rule

The order in which these orbitals are filled is given by the *n + l rule* (also known as the **Madelung rule** or the **Klechkowski rule**), where orbitals with a lower *n + l* value are filled before those with higher *n + l* values. In this context, *n* represents the principal quantum number and *l* the azimuthal quantum number; the values *l* = 0, 1, 2, 3 correspond to the *s*, *p*, *d*, and *f* labels, respectively.

The rule is based on the total number of nodes in the atomic orbital, *n + l*, which is related to the energy. In the case of equal *n + l* values, the orbital with a lower *n* value is filled first. The fact that most of the ground state configurations of neutral atoms fill orbitals following this *n + l, n* pattern was obtained experimentally, by reference to the spectroscopic characteristics of the elements.

This gives the following order for filling the orbitals:

1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p, 6s, 4f, 5d, 6p, 7s, 5f, 6d, 7p, (8s, 5g, 6f, 7d, 8p, and 9s)

The Madelung energy ordering rule applies only to neutral atoms in their ground state, and even in that case, there are several elements for which it predicts configurations that differ from those determined experimentally. Copper, chromium, and palladium are common examples of this property. According to the Madelung rule, the 4s orbital ($n + l = 4 + 0 = 4$) is occupied before the 3d orbital ($n + l = 3 + 2 = 5$). The rule then predicts the configuration of $_{29}$Cu to be $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^9$, abbreviated $[Ar]4s^2 3d^9$ where [Ar] denotes the configuration of Ar (the preceding noble gas). However the experimental electronic configuration of the copper atom is $[Ar]4s^1 3d^{10}$. By filling the 3d orbital, copper can be in a lower energy state. Similarly, chromium takes the electronic configuration of $[Ar]4s^1 3d^5$ instead of $[Ar]4s^2 3d^4$. In this case, chromium has a half-full 3d shell. For palladium, the Madelung rule predicts $[Kr]5s^2 4d^8$, but the experimental configuration $[Kr]4d^{10}$ differs in the placement of two electrons.

Valence shells

The **valence shell** is the outermost shell of an atom. It is usually (and misleadingly) said that the electrons in this shell make up its valence electrons, that is, the electrons that determine how the atom behaves in chemical reactions. Just as atoms with complete valence shells (noble gases) are the most chemically non-reactive, those with only one electron in their valence shells (alkali

metals) or just missing one electron from having a complete shell (halogens) are the most reactive.

However, this is a simplification of the truth. The electrons that determine how an atom reacts chemically are those that **travel farthest** from the nucleus, that is, those with the highest **energy**. For the transition elements, the partially filled $(n-1)$d energy level is very close in energy to the ns level and hence the d electrons in transition metals behave as valence electrons although they are not in the so-called valence shell.

Excitation and ionization

Excited state

Excitation is an elevation in energy level above an arbitrary baseline energy state. In physics there is a specific technical definition for energy level which is often associated with an atom being excited to an excited state.

In quantum mechanics an **excited state** of a system (such as an atom, molecule or nucleus) is any quantum state of the system that has a higher energy than the ground state (that is, more energy than the absolute minimum). The temperature of a group of particles is indicative of the level of excitation.

The lifetime of a system in an excited state is usually short: spontaneous or induced emission of a quantum of energy (such as a photon or a phonon) usually occurs shortly after the system is promoted to the excited state, returning the system to a state with lower energy (a less excited state or the ground state). This return to a lower energy level is often loosely described as decay and is the inverse of excitation.

Long-lived excited states are often called metastable.

Atomic excitation

A simple example of this concept comes by considering the hydrogen atom.

The ground state of the hydrogen atom corresponds to having the atom's single electron in the lowest possible orbit (that is, the spherically symmetric "1s" wavefunction, which has the lowest possible quantum numbers). By giving the atom additional energy (for example, by the absorption of a photon of an appropriate energy), the electron is able to move into an excited state (one with one or more quantum numbers greater than the minimum possible). If the photon has too much energy, the electron will cease to be bound to the atom, and the atom will become ionized.

After excitation the atom may return to the ground state or a lower excited state, by emitting a photon with a characteristic energy. Emission of photons from atoms in various excited states leads to an electromagnetic spectrum showing a series of characteristic emission lines (including, in

the case of the hydrogen atom, the Lyman, Balmer, Paschen and Brackett series.)

An atom in a high excited state is termed Rydberg atom. A system of highly excited atoms can form a long-lived condensed excited state e.g. a condensed phase made completely of excited atoms: Rydberg matter. Hydrogen can also be excited by heat or electricity.

Ionization

Ionization is the process of converting an atom or molecule into an ion by adding or removing charged particles such as electrons or ions. In the case of ionization of a gas, ion pairs are created consisting of a free electron and a positive ion.

Types of ionization

The process of ionization works slightly differently depending on whether an ion with a positive or a negative electric charge is being produced. A positively charged ion is produced when an electron bonded to an atom (or molecule) absorbs the proper amount of energy to escape from the electric potential barrier that originally confined it, thus breaking the bond and freeing it to move. The amount of energy required is called the ionization energy. A negatively charged ion is produced when a free electron collides with an atom and is subsequently caught inside the electric potential barrier, releasing any excess energy.

In general, ionization can be broken down into two types: *sequential ionization* and *non-sequential ionization*. In classical physics, only sequential ionization can take place. Non-sequential ionization violates several laws of classical physics.

Classical ionization

Applying only classical physics and the Bohr model of the atom makes both atomic and molecular ionization entirely deterministic; that is, every problem will always have a definite and computable answer. According to classical physics, it is absolutely necessary that the energy of the electron exceeds the energy difference of the potential barrier it is trying to pass. In concept, this idea should make sense: The same way a person cannot jump over a one-meter wall without jumping at least one meter off the ground, an electron cannot get over a 13.6-eV potential barrier without at least 13.6 eV of energy.

Applying to positive ionization

According to these two principles, the energy required to release an electron is *strictly* greater than or equal to the potential difference between the current bound atomic or molecular orbital and the highest possible orbital. If the energy absorbed exceeds this potential, then the electron is emitted as a free electron. Otherwise, the electron briefly enters an excited state until the energy absorbed is radiated out and the electron re-enters the lowest available state.

Applying to negative ionization

Due to the shape of the potential barrier, according to these principles, a free electron must have an energy greater than or equal to that of the potential barrier in order to make it over. If a free electron has enough energy to do so, it will be bound to the lowest available energy state, and the remaining energy will be radiated away. If the electron does not have enough energy to surpass the potential barrier, then it is forced away by the electrostatic force, described by Coulombs Law, associated with the electric potential barrier.

Sequential ionization

Sequential ionization is a description of how the ionization of an atom or molecule takes place. For example, an ion with a +2 charge can be created only from an ion with a +1 charge or a +3 charge. That is, the numerical charge of an atom or molecule must change sequentially, always moving from one number to an adjacent, or *sequential*, number.

Quantum ionization

In quantum mechanics, ionization can still happen classically, whereby the electron has enough energy to make it over the potential barrier, but there is the additional possibility of tunnel ionization.

Tunnel ionization

Tunnel ionization is ionization due to quantum tunneling. In classical ionization, an electron must have enough energy to make it over the potential barrier, but quantum tunneling allows the electron simply to go through the potential barrier instead of going all the way over it because of the wave nature of the electron. The probability of an electron's tunneling through the barrier drops off exponentially with the width of the potential barrier. Therefore, an electron with a higher energy can make it further up the potential barrier, leaving a much thinner barrier to tunnel through and, thus, a greater chance to do so.

Non-sequential ionization

When the fact that the electric field of light is an alternating electric field is combined with tunnel ionization, the phenomenon of non-sequential ionization emerges. An electron that tunnels out from an atom or molecule may be sent right back in by the alternating field, at which point it can either recombine with the atom or molecule and release any excess energy or have the chance to further ionize the atom or molecule through high-energy collisions. This additional ionization is referred to as non-sequential ionization for two reasons: One, there is no order to how the second electron is removed, and, two, an atom or molecule with a +2 charge can be created straight from an atom or molecule with a neutral charge, so the integer charges are not *sequential*. Non-sequential

ionization is often studied at lower laser-field intensities, since most ionization events are sequential when the ionization rate is high.

