

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

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正文标记说明:

蓝色 Arial 字体 (例如 **energy**): 已知的专业词汇

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

黑色 Times New Roman 字体加下划线 (例如 **postulate**): 新学的普通词汇

# 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  **$\Lambda$  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  
 [\$\Lambda\$  CDM model](#)  $\Lambda$ -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](#)  $\mathbf{r}$  from  $O$  to the [particle](#).

In general, the point particle need not be stationary relative to  $O$ , so  $\mathbf{r}$  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":

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

The quantity  $m\vec{v}$  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  $\mathbf{F}$  on another particle B, it follows that B must exert an [equal and opposite reaction force](#),  $-\mathbf{F}$ , on A. The strong form of Newton's third law requires that  $\mathbf{F}$  and  $-\mathbf{F}$  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  $\mathbf{F}$  is applied to a particle that achieves a [displacement](#)  $\Delta\mathbf{r}$ , 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  $\mathbf{r}_1$  to  $\mathbf{r}_2$  along a path  $C$ , the work done on the particle is given by the [line integral](#)

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

If the work done in moving the particle from  $\mathbf{r}_1$  to  $\mathbf{r}_2$  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  $\mathbf{r}_1$  to  $\mathbf{r}_2$  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  $v_{\text{cm}}$ , 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](#)  $\omega$ :

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

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,  $\mathbf{r}$ . 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  $\mathbf{r}$  and the momentum vector  $\mathbf{p}$  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**:

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

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

[projectiles](#) 抛体

[quantum mechanics](#) 量子力学

[reconcile](#) 调整，使和谐

[wave-particle duality](#) 波粒二象性

[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 洛伦兹力

★ 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 states a set of four laws that are valid for all systems that fall within the constraints implied by each. In the various theoretical descriptions of thermodynamics these laws may be expressed in seemingly differing forms, but the most prominent 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:  $\Delta U = Q - W$ .
- **Second law of thermodynamics:** Heat cannot spontaneously flow 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 tacitly 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 reliance 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 asserts 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 **isolated system** 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 even out 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 postulate 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  $-273.15^{\circ}\text{C}$  (degrees Celsius), or  $-459.67^{\circ}\text{F}$  (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](#):  $E=U-TS$
- [Enthalpy](#):  $H=U+pV$
- [Gibbs free energy](#):  $G=H-TS$
- [Landau potential \(Grand potential\)](#):  $\Omega=U-TS-\mu N$

## 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

[macroscopic variables](#) 宏观变量

★ **entropy** 熵

[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

circumvent 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, *νορτκελη 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:

$$F = \frac{Q_1 Q_2}{4\pi r^2 \epsilon_0} ,$$

where  $\epsilon_0$  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](#) ( $\text{N C}^{-1}$ ) or, equivalently, [volts per meter](#) ( $\text{V m}^{-1}$ ). The SI base units of the electric field are  $\text{kg m} \cdot \text{s}^{-3} \cdot \text{A}^{-1}$ . 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](#):

$$\oint_S \vec{E} \cdot d\vec{A} = \int_V \frac{\rho}{\epsilon_0} \cdot dV.$$

Alternatively, in [differential form](#), the equation becomes

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}.$$

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,  $\Phi$ , 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

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

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**, *d***l** is a vector whose magnitude is the length of the [differential](#) element of the wire, in the direction of conventional current, and  $\mu_0$  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  $\mathbf{B}$  or  $\mathbf{H}$  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  $\mathbf{B}$ -field (in tesla, T) around closed curve  $C$  is proportional to the total current  $I_{\text{enc}}$  passing through a surface  $S$  (enclosed by  $C$ ):

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

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

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  $d\mathbf{S}$  could point in either of the two directions [normal](#) to the surface; and  $I_{\text{enc}}$  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  $d\mathbf{S}$ . Also the current passing in the same direction as  $d\mathbf{S}$  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](#)  $\mathbf{J}_M$  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](#)  $\mathbf{J}_P$ .

### 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](#)  $\mathbf{P}$ . A changing state of polarization is equivalent to a current.

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

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

where the electric displacement field is defined as:

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} = \epsilon_0 \epsilon_r \mathbf{E} ,$$

where  $\epsilon_0$  is the electric constant,  $\epsilon_r$  the relative static permittivity, and  $\mathbf{P}$  is the polarization density.

Substituting this form for  $\mathbf{D}$  in the expression for displacement current, it has two components:

$$\mathbf{J}_D = \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t} .$$

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  $\mathbf{H}$ -field is (the  $\mathbf{H}$ -field is used because it includes the magnetization currents, so  $\mathbf{J}_M$  does not appear explicitly):

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

where  $\mathbf{H}$  is the magnetic H field (also called "[auxiliary magnetic field](#)", "[magnetic field intensity](#)", or just "magnetic field"),  $\mathbf{D}$  is the [electric displacement field](#), and  $\mathbf{J}_f$  is the enclosed conduction current or free current density. In differential form,

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

## 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](#)  $\mathbf{B}$  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  $\mathbf{B}$  is the magnetic field.