Vocabulary

★ isolated 孤立的，隔离的

★ nucleus 原子核

synonymous 同义，同义词

ionization 离子化

★ excitation 激发，兴奋

plasma 等离子体

★ ground state 基态

populate 居住于，定居于

★ bound state 束缚态；结合状态

★ binding energy 结合能

★ transition 转变，过渡

★ neutral 中性的

Auger effect 俄格效应

principal energy level 主能级

continuum 连续体

up to 最多，最大为，胜任

valence shell 价电子层

electronic configuration 电子构型，电子排布

actinides 超铀元素

aufbau principle 构造原理；电子充填原理

pauli exclusion principle 泡利不相容原理

★ spin 自旋

★ node 结点，节点

copper 铜

chromium 铬

palladium 钯

Ar 氩(argon)

noble gas 惰性气体

alkali metals 碱金属

transition elements 过渡元素

baseline 基线

indicative 指示，标示，说明

★ spontaneous 自发的

★ induced 诱导的，感应的

phonon 声子

★ decay 蜕变，衰退，腐烂

metastable 亚稳的

★ spectrum 波谱，光谱，范围，系列

★ sequential 按次序的，顺序的

★ violate 违反

★ deterministic 决定论的

★ surpass 超过

quantum tunneling 量子穿隧

★ exponentially 指数性地

7   Statistical mechanics   统计力学

Overview

Statistical mechanics or **statistical thermodynamics** is a branch of physics that applies probability theory, which contains mathematical tools for dealing with large populations, to the study of the *thermodynamic* behavior of systems composed of a *large* number of particles. Statistical mechanics provides a framework for relating the microscopic properties of individual atoms and molecules to the macroscopic bulk properties of materials that can be observed in everyday life, thereby explaining thermodynamics as a result of the classical- and quantum-mechanical descriptions of statistics and mechanics at the microscopic level.

Statistical mechanics provides a molecular-level interpretation of macroscopic thermodynamic quantities such as work, heat, free energy, and entropy. It enables the thermodynamic properties of bulk materials to be related to the spectroscopic data of individual molecules. This ability to make macroscopic predictions based on microscopic properties is the main advantage of statistical mechanics over classical thermodynamics. Both theories are governed by the second law of thermodynamics through the medium of entropy. However, entropy in thermodynamics can only be known empirically, whereas in statistical mechanics, it is a function of the distribution of the system on its microstates.

The essential problem in statistical thermodynamics is to calculate the distribution of a given amount of energy *E* over *N* identical systems. The goal of statistical thermodynamics is to understand and to interpret the measurable macroscopic properties of materials in terms of the properties of their constituent particles and the interactions between them. This is done by connecting thermodynamic functions to quantum-mechanical equations. Two central quantities in statistical thermodynamics are the Boltzmann factor and the partition function.

Fundamentals

Central topics covered in statistical thermodynamics include:

- Microstates and configurations
- Maxwell–Boltzmann distribution law
- Partition function

- Thermodynamic equilibrium - thermal, mechanical, and chemical.
- Internal degrees of freedom - rotation, vibration, electronic excitation, etc.
- Heat capacity – Einstein solids, polyatomic gases, etc.
- Nernst heat theorem
- Fluctuations
- Gibbs paradox
- Degeneracy

Heat capacity

Heat capacity, or thermal capacity, is the measurable physical quantity that specifies the amount of heat required to change the temperature of an object or body by a given amount. The SI unit of heat capacity is joule per kelvin, J/K.

Heat capacity is an extensive property of matter, meaning it is proportional to the size of the system. When expressing the same phenomenon as an intensive property, the heat capacity is divided by the amount of substance, mass, or volume, so that the quantity is independent of the size or extent of the sample. The molar heat capacity is the heat capacity per mole of a pure substance and the specific heat capacity, often simply called specific heat, is the heat capacity per unit mass of a material. Occasionally, in engineering contexts, the volumetric heat capacity is used.

Temperature reflects the average randomized kinetic energy of particles in matter, while heat is the transfer of thermal energy across a system boundary into the body or from the body to the environment. Translation, rotation, and a combination of the two types of energy in vibration (kinetic and potential) of atoms represent the degrees of freedom of motion which classically contribute to the heat capacity of matter, but loosely bound electrons may also participate. On a microscopic scale, each system particle absorbs thermal energy among the few degrees of freedom available to it, and at sufficient temperatures, this process contributes to the specific heat capacity that classically approaches a value per mole of particles that is set by the Dulong-Petit law. This limit, which is about 3R (25 joules per kelvin) for each mole of atoms, is achieved by many solid substances at room temperature.

For quantum mechanical reasons, at any given temperature, some of these degrees of freedom may be unavailable, or only partially available, to store thermal energy. In such cases, the specific heat capacity is a fraction of the maximum. As the temperature approaches absolute zero, the specific heat capacity of a system also approaches zero, due to loss of available degrees of freedom. Quantum theory can be used to quantitatively predict the specific heat capacity of simple systems.

Nernst heat theorem

The Nernst heat theorem was formulated by Walther Nernst early in the twentieth century and was used in the development of the third law of thermodynamics.

The Nernst heat theorem says that as absolute zero is approached, the entropy change ΔS for a chemical or physical transformation approaches 0. This can be expressed mathematically as follow

$$\lim_{T \to 0} \Delta S = 0$$

Gibbs paradox

In statistical mechanics, a semi-classical derivation of the entropy that does not take into account the indistinguishability of particles, yields an expression for the entropy which is not extensive (is not proportional to the amount of substance in question). This leads to a paradox known as the Gibbs paradox, after Josiah Willard Gibbs. The paradox allows for the entropy of closed systems to decrease, violating the second law of thermodynamics. It is possible, however, to take the perspective that it is merely the definition of entropy that is changed to ignore particle permutation (and thereby avert the paradox).

Lastly, and most importantly, the formal definition of entropy of a thermodynamic system from a statistical perspective is called statistical entropy, and is defined as:

$$S = k_B \ln \Omega$$

where k_B is Boltzmann's constant 1.38066×10^{-23} J K^{-1} and Ω is the number of microstates corresponding to the observed thermodynamic macrostate.

This equation is valid only if each microstate is equally accessible (each microstate has an equal probability of occurring).

Fundamental postulate

The fundamental postulate in statistical mechanics (also known as the equal *a priori* probability postulate) is the following:

Given an isolated system in equilibrium, it is found with equal probability in each of its accessible microstates.

This postulate is a fundamental assumption in statistical mechanics -- it states that a system in equilibrium does not have any preference for any of its available microstates. Given Ω microstates at a particular energy, the probability of finding the system in a particular microstate is $p = 1/\Omega$.

This postulate is necessary because it allows one to conclude that for a system at equilibrium, the thermodynamic state (macrostate) which could result from the largest number of microstates is also the most probable macrostate of the system.

Statistical ensembles

The modern formulation of statistical mechanics is based on the description of the physical system by an ensemble that represents all possible configurations of the system and the probability of realizing each configuration.

Each ensemble is associated with a partition function that, with mathematical manipulation, can be used to extract values of thermodynamic properties of the system. According to the relationship of the system to the rest of the universe, one of three general types of ensembles may apply, in order of increasing complexity:

- Microcanonical ensemble: describes a completely isolated system, having constant energy, as it does not exchange energy or mass with the rest of the universe.
- Canonical ensemble: describes a system in thermal equilibrium with its environment. It may only exchange energy in the form of heat with the outside.
- Grand-canonical ensemble: used in open systems which exchange energy and mass with the outside.

Microcanonical ensemble

In microcanonical ensemble N, V and E are fixed. Since the second law of thermodynamics applies to isolated systems, the first case investigated will correspond to this case.

The entropy of such a system can only increase, so that the maximum of its entropy corresponds to an equilibrium state for the system.

Because an isolated system keeps a constant energy, the total energy of the system does not fluctuate. Thus, the system can access only those of its micro-states that correspond to a given value E of the energy. The internal energy of the system is then strictly equal to its energy.

Let $\Omega(E)$ be the number of micro-states corresponding to this value of the system's energy. The macroscopic state of maximal entropy for the system is the one in which all micro-states are equally likely to occur, with probability $1/\Omega(E)$, during the system's fluctuations, and we have for the system's entropy:

$$S = -k_B \sum_{i=1}^{\Omega(E)} \frac{1}{\Omega(E)} \ln \frac{1}{\Omega(E)} = k_B \ln \Omega(E)$$

Canonical ensemble

In canonical ensemble N, V and T are fixed. Invoking the concept of the canonical ensemble, it is possible to derive the probability P_i that a macroscopic system in thermal equilibrium with its environment, will be in a given microstate with energy E_i according to the Boltzmann distribution:

$$P_i = \frac{e^{-\beta E_i}}{\sum_{j=1}^{j\text{max}} e^{-\beta E_j}}$$

$\beta = \dfrac{1}{k_B T}$ known as the **Thermodynamic beta** or **inverse temperature.**

The temperature T arises from the fact that the system is in thermal equilibrium with its environment.