### Integral form

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

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

where  $S$  is any [closed surface](#), and  $d\mathbf{A}$  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**  $\Phi_B$  through a **hypothetical surface**  $\Sigma$  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  $d\mathbf{A}$  is an element of surface area of the moving surface  $\Sigma(t)$ ,  $\mathbf{B}$  is the magnetic field, and  $\mathbf{B} \cdot d\mathbf{A}$  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  $\mathbf{B}$  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  $\mathcal{E}$ , 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),

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

the EMF on a wire loop is:

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

where  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field (aka **magnetic flux density**, **magnetic induction**),  $d\boldsymbol{\ell}$  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  $\mathcal{E}$  is the electromotive force (EMF) in volts and  $\Phi_B$  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  $\Phi_B$ , 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  $\Phi_B$  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  $\Sigma$  is a surface bounded by the [closed contour](#)  $\partial \Sigma$ ,  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field.  $d\boldsymbol{\ell}$  is an infinitesimal vector element of the contour  $\partial \Sigma$ ,  $d\mathbf{A}$  is an infinitesimal vector element of surface  $\Sigma$ .

## 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  $\mathbf{E}$ , a vector field, and the magnetic field  $\mathbf{B}$ , 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**  $\rho$  and **current density**  $\mathbf{J}$ .

In this language there are four equations. Two of them describe how the fields vary in space due to sources, if any; electric fields emanating 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 [reflection](#) says that the reflected ray lies in the plane of incidence, and the angle of reflection equals the angle of incidence.
- The law of [refraction](#) 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  $\theta_1$  and  $\theta_2$  are the angles between the normal (to the interface) and the [incident](#) 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 [fibre optics](#) 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 [scenario](#) is known as [Brewster's angle](#).

A device which produces converging or diverging light rays due to refraction is known as a [lens](#). Thin lenses produce focal points on either side that can be modelled using the [lensmaker's equation](#). In general, two types of lenses exist: [convex lenses](#), which cause parallel light rays to [converge](#), and [concave lenses](#), which cause parallel light rays to [diverge](#). Similarly to curved mirrors, thin lenses follow a simple equation that determines the location of the images given a particular [focal length](#) ( $f$ ) 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  $3.0 \times 10^8$  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  $\mu$ m) 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 ( $\lambda$ ). 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),  $\theta$  is the angular separation between the central fringe and the  $m$ th 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  $\theta$  is the angular resolution,  $\lambda$  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  $\theta$  to the normal will be refracted at an angle  $\arcsin(\sin\theta/n)$ . Thus, blue light, with its higher refractive index, is bent more strongly than red light, resulting in the well-known [rainbow](#) pattern.

## Polarization

Polarization is a general property of waves that describes the orientation of their oscillations. For [transverse waves](#) such as many electromagnetic waves, it describes the orientation of the oscillations in the plane perpendicular 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 [chirality](#).

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 [dichroic](#) 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  $\theta_i$  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,  $\text{\AA}$

★ 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 isolated 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 synonymous 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 ionization and excitation by photons or collisions with atomic particles.

While modelling atoms in isolation may not seem realistic, if one considers atoms in a gas or plasma 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 populate a shell are said to be in a bound state. The energy necessary to

remove an electron from its shell (taking it to infinity) is called the [binding energy](#). 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 [transition](#) 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 [neutral](#) 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 [Auger effect](#) may take place where the quantity of energy is transferred to one of the bound electrons causing it to go into the [continuum](#). 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 [principal energy level](#) 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 up to 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.  $1s$  before  $2s$ ). 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:

$1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p, 6s, 4f, 5d, 6p, 7s, 5f, 6d, 7p, (8s, 5g, 6f, 7d, 8p, \text{ and } 9s)$

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  ${}_{29}\text{Cu}$  to be  $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^9$ , abbreviated  $[\text{Ar}]4s^2 3d^9$  where  $[\text{Ar}]$  denotes the configuration of Ar (the preceding [noble gas](#)). However the experimental electronic configuration of the copper atom is  $[\text{Ar}]4s^1 3d^{10}$ . By filling the  $3d$  orbital, copper can be in a lower energy state. Similarly, chromium takes the electronic configuration of  $[\text{Ar}]4s^1 3d^5$  instead of  $[\text{Ar}]4s^2 3d^4$ . In this case, chromium has a [half-full](#)  $3d$  shell. For palladium, the Madelung rule predicts  $[\text{Kr}]5s^2 4d^8$ , but the experimental configuration  $[\text{Kr}]4d^{10}$  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 量子隧穿

★ 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  $\Delta S$  for a chemical or physical transformation approaches 0. This can be expressed mathematically as follow

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

## 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](#)  $1.38066 \times 10^{-23} \text{ J K}^{-1}$  and  $\Omega$  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  $\Omega$  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:

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

$\beta = \frac{1}{k_B T}$  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**:

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

where  $E_i$  is the energy of the  $i^{\text{th}}$  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**,  $\mu_j$ ,  $j = 1, \dots, n$  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  $j^{\text{th}}$  species particles in the  $i^{\text{th}}$  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

★ **statistical 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 yield more efficient procedures for computing quantum amplitudes. However, the use of canonical quantization has left its mark 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 amenable 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 emergent, second-order consequence of various limitations of the observer. This treatment focuses on explaining the behavior from the perspective 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 proposed 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

$$E = hf$$

where  $h$  is [Planck's constant](#) ( $6.626 \times 10^{-34}$  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  $\lambda$ ), 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

- $\Delta$  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  $2\pi$ ).

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 decohered 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 [singlet state](#).

## Entanglement, non-locality and hidden variables

There is much confusion about the meaning of [entanglement](#), [non-locality](#) 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 account for 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 intermediary such as a field force) with the thing that changes. Study of entanglement brings into sharp focus the dilemma between locality and the [completeness](#) or lack of completeness of quantum mechanics.