The probabilities of the various microstates must add to one, and the normalization factor in the denominator is the canonical partition function:

$$Z = \sum_{i=1}^{i\text{max}} e^{-\beta E_i}$$

where E_i is the energy of the ith microstate of the system. The partition function is a measure of the number of states accessible to the system at a given temperature.

To sum up, the probability of finding a system at temperature T in a particular state with energy E_i is

$$P_i = \frac{e^{-\beta E_i}}{Z}.$$

Thus the partition function looks like the weight factor for the ensemble.

The partition function can be used to find the expected (average) value of any microscopic property of the system, which can then be related to macroscopic variables. For instance, the expected value of the microscopic energy E is *interpreted* as the microscopic definition of the thermodynamic variable internal energy U, and can be obtained by taking the derivative of the partition function with respect to the temperature. Indeed,

$$\langle E \rangle = \frac{\sum_i E_i e^{-\beta E_i}}{Z} = -\frac{1}{Z}\frac{dZ}{d\beta}$$

The entropy can be calculated by

$$\frac{S}{k} = -\sum_i p_i \ln p_i = \sum_i \frac{e^{-\beta E_i}}{Z}(\beta E_i + \ln Z) = \ln Z + \beta U$$

which implies that

$$-\frac{\ln(Z)}{\beta} = U - TS = F$$

Having microscopic expressions for the basic thermodynamic potentials U (internal energy), S (entropy) and F (free energy) is sufficient to derive expressions for other thermodynamic quantities. The basic strategy is as follows. There may be an intensive or extensive quantity that enters explicitly in the expression for the microscopic energy E_i, for instance magnetic field

(intensive) or volume (extensive). Then, the conjugate thermodynamic variables are derivatives of the internal energy. The macroscopic magnetization (extensive) is the derivative of U with respect to the (intensive) magnetic field, and the pressure (intensive) is the derivative of U with respect to volume (extensive).

Grand canonical ensemble

In grand canonical ensemble V, T and chemical potential are fixed. If the system under study is an open system (in which matter can be exchanged), *but* particle number is not conserved, we would have to introduce chemical potentials, μ_j, $j = 1,...,n$ and replace the canonical partition function with the grand canonical partition function:

$$\Xi(V, T, \mu) = \sum_i \exp\left[\beta\left(\sum_{j=1}^n \mu_j N_{ij} - E_i\right)\right]$$

where N_{ij} is the number of jth species particles in the ith configuration. Sometimes, we also have other variables to add to the partition function, one corresponding to each conserved quantity. Most of them, however, can be safely interpreted as chemical potentials.

Equivalence between descriptions at the thermodynamic limit

All of the above descriptions differ in the way they allow the given system to fluctuate between its configurations.

In the micro-canonical ensemble, the system exchanges no energy with the outside world, and is therefore not subject to energy fluctuations; in the canonical ensemble, the system is free to exchange energy with the outside in the form of heat.

In the thermodynamic limit, which is the limit of large systems, fluctuations become negligible, so that all these descriptions converge to the same description. In other words, the macroscopic behavior of a system does not depend on the particular ensemble used for its description.

Given these considerations, the best ensemble to choose for the calculation of the properties of a macroscopic system is that ensemble which allows the result to be derived most easily.

Vocabulary

★ atistical mechanics 统计力学

probability theory 概率论

thermodynamic 热力学

populations 人口，种群，总数

★ bulk 大部分，主体，大量

★ interpretation 阐释，解释，理解，说明

spectroscopic 频谱的，光谱的

entropy 熵

microstates 微观状态

★ essential 本质的，核心的

★ identical 相同的

★ boltzmann factor 玻尔兹曼因子

★ partition function 配分函数

★ vibration 振动

polyatomic 多原子的

★ fluctuations 涨落

★ paradox 悖论

degeneracy 简并

molar heat capacity 摩尔热容

specific heat capacity 比热容

indistinguishability 同粒子不可区分性

★ perspective 透视，观点，看法

permutation 置换，排列，组合

★ *a priori* 先验的，由因及果

the equal *a priori* probability postulate 先验等概率假设

★ ensemble 系综，整体，全体

★ manipulation 操作，处理

canonical ensemble 正则系综

grand-canonical ensemble 巨正则系综

★ weight factor 权重因子

thermodynamic limit 热力学极限

8   Quantum mechanics   量子力学

Introduction

Quantum mechanics (QM – also known as **quantum physics**, or **quantum theory**) is a branch of physics which deals with physical phenomena at microscopic scales, where the action is on the order of the Planck constant. Quantum mechanics departs from classical mechanics primarily at the *quantum realm* of atomic and subatomic length scales. Quantum mechanics provides a mathematical description of much of the dual *particle-like* and *wave-like* behavior and interactions of energy and matter. Quantum mechanics is the non-relativistic limit of Quantum Field Theory (QFT), a theory that was developed later that combined Quantum Mechanics with Relativity Theory.

The name *quantum mechanics* derives from the observation that some physical quantities can change only in *discrete* amounts (Latin *quanta*), and not in a continuous way. For example, the angular momentum of an electron bound to an atom or molecule is quantized. In the context of quantum mechanics, the wave–particle duality of energy and matter and the uncertainty principle provide a unified view of the behavior of photons, electrons, and other atomic-scale objects.

The mathematical formulations of quantum mechanics are abstract. A mathematical function known as the wavefunction provides information about the probability amplitude of position, momentum, and other physical properties of a particle. Mathematical manipulations of the wavefunction usually involve the bra-ket notation, which requires an understanding of complex numbers and linear functions. The wavefunction treats the object as a quantum harmonic oscillator, and the mathematics is akin to that describing acoustic resonance. Many of the results of quantum mechanics are not easily visualized in terms of classical mechanics—for instance, the ground state in a quantum mechanical model is a non-zero energy state that is the lowest permitted energy state of a system, as opposed to a more "traditional" system that is thought of as simply being at rest, with zero kinetic energy.

The earliest versions of quantum mechanics were formulated in the first decade of the 20th century. At around the same time, the atomic theory and the corpuscular theory of light first came to be widely accepted as scientific fact; these latter theories can be viewed as quantum theories of matter and electromagnetic radiation, respectively. Early quantum theory was significantly reformulated in the mid-1920s by Heisenberg, Born and Jordan, who created matrix

mechanics; de Broglie and Schrödinger (Wave Mechanics); and Pauli and Bose (statistics of subatomic particles). And the Copenhagen interpretation of Niels Bohr became widely accepted. By 1930, quantum mechanics had been further unified and formalized by the work of Hilbert, Dirac and John von Neumann, with a greater emphasis placed on measurement in quantum mechanics, the statistical nature of our knowledge of reality, and philosophical speculation about the role of the observer. Quantum mechanics has since branched out into almost every aspect of 20th century physics and other disciplines, such as quantum chemistry, quantum electronics, quantum optics, and quantum information science. Much 19th century physics has been re-evaluated as the "classical limit" of quantum mechanics, and its more advanced developments in terms of quantum field theory, string theory, and speculative quantum gravity theories.

Quantum mechanics is essential to understanding the behavior of systems at atomic length scales and smaller. In addition, if classical mechanics truly governed the workings of an atom, electrons would really 'orbit' the nucleus. Since bodies in circular motion accelerate, they must emit radiation and collide with the nucleus in the process. This clearly contradicts the existence of stable atoms.

Quantum mechanics was initially developed to provide a better explanation and description of the atom, especially the differences in the spectra of light emitted by different isotopes of the same element, as well as subatomic particles. In short, the quantum-mechanical atomic model has succeeded spectacularly in the realm where classical mechanics and electromagnetism falter.

Broadly speaking, quantum mechanics incorporates four classes of phenomena for which classical physics cannot account:

- The quantization of certain physical properties
- Wave–particle duality
- The Uncertainty principle
- Quantum entanglement

Mathematical formulations

In the mathematical formulation of quantum mechanics, the possible states of a quantum mechanical system are represented by unit vectors (called "state vectors"). Formally, these reside in a complex separable Hilbert space - variously called the "state space" or the "associated Hilbert space" of the system - that is well defined up to a complex number of norm 1 (the phase factor). In other words, the possible states are points in the projective space of a Hilbert space,

usually called the complex projective space. Each observable is represented by a Hermitian (self-adjoint) linear operator acting on the state space. Each eigenstate of an observable corresponds to an eigenvector of the operator, and the associated eigenvalue corresponds to the value of the observable in that eigenstate. If the operator's spectrum is discrete, the observable can attain only those discrete eigenvalues.

In the formalism of quantum mechanics, the state of a system at a given time is described by a complex wave function, also referred to as state vector in a complex vector space. This abstract mathematical object allows for the calculation of probabilities of outcomes of concrete experiments. For example, it allows one to compute the probability of finding an electron in a particular region around the nucleus at a particular time. Contrary to classical mechanics, one can never make simultaneous predictions of conjugate variables, such as position and momentum, with accuracy. For instance, electrons may be considered (to a certain probability) to be located somewhere within a given region of space, but with their exact positions unknown. Contours of constant probability, often referred to as "clouds", may be drawn around the nucleus of an atom to conceptualize where the electron might be located with the most probability. Heisenberg's uncertainty principle quantifies the inability to precisely locate the particle given its conjugate momentum.

According to one interpretation, as the result of a measurement the wave function containing the probability information for a system collapses from a given initial state to a particular eigenstate. The possible results of a measurement are the eigenvalues of the operator representing the observable — which explains the choice of *Hermitian* operators, for which all the eigenvalues are real. The probability distribution of an observable in a given state can be found by computing the spectral decomposition of the corresponding operator. Heisenberg's uncertainty principle is represented by the statement that the operators corresponding to certain observables do not commute.

The probabilistic nature of quantum mechanics thus stems from the act of measurement. This is one of the most difficult aspects of quantum systems to understand. It was the central topic in the famous Bohr-Einstein debates, in which the two scientists attempted to clarify these fundamental principles by way of thought experiments. In the decades after the formulation of quantum mechanics, the question of what constitutes a "measurement" has been extensively studied. Newer interpretations of quantum mechanics have been formulated that do away with the concept of "wavefunction collapse" . The basic idea is that when a quantum system interacts with a measuring apparatus, their respective wavefunctions become entangled, so that the original quantum system ceases to exist as an independent entity.

Generally, quantum mechanics does not assign definite values. Instead, it makes a prediction using a probability distribution; that is, it describes the probability of obtaining the possible

outcomes from measuring an observable. Often these results are skewed by many causes, such as dense probability clouds. Probability clouds are approximate, but better than the Bohr model, whereby electron location is given by a probability function, the wave function eigenvalue, such that the probability is the squared modulus of the complex amplitude, or quantum state nuclear attraction. Naturally, these probabilities will depend on the quantum state at the "instant" of the measurement. Hence, uncertainty is involved in the value. There are, however, certain states that are associated with a definite value of a particular observable. These are known as eigenstates of the observable ("eigen" can be translated from German as meaning "inherent" or "characteristic").

The time evolution of a quantum state is described by the Schrödinger equation, in which the Hamiltonian (the operator corresponding to the total energy of the system) generates the time evolution. The time evolution of wave functions is deterministic in the sense that - given a wavefunction at an *initial* time - it makes a definite prediction of what the wavefunction will be at any *later* time.

During a measurement, on the other hand, the change of the initial wavefunction into another, later wavefunction is not deterministic, it is unpredictable (i.e., random).

Wave functions change as time progresses. The Schrödinger equation describes how wavefunctions change in time, playing a role similar to Newton's second law in classical mechanics. The Schrödinger equation, applied to the aforementioned example of the free particle, predicts that the center of a wave packet will move through space at a constant velocity (like a classical particle with no forces acting on it). However, the wave packet will also spread out as time progresses, which means that the position becomes more uncertain with time. This also has the effect of turning a position eigenstate (which can be thought of as an infinitely sharp wave packet) into a broadened wave packet that no longer represents a (definite, certain) position eigenstate.

Some wave functions produce probability distributions that are constant, or independent of time - such as when in a stationary state of constant energy, time vanishes in the absolute square of the wave function. Many systems that are treated dynamically in classical mechanics are described by such "static" wave functions. For example, a single electron in an unexcited atom is pictured classically as a particle moving in a circular trajectory around the atomic nucleus, whereas in quantum mechanics it is described by a static, spherically symmetric wavefunction surrounding the nucleus (note, however, that only the lowest angular momentum states, labeled *s*, are spherically symmetric).

The Schrödinger equation acts on the *entire* probability amplitude, not merely its absolute value. Whereas the absolute value of the probability amplitude encodes information about probabilities, its phase encodes information about the interference between quantum states. This gives rise to the "wave-like" behavior of quantum states. As it turns out, analytic solutions of the

Schrödinger equation are available for only a very small number of relatively simple model Hamiltonians, of which the quantum harmonic oscillator, the particle in a box, the hydrogen molecular ion, and the hydrogen atom are the most important representatives. Even the helium atom - which contains just one more electron than does the hydrogen atom - has defied all attempts at a fully analytic treatment.

There exist several techniques for generating approximate solutions, however. In the important method known as perturbation theory, one uses the analytic result for a simple quantum mechanical model to generate a result for a more complicated model that is related to the simpler model by (for one example) the addition of a weak potential energy. Another method is the "semi-classical equation of motion" approach, which applies to systems for which quantum mechanics produces only weak (small) deviations from classical behavior. These deviations can then be computed based on the classical motion. This approach is particularly important in the field of quantum chaos.

Quantization

In physics, quantization is the process of transition from a classical understanding of physical phenomena to a newer understanding known as "quantum mechanics". It is a procedure for constructing a quantum field theory starting from a classical field theory. This is a generalization of the procedure for building quantum mechanics from classical mechanics. One also speaks of **field quantization**, as in the "quantization of the electromagnetic field", where one refers to photons as field "quanta". This procedure is basic to theories of particle physics, nuclear physics, condensed matter physics, and quantum optics.

The fundamental notion that a physical property may be "quantized," is referred to as "the hypothesis of quantization". This means that the magnitude can take on only certain discrete values.

Quantization methods

Quantization converts classical fields into operators acting on quantum states of the field theory. The lowest energy state is called the vacuum state and may be very complicated. The reason for quantizing a theory is to deduce properties of materials, objects or particles through the computation of quantum amplitudes. Such computations have to deal with certain subtleties called renormalization, which, if neglected, can often lead to nonsense results, such as the appearance of infinities in various amplitudes. The full specification of a quantization procedure requires methods of performing renormalization.

The first method to be developed for quantization of field theories was canonical quantization. While this is extremely easy to implement on sufficiently simple theories, there are

many situations where other methods of quantization <u>yield</u> more efficient procedures for computing quantum amplitudes. However, the use of canonical quantization has <u>left its mark</u> on the language and interpretation of quantum field theory.

Canonical quantization

Canonical quantization of a field theory is analogous to the construction of quantum mechanics from classical mechanics. The classical field is treated as a dynamical variable called the canonical coordinate, and its time-derivative is the canonical momentum. One introduces a commutation relation between these which is exactly the same as the commutation relation between a particle's position and momentum in quantum mechanics. Technically, one converts the field to an operator, through combinations of creation and annihilation operators. The field operator acts on quantum states of the theory. The lowest energy state is called the vacuum state. The procedure is also called second quantization.

This procedure can be applied to the quantization of any field theory: whether of fermions or bosons, and with any internal symmetry. However, it leads to a fairly simple picture of the vacuum state and is not easily <u>amenable</u> to use in some quantum field theories, such as quantum chromodynamics which is known to have a complicated vacuum characterized by many different condensates.

Wave-particle duality

Wave–particle duality postulates that all particles exhibit both wave and particle properties. A central concept of quantum mechanics, this duality addresses the inability of classical concepts like "particle" and "wave" to fully describe the behavior of quantum-scale objects. Standard interpretations of quantum mechanics explain this paradox as a fundamental property of the Universe, while alternative interpretations explain the duality as an <u>emergent</u>, second-order consequence of various limitations of the observer. This treatment focuses on explaining the behavior from the <u>perspective</u> of the widely used Copenhagen interpretation, in which wave–particle duality serves as one aspect of the concept of complementarity, that one can view phenomenon in one way or in another, but not both simultaneously.

Huygens and Newton

The earliest comprehensive theory of light was advanced by Huygens, who <u>proposed</u> a wave theory of light, and in particular demonstrated how waves might interfere to form a wavefront, propagating in a straight line. However, the theory had difficulties in other matters, and was soon overshadowed by Isaac Newton's corpuscular theory of light. That is, Newton proposed that light

consisted of small particles, with which he could easily explain the phenomenon of reflection. With considerably more difficulty, he could also explain refraction through a lens, and the splitting of sunlight into a rainbow by a prism. Newton's particle viewpoint went essentially unchallenged for over a century.

Young, Fresnel, and Maxwell

In the early 19th century, the double-slit experiments by Young and Fresnel provided evidence for Huygens' wave theories. The double-slit experiments showed that when light is sent through a grid, a characteristic interference pattern is observed, very similar to the pattern resulting from the interference of water waves; the wavelength of light can be computed from such patterns. The wave view did not immediately displace the ray and particle view, but began to dominate scientific thinking about light in the mid 19th century, since it could explain polarization phenomena that the alternatives could not.