[Bell's theorem](#) and related results rule out a local realistic explanation for quantum mechanics (one which obeys the principle of locality while also ascribing 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 portrayed as being equivalent to entanglement. While it is true that a bipartite 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  $\alpha$ , 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

★ [schrodinger 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:

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

$$x' = \frac{x - vt}{\sqrt{1 - v^2/c^2}}, \quad y' = y, \quad z' = z,$$

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  $vx/c^2$ .

The equation  $t' = \text{constant}$  defines a "line of simultaneity" in the  $(x', t')$  coordinate system for the second (moving) observer, just as the equation  $t = \text{constant}$  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  $t - vx/c^2 = \text{constant}$ . 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  $\Delta t$  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  $2.22 \mu\text{s}$ , 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  $E_0 = m_0c^2$ . 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 as though 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 ( $9 \times 10^{13}$  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  $m(\text{relativistic}) = E / c^2$ . 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  $\mu$  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

★ **deposit** 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

# 考研复试面试冲关之百问百答

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## 第一篇 复试综合面试常见问题

### 一、有关复试流程问题

#### 1. 分数线出来了我该怎么办？

- A、 高分上第一志愿→准备复试
- B、 低分上第一志愿→准备复试 / 联系调剂学校
- C、 未投上第一志愿→联系调剂 / 同时准备复试

#### 2. 复试到底有哪些规定？

每个学校根据教育部的规定，结合本校的实际情况，制定出本校复试相关规定。

#### 3. 复试的大致流程怎样？

复试通知书（网上公布或电话通知）→准备复试的相关材料→到复试单位参加复试

#### 4. 复试的具体流程怎样？

报道→体检→专业笔试、听力考试→专业面试、英语口语→加试

#### 5. 复试要带哪些材料？

一定要仔细阅读复试单位的相关规定。学生证、准考证、身份证、本科成绩单（要有学校教务处公章）、毕业证、学历证、四六级证书等证书、大学期间获得的奖状或者工作期间取得的一些成果等这些一定要带。（最好把这些资料复印一份备份），另外，考生最好能带上一寸免冠照片几张（体检要用）

#### 6. 一定要带准考证吗？

最好带上，有的学校虽然没有特别说明，但在必要的时候可能会用到，比如凭准考证进入复试考场（监考人不一定是老师，有可能是秘书或者研究生，如果有没有准备齐全就会有有时不让进场的麻烦）。

#### 7. 为什么要带四六级等相关证书呀？

因为四六级等相关证书可以在复试中加分，但每个学校比例不一样，有的学校比较少，而有的院校这部分的比例却可以占到复试总分的百分之左右十。

#### 8. 为什么还要复印这些证书？

证书的原件不可能留给学校，用来审核你的资料是否真实，复印件要给学校留档。

#### 9. 体检严格吗？包括哪些项目？

除了军事院校以外，一般都只是进行常规性的体验，不会很严格。

#### 10. 我的视力不好，会有影响吗？

除了对视力有要求的专业外，一般情况不会。

#### 11. 现在复学校还没有发出相关的复试通知，该怎么办？

请参照往年的复试办法，对复试过程有大致了解，抓紧时间复习。

#### 12. 复试结果一般会在什么时候出来？

有的学校当天就公布，有的学校要迟几天。

#### 13. 复试过了就一定被录取了吗？

还有政审过程，如果没有什么意外，一般复试过了就意味录取。

#### 14. 政审函包括什么东西呀？

一般由自己所在的单位填写，自己不能看，里面有一些是有关个人表现的，所以不用过于担忧。

#### 15. 录取通知书什么时候发呢？

5月中旬到7月初。

**16. 复试时会不会很黑？**

黑不黑你自己没有经历过是不会知道的，在面试复试的时候的确会有一些这样的现象，但这毕竟是少数，而导师更多关心的其实还是这个学生的综合素质，所以这个问题不是你自己目前最应该关心的问题，你所要做的就是复试前努力加强自己的综合实力。

**17. 应该什么时候开始准备复试？**

前面已经提到，仅仅用出分后短短半个月时间进行盲目复习是万万不行的，因为这无异于是“自杀”。

跨考教育建议考生，尤其是跨校、跨专业的考生，至少要在国家线（或自主院校分数线）划定前一到两个月开始系统复习。

以下是跨考教育为复试考生专门研发的系统的、有针对性的复习课程，无论你是否参加我们的辅导，至少可以参考此规划提前开始你的复试备考。

**第一阶段：初试结束——分数线出来前**

对应院校研究生+班主任制定科学学习规划

提前一到两个月，任务式自学，班主任定期检查作业

夯实专业课和英语基础，准备面试素材

**第二阶段：成绩出来后**

对应院校研究生密授专业课，真题、专业方向、导师选择深度指导

综合面试+英语面试，真题模拟演练，三天三夜超大强度封闭集训

**第三阶段：集中强化课程结束——复试考试**

各科老师一对一设计冲刺方案

各种形式无限次答疑

网上YY课堂考前全真模拟及点评

**二、有关复试调剂的问题**

**17. 同时填写几个招生单位的调剂表会不会发生冲突？**

不会，最终决定权在你手里，你可以选择到自己喜欢的学校去复试。

**18. A区就只能调剂到B区吗？**

不一定。如果你上了A区线，没有达到学校的复试要求，你可以联系A区的其他学校。

**19. 我想调剂到我喜欢的学校，但不知道是否有调剂名额？**

要跟学校联系。招生简章上的招生人数只是一个概数，虚数，一般都会多招3到5个。

**20. 怎么才能提高调剂成功率？**

填报调剂系统，给招生办电话，发邮件，多管齐下。

**21. 我打了招生办的联系电话，可总是打不通，怎么办？**

一般调剂情况学校都会公布在网上，仔细看就可以了，这段时间都如此，很少有人打进去。

**22. 调剂系统的一些内容可以修改，怎么回事？**



可以修改的内容，考生可以不断完善，为招生单位提供更完整的资料。

**23. 调剂什么时候有结果？**

7天不算短，半个月不算长。分数不高的建议同时填几个学校。耐心等待。

**三、有关复试心态的问题**

**24. 复试面试中到底考察我们哪方面的能力呢？**

复试面试过程中其实主要考察考生的综合素质。包括考生本科期间的能力结构、知识结构、计算机操作能力、外语能力和应变能力，在回答问题的时候并不要求十分精准的答案，但是要求考生流畅清楚以及有逻辑性的陈述即可。