In the late 19th century, James Clerk Maxwell explained light as the propagation of electromagnetic waves according to the Maxwell equations. These equations were verified by experiment by Heinrich Hertz in 1887, and the wave theory became widely accepted.

Einstein's explanation of the photoelectric effect

In 1905, Albert Einstein provided an explanation of the photoelectric effect, a hitherto troubling experiment that the wave theory of light seemed incapable of explaining. He did so by postulating the existence of photons, quanta of light energy with particulate qualities.

In the photoelectric effect, it was observed that shining a light on certain metals would lead to an electric current in a circuit. Presumably, the light was knocking electrons out of the metal, causing current to flow. However, using the case of potassium as an example, it was also observed that while a dim blue light was enough to cause a current, even the strongest, brightest red light available with the technology of the time caused no current at all. According to the classical theory of light and matter, the strength or amplitude of a light wave was in proportion to its brightness: a bright light should have been easily strong enough to create a large current. Yet, oddly, this was not so.

Einstein explained this conundrum by postulating that the electrons can receive energy from electromagnetic field only in discrete portions (quanta that were called photons): an amount of energy E that was related to the frequency f of the light by

$$E = h f$$

where h is Planck's constant (6.626×10^{-34} J·s). Only photons of a high enough frequency (above a certain *threshold* value) could knock an electron free. For example, photons of blue light had sufficient energy to free an electron from the metal, but photons of red light did not. More intense

light above the threshold frequency could release more electrons, but no amount of light (using technology available at the time) below the threshold frequency could release an electron. To "violate" this law would require extremely high intensity lasers. Intensity-dependent phenomena have now been studied in detail with such lasers.

De Broglie's wavelength

In 1924, Louis-Victor de Broglie formulated the de Broglie hypothesis, claiming that *all* matter, not just light, has a wave-like nature; he related wavelength (denoted as λ), and momentum (denoted as *p*):

$$\lambda = \frac{h}{p}$$

This is a generalization of Einstein's equation above, since the momentum of a photon is given by $p = E/c$ and the wavelength (in a vacuum) by $\lambda = c/f$, where c is the speed of light in vacuum.

Heisenberg's uncertainty principle

In his work on formulating quantum mechanics, Werner Heisenberg postulated his uncertainty principle, which states:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Where

- Δ here indicates standard deviation, a measure of spread or uncertainty;
- x and p are a particle's position and linear momentum respectively.
- $\hbar$ is the reduced Planck's constant (Planck's constant divided by 2π).

Heisenberg originally explained this as a consequence of the process of measuring: Measuring position accurately would disturb momentum and vice-versa, offering an example (the "gamma-ray microscope") that depended crucially on the de Broglie hypothesis. It is now thought, however, that this only partly explains the phenomenon, but that the uncertainty also exists in the particle itself, even before the measurement is made.

In fact, the modern explanation of the uncertainty principle, extending the Copenhagen interpretation first put forward by Bohr and Heisenberg, depends even more centrally on the wave nature of a particle: Just as it is nonsensical to discuss the precise location of a wave on a string, particles do not have perfectly precise positions; likewise, just as it is nonsensical to discuss the wavelength of a "pulse" wave traveling down a string, particles do not have perfectly precise momenta (which corresponds to the inverse of wavelength). Moreover, when position is relatively well defined, the wave is pulse-like and has a very ill-defined wavelength (and thus momentum). And conversely, when momentum (and thus wavelength) is relatively well defined, the wave looks long and sinusoidal, and therefore it has a very ill-defined position.

De Broglie himself had proposed a [pilot wave](#) construct to explain the observed wave–particle duality. In this view, each particle has a well-defined position and momentum, but is guided by a wave function derived from Schrödinger's equation. The pilot wave theory was initially rejected because it generated non-local effects when applied to systems involving more than one particle. Non-locality, however, soon became established as an integral feature of quantum theory, and David Bohm extended de Broglie's model to explicitly include it. In the resulting representation, also called the de Broglie–Bohm theory or Bohmian mechanics, the wave–particle duality is not a property of matter itself, but an appearance generated by the particle's motion subject to a guiding equation or quantum potential.

Quantum entanglement

Quantum entanglement is a physical phenomenon that occurs when particles such as photons, electrons, molecules as large as buckyballs, and even small diamonds interact and then become separated, with the type of interaction such that each resulting member of a pair is properly described by the same quantum mechanical description (state), which is indefinite in terms of important factors such as position, momentum, spin, polarization, etc.

Quantum entanglement is a form of [quantum superposition](#). When a measurement is made and it causes one member of such a pair to take on a definite value (e.g., clockwise spin), the other member of this entangled pair will at any subsequent time be found to have taken the appropriately correlated value (e.g., counterclockwise spin). Thus, there is a correlation between the results of measurements performed on entangled pairs, and this correlation is observed even though the entangled pair may have been separated by arbitrarily large distances. In quantum entanglement, part of the transfer happens instantaneously.

This behavior is consistent with quantum-mechanical theory, has been demonstrated experimentally, and is an area of extremely active research by the physics community. However there is some heated debate about whether a possible classical underlying mechanism could explain why this correlation occurs instantaneously even when the separation distance is large. The difference in opinion derives from espousal of various interpretations of quantum mechanics.

Research into quantum entanglement was initiated by a 1935 paper by Albert Einstein, Boris Podolsky, and Nathan Rosen describing the EPR paradox and several papers by Erwin Schrödinger shortly thereafter. Although these first studies focused on the counterintuitive properties of entanglement, with the aim of criticizing quantum mechanics, eventually entanglement was verified experimentally, and recognized as a valid, fundamental feature of quantum mechanics. The focus of the research has now changed to its utilization as a resource for communication and computation.

Concept

Quantum systems can become entangled through various types of interactions. If entangled, one constituent cannot be fully described without considering the other(s). They remain entangled until a measurement is made or <u>decohered</u> by the environment.

An example of entanglement occurs when subatomic particles decay into other particles. These decay events obey the various conservation laws, and as a result, pairs of particles can be generated so that they are in some specific quantum states. For instance, a pair of these particles may be generated having a two-state spin: one must be spin up and the other must be spin down. This type of entangled pair, where the particles always have opposite spin, is known as the *spin anti-correlated* case, and if the probabilities for measuring each spin are equal, the pair is said to be in the <u>singlet state</u>.

Entanglement, non-locality and hidden variables

There is much confusion about the meaning of entanglement, <u>non-locality</u> and hidden variables and how they relate to each other. As described above, entanglement is an experimentally verified and accepted property of nature, which has critical implications for the interpretations of quantum mechanics. The question becomes, "How can one <u>account for</u> something that was at one point indefinite with regard to its spin (or whatever is in this case the subject of investigation) suddenly becoming definite in that regard even though no physical interaction with the second object occurred, and, if the two objects are sufficiently far separated, could not even have had the time needed for such an interaction to proceed from the first to the second object?" The latter question involves the issue of locality, i.e., whether for a change to occur in something the agent of change has to be in physical contact (at least via some <u>intermediary</u> such as a field force) with the thing that changes. Study of entanglement brings into sharp focus the <u>dilemma</u> between locality and the completeness or lack of completeness of quantum mechanics.

Bell's theorem and related results <u>rule out</u> a local realistic explanation for quantum mechanics (one which obeys the principle of locality while also <u>ascribing</u> definite values to quantum observables). However, in other interpretations, the experiments that demonstrate the apparent non-locality can also be described in local terms: If each distant observer regards the other as a quantum system, communication between the two must then be treated as a measurement process, and this communication is strictly local. In particular, in the many worlds interpretation, the underlying description is fully local. More generally, the question of locality in quantum physics is extraordinarily subtle and sometimes hinges on precisely how it is defined.

In the media and popular science, quantum non-locality is often <u>portrayed</u> as being equivalent to entanglement. While it is true that a <u>bipartite</u> quantum state must be entangled in order for it to

produce non-local correlations, there exist entangled states that do not produce such correlations. A well-known example of this is the Werner state that is entangled for certain values of , but can always be described using local hidden variables. In short, entanglement of a two-party state is necessary but not sufficient for that state to be non-local. It is important to recognize that entanglement is more commonly viewed as an algebraic concept, noted for being a precedent to non-locality as well as to quantum teleportation and to superdense coding, whereas non-locality is defined according to experimental statistics and is much more involved with the foundations and interpretations of quantum mechanics.