**25. 复试面试中我应该怎样表现呢？**

复试中首先要态度端正，不要表现出一副无所谓或者满不在乎的样子，同时要控制好回答问题的时间。

**26. 复试面试中的问题是不是都特别难？**

考生其实不必过于紧张，撇开学术问题，导师或许营造轻松对话氛围，让学生放松下来，就爱好，兴趣等等畅所欲言，学生也大可不必紧张，时刻提防，只要口气自然自信沉着即可，过分城府和老道反而适得其反。最后，考研复试本质上是一场面试活动，一场人与人之间的会面交流，作为学生一方，要着装得体，言谈温雅，谦虚诚恳，甚至注意手机调至振动等等细节，这些实属交往所尚之礼节，无须赘述。

**27. 要不要提前到复试院校地点？**

至少保证提前一天到。第一，熟悉考场环境。第二，可以看点书准备复试。

**28. 面试一般会有几个老师？**

通常来说大约在五位到八位之间。但有的学校可能只有三个，有的学校却有十个。

**29. 复试面试的时候我究竟应该怎样着装？**

不管你穿什么衣服，都应该做到整洁、得体、大方、朴素，关键是自己觉得自在。如果你平时没有穿西服，复试时候穿西服，你自己本身就不自在。如果是应届考生，建议保留“学生样”，工作了，就应该有“工作过的样子”，男生最好不要留长发，除非是搞艺术类的。女生不要穿吊带，高跟鞋，耳环、首饰，千万不能涂指甲。

**30. 进入复试考场前会很紧张，怎么办？**

很正常的反应。建议没有轮到自己复试之前，不要和其他的考生朋友谈论关于复试的事，只会更加紧张，可以在离复试不远的地方看看所带的复试资料，或者听点音乐，进去后你就很快会消除紧张感。

**31. 进入面试考场时怎么做？**

如果没有秘书带领，一定要轻轻敲门，待应允后再进去，进去后，一定要向在座的所有考官（导师）进行问好，如“各位老师好”、“下午好”等等，进行行礼，然后坐下。

**32. 分数线出来了，我却更担忧了，该怎么办？**

能解决的问题不用担心，不能解决的问题担忧也没有用。别人能解决的问题，如果你不能，那就是你个人问题，所以一定要在复试前做好心态调整工作。

**33. 还没有最终确定复试学校，该怎么复习？**

调剂成功前，先看原来报考学校的参考书目，确定后赶快看调剂学校的复试，看看有什么参考书目，再做新的计划。

**34. 在复试阶段的考生都是什么心态呢？**

在复试阶段，很多考生都会“瞻前顾后”。“瞻前”就是对过去的事情（如初试）进行评价，过分地关注。比如有的考生初试成绩很好，但他认为那是因为运气好、发挥好，因此对复试的信心和把握不大；有的考生初试成绩不好，排名靠后，于是就反省自己，自责当初应该如何努力、如何复习，整个人被自责的情绪控制。所谓“顾后”就是对将来还未发生的事情过分担忧。很多通过初试的考生，特别是分数并不是很高的考生，在复试的过程中会更加紧张和焦虑，担心诸如“复试是不是也能取得好成绩？”、“能不能争取到公费指标？”、“会不会优先考虑本校学生？”、“自己想报考的导师是不是愿意招自己？”等问题。

#### 四、有关复试面试技巧问题

##### 35. 考生应该在复试面试考场中如何介绍自己？

最重要的不是答案。自我介绍要进行一定的事前准备，你的经历比你的名字更重要。重点介绍你做过什么研究、论文题目是什么等学术方面的经验，其他证明自己能力的事情都可以简要介绍。回答问题的过程是考生综合能力的展现过程。

##### 36. 该怎么样组织语言回答复试面试中的问题？

拿到题目，应该考虑要套用哪个理论，从哪个角度入手，一共要分为几点来答。这样条例才清晰。如果能举例子，最好用上，例子最能说明问题。一个同学被我们冠以“两面性”的绰号是这样来的，他说自己在复试时，每个题目都从正反两个方面阐述，感觉效果还可以。不妨借鉴。

##### 37. 如果问读了哪些书，哪些著作，哪些期刊，该怎么回答？

这个题目出现的几率几乎是百分之百，当然是学校自己定的参考书目了，有的学校参考书目是自己编写的，如果你说看了某某大师的著作，就没有提到他们学校的，他们会怎么想？

##### 38. 问到你是如何看待某一本著作，或者期刊的，怎么回答？

这个和上个题目差不多，能写书的说明都不是等闲之辈，最好是中性回答，不带个人偏见，或者就书中的一个观点进行阐述，如果导师刚好问到一个他不喜欢的著作或者那位作者，你却夸奖一番，估计就有问题了。

所以如果你想要高分，那就需要在表达的逻辑性和表达的深度上有所加强。

##### 39. 今年发生了\*\*\*事件，请您谈谈对此的看法。

这也是热点型题目，而且是命题型。这部分内容的准备起来，要求的量比较大。但你可以参考如下的准备策略：

- 1) 参考就是导师的研究方向。导师的研究方向反映了这阶段他关注的焦点，面试的时候他的兴趣点，也很可能与他的研究方向有关。
- 2) 多看相关专业领域的一些权威期刊，对所报考导师的学术观点、论文、专著应有较深的了解。
- 3) 关注一下相关评委的研究方向，毕竟不是你的导师的评委也可能提出一些问题。

特别提醒：如果你的观点和导师的一致或者可以在他的基础上有所创新，那他一定会对你留下不错的印象。

##### 40. 对于你所报考的专业，你曾看过什么著名的书，作者，成书的朝代或者时间，书的编目方式，以及该本书的主要学术思想，有哪一条对你印象最为深刻，并请简单阐述。

建议：准备一到两个案例。

如果实在没有准备就上了考场，那就如实回答，以博得诚实的好感。

**41. 请你举一个今年发生的与你所报专业相关的热点事件，并谈谈对这些热点事件的看法。**

对策：理念联系实际，事先准备一些热点的分析提纲。

建议：关注行业热点，并主动进行分析。

**42. 如果问到刚好是我所不知道，或者没有底的怎么办？**

在专业面试时，很多考生都会被问到不懂的问题。此时考生一定要诚实，就说不是很了解，不要不懂装懂。导师既然问了那个问题，表明导师对问题很了解，靠蒙是不能过关的。

考生最好在告诉导师不懂后，利用一定的面试技巧尝试着对问题进行自己的分析和理解，这样老师会感觉，这个学生虚心诚实，善于思考，也会给给老师应急应变能力比较强的好印象。

所以考生在复试前一定要运用面试技巧增强自己的考场应急应变能力。

**43. 自己今后研究的优势在哪里？**

这三个问题是发难式提问。考生应该从逻辑方法，思维习惯等上层角度去论证和应答，因为任何专业尽管其学科内容不尽相同，但研究问题的逻辑方法却大致可共享并普适。

【例】“你本科的化学专业会对今后所研究的企业管理专业有何帮助呢？”

【答】四年化学学科的研习培养出自己注重条理逻辑和追究方法步骤的这一理工科思维习惯，而随着管理学等人文学科的进一步发展和研究的深入，需要相当的数据支持已是方向之一，那么严谨的理性思维便可为发散浪漫的人文体验提供理论支持和逻辑化规范等等。

**44. 研究生毕业后打算如何——求职抑或深造？**

该类问题旨在探寻学生的读研目的，回答这些问题时，提醒大家实事求是上策，诚实坦荡是要旨。

建议：先自己想想清楚这个问题。如果考生第一次参加复试，比较迷茫，一些问题不能很好地组织语言回答，可以随时咨询。

## 第二篇 复试英语 FAQ

### 一、英语听力常见问题

**45. 如何准备英语听力？**

英语听力部分，大多数学校都以现有的成型考试为参考。考生在准备听力复试的过程中，对于现有的成熟英语考试的听力部分一定要重视，比如六级听力、托福听力和雅思听力应该是复习的重点。在复习时可以有针对性地做一些六级或托福听力或雅思听力的试题。平时大量听力练习的空隙，觉得做题枯燥了，收听一下英语新闻，看看发音清晰的英文影片，再放松欣赏的同时又培养了语感，真可谓一举两得。

**46. 听力学习注意事项一：培养良好的听音习惯，听读顺序要合理**

可能很多同学都有类似的同感，在听材料之前，都需要先第一下文字资料，但是正是因为这些文字资料的影响，而影响了对听的内容的正确理解。在外语学习过程中，学习者多数情况下都是先习得文字符号，从书面材料开始，通过视觉即阅读来接收、理解信息，即便是在输入音响信息时，脑子里也总是自觉不自觉地想着文字符号。这样久而久之就产生了对文字形式的依赖性，形成了本末倒置的不良听音习惯。考生在复习中切忌读后听音。先将听力材料读一遍，然后再听，表面上似乎听懂了，但实际上是读懂的，是靠脑子里储存的对阅读的记忆来理解音响信息的。照此下去，阅读非但不能帮助反而束缚和制约了听力的发展和提高。也切忌边听边读。听、读同时进行，似乎有助于听懂，但如果长期如此，会同样使听力陷入误区，即不能将大脑的思维活动集中在音响信息上，而是在听、读之间往返，听觉、视觉交替进行，导致精力分散，无法专心致志。

老师建议大家：一定要先听，即使一下子听不懂，也不要忙于看文字材料，这时再听第二遍、第三遍，如果还是听不懂，再求助于文字材料，但此时至少所听内容的语音形式已在你脑子里留下了一定的印象，甚至还能重复出来，借助于阅读使你理解了这些语音信息，一旦同样信息在另一种场合再现时，便不再成为难点，这才能达到阅读促进听力的目的。

#### 47. 听力学习注意事项二：边听边记关键词 训练短期记忆能力

听力复试题大部分都是非常具体的细节，音响信息瞬间即逝，有时单凭大脑记忆是不够的，需要强化记忆的内容必须随时笔录下来，对此考研1号网建议考生：

1、练习听写，平时听录音时就要有意识地将关键信息写下来，一方面训练信息接受的准确性；另一方面培养短期记忆、正确拼写单词的能力。练习听写还能强制性地迫使自己全神贯注、积极思考。