Vocabulary

★ quantum mechanics　量子力学

action　作用量，作用，动作

★ planck constant　普朗克常数

departs　离开，偏离

non-relativistic　非相对论的

quantum field theory　量子场论

★ discrete　离散的

★ wave-particle duality　波粒二象性

probability amplitude　概率幅度，几率幅

bra-ket notation　狄拉克符号

harmonic oscillator　谐振子

akin　同类，类似于

acoustic resonance　声学共振

corpuscular　微粒子的

matrix mechanics　矩阵力学

★ Copenhagen interpretation　哥本哈根诠释

★ speculation　猜测，思索，思考

★ aspect　方面，外观

speculative　猜测性的

★ contradicts　与...矛盾，抵触

isotope　同位素

falter　蹒跚，结巴，支吾

★ incorporates　合并，混和，包含

quantum entanglement　量子纠缠

unit vectors　单位矢量

reside　居住在，属于

complex separable hilbert space　可分离的复数希尔伯特空间

★ projective space　投影空间

self-adjoint　自伴随的，自共轭的

★ eigenstate　本征态

★ eigenvector　本征矢量

★ attain　达到，获得

★ concrete　具体的，混凝土

★ simultaneous　同时的

conjugate variables　共轭变量

conceptualize　使概念化，构思

spectral decomposition　频谱分解

★ represent　表示，表现，描述，代表

★ commute　交换，代偿，对易

stems from　源自，由...造成

★ debate　辩论

★ apparatus　设备，仪器

cease　停止，结束

skew　弯曲，偏移，影响...的准确性

squared modulus　模平方

★ hamiltonian　哈密顿量

★ schrödinger equation　薛定谔方程

defy 使落空，蔑视，违抗

quantum chaos 量子混沌

quantization 量子化

speaks of 说到，表明

refers to as 说到，指的是

★ operator 算符

subtlety 微妙，巧妙

renormalization 重整化，正则化

★ yield 产出，产量，提供

left its mark 留下印记

canonical coordinate 正则坐标

commutation relation 交换关系；对易关系

creation operator 创生算符

annihilation operator 湮灭算符

★ amenable 顺从的；适合处理的

quantum chromodynamics 量子色动力学

condensate 浓缩物，凝聚态(?)

emergent 浮现的，紧急的

★ perspective 看法，观点，透视图

★ complementarity 互补性

★ propose 建议，认为，提议

photoelectric effect 光电效应

hitherto 迄今，至今

★ proportion to 成比例，正比于，相称

oddly 奇怪地

conundrum 谜题

laser 激光

★ standard deviation 标准偏差

★ crucially 决定性的，重要的

nonsensical 无意义的

conversely 相反

pilot wave 导航波

construct 构造，建造，构思，结构

buckyball 富勒烯/巴基球（由碳原子构成的大型封闭球状结构）

quantum superposition 量子叠加

espousal 支持，拥挤，婚嫁

counterintuitive 违反直觉的

decohere 使...散开，使...不相干

singlet state 单峰态

non-locality 非定域性

★ account for 解释

intermediary 媒介物

★ dilemma 困境，进退两难

completeness 完整性，完备性

★ rule out 排除，不考虑

ascribe 把...归于

portray 描绘

bipartite 由两部分组成的，二分的

teleportation 远距传物

superdense coding 超密编码

9   Special relativity   狭义相对论

Introduction

In physics, **special relativity** is a fundamental theory concerning space and time, developed by Albert Einstein in 1905 as a modification of Galilean relativity. The theory was able to explain some pressing theoretical and experimental issues in the physics of the time involving light and electrodynamics.

Einstein postulated that the speed of light in free space is the same for all observers, regardless of their motion relative to the light source. This postulate stemmed from the assumption that Maxwell's equations of electromagnetism, which predict a specific speed of light in a vacuum, hold in any inertial frame of reference. This prediction contradicted the laws of classical mechanics, which had been accepted for centuries, by arguing that time and space are not fixed and in fact change to maintain a constant speed of light regardless of the relative motions of sources and observers. Einstein's approach was based on thought experiments, calculations, and the principle of relativity, which is the notion that all physical laws should appear the same to all inertial observers.

The predictions of special relativity are almost identical to those of Galilean relativity for most everyday phenomena, in which speeds are much lower than the speed of light, but it makes different, non-obvious predictions for objects moving at very high speeds. These predictions have been experimentally tested on numerous occasions since the theory's inception. The major predictions of special relativity are:

- Relativity of simultaneity: Observers who are in motion with respect to each other may disagree on whether two events occurred at the same time or one occurred before the other.
- Time dilation (An observer watching two identical clocks, one moving and one at rest, will measure the moving clock to tick more slowly)
- Length contraction (Along the direction of motion, a rod moving with respect to an observer will be measured to be shorter than an identical rod at rest), and
- The equivalence of mass and energy (written as $E = mc^2$).

Special relativity predicts a non-linear velocity addition formula which prevents speeds greater than that of light from being observed. In 1908, Hermann Minkowski reformulated the theory based on different postulates of a more geometrical nature. This approach considers space

and time as being different components of a single entity, the spacetime. Likewise, energy and momentum are the components of the four-momentum, and the electric and magnetic field are the components of the electromagnetic tensor.

As Galilean relativity is now considered an approximation of special relativity valid for low speeds, special relativity is considered an approximation of the theory of general relativity valid for weak gravitational fields. General relativity postulates that physical laws should appear the same to *all* observers (an accelerating frame of reference being equivalent to one in which a gravitational field acts), and that gravitation is the effect of the curvature of spacetime caused by energy (including mass).

Relativity of simultaneity

In physics, the **relativity of simultaneity** is the concept that *distant simultaneity* – whether two spatially separated events occur at the same time – is not absolute, but depends on the observer's reference frame.

According to the special theory of relativity, it is impossible to say in an *absolute* sense whether two distinct events occur at the same time if those events are separated in space, such as a car crash in London and another in New York. The question of whether the events are simultaneous is *relative*: in some reference frames the two accidents may happen at the same time, in other frames (in a different state of motion relative to the events) the crash in London may occur first, and in still other frames the New York crash may occur first. However, if the two events are causally connected ("event A causes event B"), the causal order is preserved (i.e., "event A precedes event B") in all frames of reference.

Lorentz transformations

The relativity of simultaneity can be calculated using Lorentz transformations, which relate the coordinates used by one observer to coordinates used by another in uniform relative motion with respect to the first.

Assume that the first observer uses coordinates labeled $t, x, y,$ and z, while the second observer uses coordinates labeled $t', x', y',$ and z'. Now suppose that the first observer sees the second moving in the x-direction at a velocity v. And suppose that the observer's coordinate axes are parallel and that they have the same origin. Then, the Lorentz transformations show that the coordinates are related by the equations:

$$t' = \frac{t - v\,x/c^2}{\sqrt{1 - v^2/c^2}}\ ,$$

$$x' = \frac{x - v\,t}{\sqrt{1 - v^2/c^2}}\ , \qquad y' = y\ , \quad z' = z\ ,$$

where c is the speed of light.

If two events happen at the same time in the frame of the first observer, they will have identical values of the t-coordinate. However, if they have different values of the x-coordinate (different positions in the x-direction), we see that they will have different values of the t' coordinate; they will happen at different times in that frame. The term that accounts for the failure of absolute simultaneity is that $v\,x/c^2$.

The equation $t' = $ constant defines a "line of simultaneity" in the (x', t') coordinate system for the second (moving) observer, just as the equation $t = $ constant defines the "line of simultaneity" for the first (stationary) observer in the (x, t) coordinate system. We can see from the above equations for the Lorentz transform that t' is constant if and only if $t - v\,x/c^2 = $ constant. Thus the set of points that make t constant are different from the set of points that makes t' constant. That is, the set of events which are regarded as simultaneous depends on the frame of reference used to make the comparison.

Time dilation and length contraction

Relative velocity time dilation

When two observers are in relative uniform motion and uninfluenced by any gravitational mass, the point of view of each will be that the other's (moving) clock is ticking at a *slower* rate than the local clock. The faster the relative velocity, the greater the magnitude of time dilation. This case is sometimes called special relativistic time dilation.

For instance, two rocket ships (A and B) speeding past one another in space would experience time dilation. If they somehow had a clear view into each other's ships, each crew would see the others' clocks and movement as going too slowly. That is, inside the frame of reference of Ship A, everything is moving normally, but everything over on Ship B appears to be moving slower (and vice versa).

Time dilation due to relative velocity

The formula for determining time dilation in special relativity is:

$$\Delta t' = \gamma\,\Delta t = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where Δt is the time interval between two co-local events (i.e. happening at the same place) for an observer in some inertial frame (e.g. ticks on his clock), this is known as the proper time, $\Delta t'$ is the time interval between those same events, as measured by another observer, inertially moving with velocity v with respect to the former observer, v is the relative velocity between the observer and the moving clock, c is the speed of light, and

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

is the Lorentz factor.