2、学会用最简单、最省时、自己最熟悉的符号记录信息，只要自己能识别的，汉字、代码、符号什么都行。长单词可以暂记两三个字母，用箭头表示方位或发展方向等。总之，要有意识地训练自己的速记能力，借助于记录，使自己听得准，听得全，记住得多，回答得正确。

#### 48. 听力学习注意事项三：熟记语篇衔接词把握信息走向

在做新题型、完形填空和阅读理解时我们已经说过，语篇衔接词的重要性。听力也是一样的，在听音过程中，考生的思路要想跟上录音的意流，把握信息的走向，必须将注意力投放在这些衔接词上，这对提高获取信息的效率起着至关重要的作用。比如表示列举、增补关系的 *and*、*in addition to*、*one more thing* 等；表示转折或对比关系的如 *although*、*by contrast*、*as a matter of fact* 等；表示顺序或序列关系的如 *first*、*before*、*first of all* 等；表示解释或强调关系的如 *that is*、*in particular*、*I mean* 等；表示因果关系的如 *as a result*、*therefore*、*since* 等；表示归纳、结论性关系的如 *as a result*、*altogether*、*finally* 等；

掌握了上述词及其功能，考生就能意识到说话人先说什么、后说什么，什么时候转问题，即便是遇到生词或错过了一两句，也可以对上下文内容做出合乎逻辑的推测判断，保持思维的连贯性，更好地理解整个语段的内容。

#### 49. 听力学习注意事项四：选择合适的听力材料，精、泛结合

选择合适的听力训练材料，对于有效利用时间，少走弯路，在相对短的时间内提高听力水平也是一个重要因素。关于听力材料的选择，我们认为，应该从两方面考虑：一是难度适中，即从自己的实际水平出发，选择难易程度适合的材料。材料难度太大，会丧失信心、失去兴趣，产生恐惧感；过于简单，易盲目乐观、缺少压力，不



利于提高。跨考教育建议广大考生可以选择正常速度的录音，过快或者过慢都不利于锻炼考生的听力能力。

二是录音材料的种类。现在市场上录音材料一种是教材中阅读课文的录音带，第二种是听力教材的录音带，属于专门用来训练听力技能的录音，其特点是，从练习语音开始，分步骤、按阶段、循序渐进、系统完整，既有讲解又有练习，还总结归纳方法技巧，并按题材分单元逐个训练，适于学生从低到高，由易到难，打好扎实的基础，逐步提高水平。

#### 50. 英语听力复试是美语还是英式英语？

在考研复试中，主流基本上美语。

#### 51. 如何加强听力训练？

在听力测试中，如果考生听不懂问题，将无法正确回答。因此要找一些相当于大学英语四六级难度的听力资料作听写训练。考生不必把听到的每一句都分毫不差地写出来，只要抓住材料中的关键信息即可。通过边听边记笔记，考生要着重训练分辨重要信息与次要信息的能力。如考生要特别注意那些表示否定的单词：but, seldom, little 之类的，并要注意人名、地名、数据等重要信息。辅导书中类似技巧非常多，考生要认真总结，灵活运用。这是基本功，其他一切解题技巧都要围绕着这个基本功进行。

#### 52. 听力材料是不是越难越好？

在选择材料时，考生不需要专门找标准的英语材料。这些材料往往较难，考生不易听懂，会丧失信心，增加恐惧。一般来说，考生只要用《新概念第二册》、《Special English》或难度接近的材料就可以。考生要尽量坚持每天练习，如果有条件，也可适量听听英文广播节目、看看英文电影，既缓解紧张心情，又增强语感。

#### 53. 听的时候是不是不能遗漏细节？

很多考生在听力测试时生怕漏掉任何一个重要信息或有题目听不懂，其实这都是正常现象。中国人听中国人讲话，也不一定全能听清楚，逐字逐句都能记住就更难了。如果考生在考试时遇到听不清楚的句子，不要紧张，及时调整心态，将后面的内容听清楚。有些考生为了力求完美，纠缠在一句话上反复琢磨，导致后面的内容没有听到。其实，错过的内容，可尽量通过后面的内容推断。

#### 54. 听材料的时候是不是有技巧？

在听力测试中，考生要经历两个阶段。第一阶段是拿到题目后，先对答案进行猜测，做上标记，以减少听材料时阅读选项的时间，有更多时间用于分析和思考；第二阶段是在听不懂的情况下，要根据经验和技巧，用余下的时间进行猜测。此时，考生不管有没有把握一定要把猜测的答案写上。

## 二、英语口语常见问题

#### 55. 如何准备英语口语？

对口语的考查，各个学校各不相同。有的学校制定了非常详细的标准和流程，甚至规定了每个老师发问的方式和时间；有的只是面试老师的自由发挥，成绩也基本上由面试老师主观判定。不管面试是否严格控制，考生对下面几个问题一定要认真准备：一是自我介绍，如自己来自什么地方，毕业学校，所学专业，业余喜好，家庭基本情况等信息；二是做好用英语讲解自己专业的准备。口语测试时老师有可能要求你就本专业展开话题，考查你用英语讲解陌生概念的能力。因此考生对此要有所

准备，先用笔头组织这些问题的要点，然后再以这些词组织语言。在阅读专业文献时，也要多积累一些专业方面的英语词汇。当然提问的问题不可能难度太高。

#### 56. 复试英语口语的评价标准是什么？

- 1) 语言准确性（语法和用词的准确性、语法结构的复杂性、词汇的丰富程度、发音的准确性）
- 2) 话语的长短和连贯性（内容的连贯性、寻找合适词语而造成的停顿频率及长短、表达思想的语言长短等）
- 3) 语言的灵活性和适合性（语言表达是否灵活、自然，话语是否得体，语言能否与语境、动能和目的相适应）