Muon lifetime

A comparison of muon lifetimes at different speeds is possible. In the laboratory, slow muons are produced, and in the atmosphere very fast moving muons are introduced by cosmic rays. Taking the muon lifetime at rest as the laboratory value of 2.22 μs, the lifetime of a cosmic ray produced muon traveling at 98% of the speed of light is about five times longer, in agreement with observations. In this experiment the "clock" is the time taken by processes leading to muon decay, and these processes take place in the moving muon at its own "clock rate", which is much slower than the laboratory clock.

Length contraction

In physics, **length contraction** is the physical phenomenon of a decrease in length detected by an observer of objects that travel at any non-zero velocity relative to that observer. This contraction (more formally called Lorentz contraction) is usually only noticeable at a substantial fraction of the speed of light; the contraction is only in the direction parallel to the direction in which the observed body is travelling. This effect is negligible at everyday speeds, and can be ignored for all regular purposes. As the magnitude of the velocity approaches the speed of light, the effect becomes dominant, as can be seen from the formula:

$$L = \frac{L_0}{\gamma(v)} = L_0\sqrt{1 - v^2/c^2}$$

L_0 is the proper length (the length of the object in its rest frame), L is the length observed by an observer in relative motion with respect to the object.

Mass-energy equivalence

A physical system has a property called energy and a corresponding property called mass; the two properties are equivalent in that they are always both present in the same (i.e. constant) proportion to one another. Mass–energy equivalence arose originally from special relativity, as

developed by Albert Einstein, and is described by the famous equation:

$$E = mc^2$$

where E is energy, m is mass, and c is the speed of light. Thus, Einstein stated that the universal proportionality factor between equivalent amounts of energy and mass is equal to the speed of light squared. This also serves to convert units of mass to units of energy, no matter what system of measurement units is used.

Since there are different ways to define the mass of a body, $E=mc^2$ can indicate slightly different meanings. For instance, m or m_0 is called the invariant mass or rest mass of a body, which is related to the rest energy by $E_0 = m_0 c^2$. In other texts, the mass is defined in connection with relativistic momentum or energy, called relativistic mass m_{rel}. So in this context the formula $E = m_{rel} c^2$ indicates that energy always exhibits relativistic mass in whatever form the energy takes. Mass–energy equivalence does not imply that mass may be "converted" to energy, but it allows for *matter* to disappear, leaving only its associated energy behind, as non-material energy. *Mass* remains conserved (i.e., the quantity of mass remains constant), since it is a property of matter and also any type of energy. Energy is also conserved. In physics, mass must be differentiated from matter. Matter, when seen as certain types of particles, *can* be created and destroyed (as in particle annihilation or creation), but an isolated system of precursors and products of such reactions, as a whole, retains both the original mass and energy throughout the reaction.

When the system is not isolated, and energy is *removed* from a system (for example in nuclear fission or nuclear fusion), some mass is always removed along with the energy, according to their equivalence where one always accompanies the other. This energy thus is associated with the missing mass, and this mass will be added to any other system which absorbs the removed energy. In this situation $E = mc^2$ can be used to calculate how much mass goes along with the removed energy. It also tells how much mass will be added to any system which later absorbs this energy. This was the original use of the equation when derived by Einstein.

$E=mc^2$ has sometimes been used as an explanation for the origin of energy in nuclear processes, but mass–energy equivalence does not explain the origin of such energies. Instead, this relationship merely indicates that the large amounts of energy released in such reactions may exhibit enough mass that the mass-loss may be measured, when the released energy (and its mass) have been removed from the system. For example, the loss of mass to an atom and a neutron, as a result of the capture of the neutron and the production of a gamma ray, has been used to test mass-energy equivalence to high precision, as the energy of the gamma ray may be compared with the mass defect after capture. In 2005, these were found to agree to 0.0004%, the most precise test of the equivalence of mass and energy to date. This test was performed in the World Year of Physics 2005, a centennial celebration of Einstein's achievements in 1905.

Conservation of mass and energy

Mass and energy can be seen as two names (and two measurement units) for the same underlying, conserved physical quantity. Thus, the laws of conservation of energy and conservation of (total) mass are equivalent and both hold true.

On the other hand, if the conservation of mass law is interpreted as conservation of *rest* mass, this does not hold true in general. The *rest* energy (equivalently, rest mass) of a particle can be converted, not "to energy" (it already *is* energy (mass)), but rather to *other* forms of energy (mass) which require motion, such as kinetic energy, thermal energy, or radiant energy; similarly, kinetic or radiant energy can be converted to other kinds of particles which have rest energy (rest mass). In the transformation process, neither the total amount of mass nor the total amount of energy changes, since both are properties which are connected to each other via a simple constant. This view requires that if either energy or (total) mass disappears from a system, it will always be found that both have simply moved off to another place, where they may both be measured as an increase of both energy and mass corresponding to the loss in the first system.

Fast-moving objects and systems of objects

When an object is pulled in the direction of motion, it gains momentum and energy, but when the object is already traveling near the speed of light, it cannot move much faster, no matter how much energy it absorbs. Its momentum and energy continue to increase without bounds, whereas its speed approaches a constant value—the speed of light. This implies that in relativity the momentum of an object cannot be a constant times the velocity, nor can the kinetic energy be a constant times the square of the velocity.

A property called the relativistic mass is defined as the ratio of the momentum of an object to its velocity. Relativistic mass depends on the motion of the object, so that different observers in relative motion see different values for it. If the object is moving slowly, the relativistic mass is nearly equal to the rest mass and both are nearly equal to the usual Newtonian mass. If the object is moving quickly, the relativistic mass is greater than the rest mass by an amount equal to the mass associated with the kinetic energy of the object. As the object approaches the speed of light, the relativistic mass grows infinitely, because the kinetic energy grows infinitely and this energy is associated with mass.

The relativistic mass is always equal to the total energy (rest energy plus kinetic energy) divided by c^2. Because the relativistic mass is exactly proportional to the energy, relativistic mass and relativistic energy are nearly synonyms; the only difference between them is the units. If length and time are measured in natural units, the speed of light is equal to 1, and even this difference disappears. Then mass and energy have the same units and are always equal, so it is redundant to

speak about relativistic mass, because it is just another name for the energy. This is why physicists usually reserve the useful short word "mass" to mean rest-mass, or invariant mass, and not relativistic mass.

The relativistic mass of a moving object is larger than the relativistic mass of an object that is not moving, because a moving object has extra kinetic energy. The *rest mass* of an object is defined as the mass of an object when it is at rest, so that the rest mass is always the same, independent of the motion of the observer: it is the same in all inertial frames.

For things and systems made up of many parts, like an atomic nucleus, planet, or star, the relativistic mass is the sum of the relativistic masses (or energies) of the parts, because energies are additive in isolated systems. This is not true in systems which are open, however, if energy is subtracted. For example, if a system is *bound* by attractive forces, and the energy gained due to the forces of attraction in excess of the work done is removed from the system, then mass will be lost with this removed energy. For example, the mass of an atomic nucleus is less than the total mass of the protons and neutrons that make it up, but this is only true after this energy from binding has been removed in the form of a gamma ray (which in this system, carries away the mass of the energy of binding). This mass decrease is also equivalent to the energy required to break up the nucleus into individual protons and neutrons (in this case, work and mass would need to be supplied). Similarly, the mass of the solar system is slightly less than the masses of sun and planets individually.

For a system of particles going off in different directions, the invariant mass of the system is the analog of the rest mass, and is the same for all observers, even those in relative motion. It is defined as the total energy (divided by c^2) in the center of mass frame (where by definition, the system total momentum is zero). A simple example of an object with moving parts but zero total momentum is a container of gas. In this case, the mass of the container is given by its total energy (including the kinetic energy of the gas molecules), since the system total energy and invariant mass are the same in any reference frame where the momentum is zero, and such a reference frame is also the only frame in which the object can be weighed. In a similar way, the theory of special relativity posits that the thermal energy in all objects (including solids) contributes to their total masses and weights, even though this energy is present as the kinetic and potential energies of the atoms in the object, and it (in a similar way to the gas) is not seen in the rest masses of the atoms that make up the object.

In a similar manner, even photons (light quanta), if trapped in a container space (as a photon gas or thermal radiation), would contribute a mass associated with their energy to the container. Such an extra mass, in theory, could be weighed in the same way as any other type of rest mass. This is true in special relativity theory, even though individually photons have no rest mass. The

property that trapped energy *in any form* adds weighable mass to systems that have no net momentum is one of the characteristic and notable consequences of relativity. It has no counterpart in classical Newtonian physics, in which radiation, light, heat, and kinetic energy never exhibit weighable mass under any circumstances.