#### 57. 复试英语口语测试包括哪几个部分？

第一部分：考查学生理解并回答有关日常生活、家庭、工作、学习等问题的能力(3--5分钟)。

第二部分：考查学生连续表达的能力。考生从所给的问题中选择一个话题，就此话题表达自己的看法(7--10分钟)。

第三部分：部分院校复试中会加入专业英语的内容。

#### 58. 复试英语口语如何评价成绩？

- 1) 优秀--能用外语就指定的话题进行口头交流，基本没有困难
- 2) 良好--能用外语就指定的题材进行口头交流，虽有些困难，但不影响交流
- 3) 及格--能用外语就指定的话题进行简单的口头交流
- 4) 不及格--不具有口头表达能力

#### 59. 英语口语常问话题（一）

第一个经常问得话题是考研原因通常我们可以从以下三个方面来回答。

- 1) 兴趣，即强调对所报考的专业怀有极大的兴趣(have significant interest in...)。如果本科就读的专业与报考的专业一致，则可以说明想继续深造(further education)的愿望。如果不一致，则要说明报考专业对你的吸引力(...appeals to/attracts me a lot)。
- 2) 优势，即强调研究生相对于本科生在知识、学术方面的优势，如：知识面更广(wider knowledge)，学术更专业(more professional)，眼界更广阔等(broaden one's horizon)。
- 3) 益处，即强调考研对你的未来的积极影响(have a positive effect on...)，可以从求职、职业规划、人生经历等方面入手进行说明。可参考的词汇、短语如下：be helpful, contribute to, be beneficial to, be conducive to, be a definite advantage, become a strong point when it comes to...等等。

对于那些在职考生或有工作经验的考生来说，考官更倾向于提问他们为什么（放弃工作而）重新学习。考生可以直言在工作发现某些知识或技能很重要，希望能通过学习在这些方面进行提高(In my work, I found ... is rather important. I always believe that one will easily lag behind unless he keeps on learning. So I choose to go back to school and improve myself. )。

#### 60. 英语口语常问话题(二)

考官有时会询问考生对未来的一些规划，其目的在于试探考生是否对时间、学习、人生有一定计划性和掌控能力。

- 1) 学习规划。关于这一话题，考官通常会以一种较婉转的方式提问，如：What do you expect to achieve during your study if you are enrolled into this university? 回答这一类的问题时，不仅仅要回答想学到什么样的知识、成为什么样的人，最好能够稍

微说说你会/计划怎样学习(即学习方法)。无论是倾向于学术理论性的还是侧重于实验研究性的，都要把握一个原则：理论联系实际，同时主次分明。

2) 职业生涯规划。职业生涯规划其实就是明确自己未来的职业方向，虽然考官不常对此提问(基本上也是提问考生对所报考专业的就业前景持何种态度)，但是这个话题实际上涉及了一个人对自己的性格、天赋、兴趣、能力以及社会现状进行综合分析的能力，还同时也可以看出他对自己未来人生的一种期望、信念和热情，因此考生也可对此稍做准备，甚至可以将其放在自我介绍中(不建议口语不太理想的考生这样做)。

需要注意的是，职业生涯规划一定要根据自己的实际情况加以定夺，尤其要注意与所报考专业的契合度。

#### 61. 英语口语常问问题(三)

自我介绍。要求简洁、有新意，能够让考官记住你。最重要的是，发音要准，不要太快，以别人听懂为目的。但注意一定要听考官的指示语，听到考官说：Can you introduce yourself briefly/ say something about yourself 后再开始。其实现在许多口语考试为了避免考生背诵准备好的自我介绍，都去除了这个部分，而是由一些简单问题来代替，如：

Where are you from? Could you say something about your hometown?

Could you say something about your family?

What do you usually do in your leisure time?

What's your favorite TV program?

Who is the most important person in your family?

#### 62. "What would you like to be doing five years after graduation?"("在毕业以后5年内你想做些什么?")

Know what you can realistically accomplish. You can find out by talking to others MBA about what they accomplished in their first five years with a particular company after graduation.

"I hope to do my best I can be at my job and because many in this line of work are promoted to area manager, I am planning on that also."

#### 63. "What is your greatest strength?"("你最突出的优点是什么?")

这是很多面试考官喜欢问的一个问题。

这是你"展示自己"的最佳机会，不要吹嘘自己或过于自负，但要让考官知道你相信自己，你知道自己的优点。

如可答："我认为我最大的优点是能够执着地尽力把事情办好。当做完一个项目而其成果又正合我的预想时，我会有一种真正的成就感。我给自己定了一些高目标。比如说，我要成为出色的毕业生。尽管在大学一年级时我启动慢了些，但最终我以优等论文完成了学业。

#### 64. "What is your greatest weakness?"("你最大的弱点是什么?")

你不应该说你没有任何弱点，以此来回避这个问题；每个人都有弱点。最佳策略是承认你的弱点，但同时表明你在予以改进，并有克服弱点的计划。

可能的话，你可说出一项可能会给公司带来好处的弱点，如可说："我是一个完美主义者。研究做得不漂亮，我是不会撒手的。"

#### 65. "How do you feel about your progress to date?"("对于你至今所取得的进步你是怎样看的?")

Never apologize for what you have done.