Just as the relativistic mass of isolated system is conserved through time, so also is its invariant mass. It is this property which allows the conservation of all types of mass in systems, and also conservation of all types of mass in reactions where matter is destroyed (annihilated), leaving behind the energy that was associated with it (which is now in non-material form, rather than material form). Matter may appear and disappear in various reactions, but mass and energy are both unchanged in this process.

Relativistic energy-momentum relation

In inertial reference frames other than the rest frame or center of mass frame, the equation $E=mc^2$ remains true if the energy is the relativistic energy *and* the mass the relativistic mass. It is also correct if the energy is the rest or invariant energy (also the minimum energy), *and* the mass is the rest mass, or the invariant mass. However, connection of the **total or relativistic energy** (E_r) with the **rest or invariant mass** (m_0) requires consideration of the system total momentum, in systems and reference frames where the total momentum has a non-zero value. The formula then required to connect the two different kinds of mass and energy, is the extended version of Einstein's equation, called the relativistic energy–momentum relation:

$$E_r^2 - |\vec{p}|^2 c^2 = m_0^2 c^4$$
$$E_r^2 - (pc)^2 = (m_0 c^2)^2$$

Binding energy and the "mass defect"

Whenever any type of energy is removed from a system, the mass associated with the energy is also removed, and the system therefore loses mass. This mass defect in the system may be simply calculated as $\Delta m = \Delta E/c^2$, and this was the form of the equation historically first presented by Einstein in 1905. However, use of this formula in such circumstances has led to the false idea that mass has been "converted" to energy. This may be particularly the case when the energy (and mass) removed from the system is associated with the *binding energy* of the system. In such cases, the binding energy is observed as a "mass defect" or deficit in the new system. The fact that the released energy is not easily weighed in many such cases, may cause its mass to be neglected <u>as though</u> it no longer existed. This circumstance, along with the real conversion of matter (not mass) to energy in some high energy particle reactions, has caused the conversion of *matter* to energy

(which occurs) to be conflated with the false idea of conversion of *mass* to energy, which does not occur.

The difference between the rest mass of a bound system and of the unbound parts is the binding energy of the system, if this energy has been removed after binding. For example, a water molecule weighs a little less than two free hydrogen atoms and an oxygen atom; the minuscule mass difference is the energy that is needed to split the molecule into three individual atoms (divided by c^2), and which was given off as heat when the molecule formed (this heat had mass). Likewise, a stick of dynamite in theory weighs a little bit more than the fragments after the explosion, but this is true only so long as the fragments are cooled and the heat removed. In this case the mass difference is the energy/heat that is released when the dynamite explodes, and when this heat escapes, the mass associated with it escapes, only to be deposited in the surroundings which absorb the heat (so that total mass is conserved).

Such a change in mass may only happen when the system is open, and the energy and mass escapes. Thus, if a stick of dynamite is blown up in a hermetically sealed chamber, the mass of the chamber and fragments, the heat, sound, and light would still be equal to the original mass of the chamber and dynamite. If sitting on a scale, the weight and mass would not change. This would in theory also happen even with a nuclear bomb, if it could be kept in an ideal box of infinite strength, which did not rupture or pass radiation. Thus, a 21.5 kiloton (9×10^{13} joule) nuclear bomb produces about one gram of heat and electromagnetic radiation, but the mass of this energy would not be detectable in an exploded bomb in an ideal box sitting on a scale; instead, the contents of the box would be heated to millions of degrees without changing total mass and weight. If then, however, a transparent window (passing only electromagnetic radiation) were opened in such an ideal box after the explosion, and a beam of X-rays and other lower-energy light allowed to escape the box, it would eventually be found to weigh one gram less than it had before the explosion. This weight-loss and mass-loss would happen as the box was cooled by this process, to room temperature. However, any surrounding mass which had absorbed the X-rays (and other "heat") would **gain** this gram of mass from the resulting heating, so the mass "loss" would represent merely its relocation. Thus, no mass (or, in the case of a nuclear bomb, no matter) would be "converted" to energy in such a process. Mass and energy, as always, would both be separately conserved.

Massless particles

Massless particles have zero rest mass. Their relativistic mass is simply their relativistic energy, divided by c^2, or m(relativistic) = E/c^2. The energy for photons is $E = hf$ where h is Planck's constant and f is the photon frequency. This frequency and thus the relativistic energy are frame-dependent.

If an observer runs away from a photon in the direction it travels from a source, having it catch

up with the observer, then when the photon catches up it will be seen as having less energy than it had at the source. The faster the observer is traveling with regard to the source when the photon catches up, the less energy the photon will have. As an observer approaches the speed of light with regard to the source, the photon looks redder and redder, by relativistic Doppler effect (the Doppler shift is the relativistic formula), and the energy of a very long-wavelength photon approaches zero. This is why a photon is *massless*; this means that the rest mass of a photon is zero.

Massless particles contribute rest mass and invariant mass to systems

Two photons moving in different directions cannot both be made to have arbitrarily small total energy by changing frames, or by moving toward or away from them. The reason is that in a two-photon system, the energy of one photon is decreased by chasing after it, but the energy of the other will increase with the same shift in observer motion. Two photons not moving in the same direction will exhibit an inertial frame where the combined energy is smallest, but not zero. This is called the center of mass frame or the center of momentum frame; these terms are almost synonyms (the center of mass frame is the special case of a center of momentum frame where the center of mass is put at the origin). The most that chasing a pair of photons can accomplish to decrease their energy is to put the observer in frame where the photons have equal energy and are moving directly away from each other. In this frame, the observer is now moving in the same direction and speed as the center of mass of the two photons. The total momentum of the photons is now zero, since their momentums are equal and opposite. In this frame the two photons, as a system, have a mass equal to their total energy divided by c^2. This mass is called the invariant mass of the pair of photons together. It is the smallest mass and energy the system may be seen to have, by any observer. It is only the invariant mass of a two-photon system that can be used to make a single particle with the same rest mass.

If the photons are formed by the collision of a particle and an antiparticle, the invariant mass is the same as the total energy of the particle and antiparticle (their rest energy plus the kinetic energy), in the center of mass frame, where they will automatically be moving in equal and opposite directions (since they have equal momentum in this frame). If the photons are formed by the disintegration of a *single* particle with a well-defined rest mass, like the neutral pion, the invariant mass of the photons is equal to rest mass of the pion. In this case, the center of mass frame for the pion is just the frame where the pion is at rest, and the center of mass does not change after it disintegrates into two photons. After the two photons are formed, their center of mass is still moving the same way the pion did, and their total energy in this frame adds up to the mass energy of the pion. Thus, by calculating the invariant mass of pairs of photons in a particle detector, pairs can be identified that were probably produced by pion disintegration.

A similar calculation illustrates that the invariant mass of systems is conserved, even when

massive particles (particles with rest mass) within the system are converted to massless particles (such as photons). In such cases, the photons contribute invariant mass to the system, even though they individually have no invariant mass or rest mass. Thus, an electron and positron (each of which has rest mass) may undergo annihilation with each other to produce two photons, each of which is massless (has no rest mass). However, in such circumstances, no system mass is lost. Instead, the system of both photons moving away from each other has an invariant mass, which acts like a rest mass for any system in which the photons are trapped, or that can be weighed. Thus, not only the quantity of relativistic mass, but also the quantity of invariant mass does not change in transformations between "matter" (electrons and positrons) and energy (photons).

Vocabulary

★ special relativity 狭义相对论

★ concern 涉及，关注，关系到，担心

★ issue 议题，问题，发行

★ postulate 假设

relative to 相对于

stemmed from 来源于

inertial frame of reference 惯性参考系

★ contradict 抵触，与...矛盾

★ argue 主张，争辩，论证

approach 靠近，接近，方法

inception 创始，起初，开端

simultaneity 同时性

★ with respect to 至于，有关，相对

time dilation 时间膨胀

length contraction 时间收缩

electromagnetic tensor 电磁张量

general relativity 广义相对论

gravitational fields 重力场

curvature 曲率

★ transformations 变换

proper time 原时，固有时间

muon μ子

★ dominant 显性的，显著的，占优势的

mass–energy equivalence 质量-能量等价性

precursor 前体，前任

retain 保留，维持

nuclear fission 核裂变

nuclear fusion 核聚变

neutron 中子

centennial celebration 百年庆典

★ bound 界限，边界，级限，bind 的过去式

★ redundant 多余的，冗余的

posit 假设，论断，安置

mass defect 质量亏损

★ as though 恰如，好像

minuscule 微小的，小写字的

dynamite 炸药

★ deposite 沉积，储存，存款

hermetically 牢牢地，密封地

rupture 破裂

relocation 重新安置

disintegration 蜕变，分解

neutral pion 中性介子

★ identify 识别

positron 正电子