"I think I did well in school. In fact, in a number of courses I received the highest exam scores in the class."

绝不要对你以前的所作所为表示内疚。

如可答："我认为我在学校表现不错。事实上，有好几门功课我的成绩居全班第一。

### 三、英语复试常见问题

**66. 在英语面试中我怕老师问问题，所以我的英文自我介绍就多一点，行吗？**

不管多么长，老师还是会问你问题，如果你自我介绍说得长，回答问题时候你却回答得很少或者回答不上来，那你损失可就大了。

**67. 我的口语不错，面试时候多说一点老师会不会给多一点分？**

看情况。表现欲太强不一定见得是好事。还有，千万不要和老师争论。

**68. 四六级没过，复试能不能被淘汰？**

担心得有点多了，据了解，很多人都没有过四六级，当然，过了更好。可以加分的。

**69. 英语口语复试的常见考查形式？**

老师与学生的问答，两个学生的对话，一组学生的讨论。

**70. 口语复试的准备材料**

应试材料的准备：为了准备口语考试，可以准备一些材料，如《英语中级口语教程》、《四、六级英语口语应试》等。当然如果确定参加哪种英语口语，又了解其口语考试的形式与内容，选择针对其考试的口语材料更为有效，如雅思口语、托福口语等。

**71. 回答考官问题**

此处不再赘述，但有一点要注意，千万不要只回答“YES”或“NO”，而是要加上你的 reason 或者是 example.

**72. 最后问题**

最后，考官还会问你一个问题，这是你进一步展示自己的大好机会，如果前面不太理想，也可借此补救一下。

**73. 结束**

考官明确说出：This is the end of the test, thank you. 说明考试正式结束。站起来，拿好自己的东西，如准考证，与考官说再见：Thank you, goodbye. 或 Thank you for your interview goodbye. 然后离开。注意考试结束后不要问老师关于得分的问题，应该马上礼貌的离开。

**74. 英语复试加入了笔试？**

201\*年大规模泄题的情况下，一些高校的无奈之举。

## 第三篇 复试专业课常见问题

### 一、有关导师的问题

**75. 现在可以联系导师了吗？**

可以，但要懂得方法，别让老师烦你就好。



**76. 联系之前须要了解导师的情况吗？**

这个是必须的。一般来说，我们建议从以下几个方面去了解你未来的导师。导师的经历、当下的工作状况、学术研究情况、师生相处情况。导师的经历主要是指导师的籍贯、学习经历、工作经历；当下工作状况主要是指职称、是否兼有行政职务；学术研究情况是指导师出版的著作、发表的文章、在其研究领域的学术立场、学术研究风格；师生相处情况指导师对学生的态度、原则、要求以及日常交往情况，甚至导师生活中的某些个人喜好等等，这些情况主要从日常教学和师生交往（尤其是节庆日公共活动）中了解。

**77. 如何联系导师呢？**

邮件是最好的方式，须要注意邮件的格式。

打电话也可以，但要事先准备好谈话的提纲，并注意打电话的礼节。

**78. 用邮件联系导师须要注意什么呢？**

用邮件联系导师时，首先要特别注意邮件的写作格式和用语。邮件格式正确与否，显示的是你个人的职业素养，用语准确与否显示的是你个人的文化素养。

其次，关于邮件的内容很重要。联系导师主要是告诉导师报考他研究生的信心以及决心，其次是显示出自己的能力和可塑性，再次是给导师留下好的印象。

最后，写邮件时要特别注意内容的结构与逻辑性，切记要反复打草稿，直到你搞清所写内容之间的关系。

**79. 导师不回我的邮件怎么办？**

导师一般都不会回邮件，除非你先前和他有过交流。

即使你遇到了不回邮件的情况，也不要着急。不回邮件的可能原因很多，而你前面一封高质量的邮件如果已经让导师看过，并留下了良好的印象，也会有助于你的成功。

**80. 电话联系导师须要注意什么呢？**

如果你一定要打电话，可以参照如下的流程：

- 1) 编制与导师电话沟通的内容提纲，包括开场问候语、问题大纲及结束语。
- 2) 如果是手机联系，要先发短信告知，简单介绍自己，并询问他接电话是否方便。
- 3) 得到导师回复确认后，隔 3~5 分钟再拨打，但时间间隔不要过长。如果导师表示现在时间不方便，可以再以短信形式进一步沟通方便的时间，导师确认后，自己在短信形式回复，表示谨记，会在约定的时间打电话（注意可以表示正式沟通前，会再短信与导师确认一下）。
- 1) 如果导师没有回复短信，隔段时间再发，如果还不回，请别再用电话联系。
- 3) 如果是联系导师的办公电话，可以在工作时间拨打。须要注意的是：首先要询问对方是不是 XX 教授（事先了解其正确的职务），得到确认后，简短表明本次电话的意图，并询问导师是不是方便。如果得到肯定回答，则按事先拟好的提纲沟通；如果导师表示不方便，可以约一下时间，表达沟通的意愿。

**81. 与导师沟通什么内容比较合适呢？**

沟通的内容一般来说是由你自身的情况来确定的，但下面的内容可以做参与。个人基本情况（如姓名、年龄、性别），学习情况（毕业学校（非应届生可介绍工作单位与经历）、本科所学过的主要课程），毕业论文题目与要点，曾经阅读过的主要书籍，研究方向和兴趣等。若导师有兴趣，便会增加成功的机率。

**82. 我想提前去见导师，能见到么？**

这要看你去见的导师是怎么样的一个人的，他是否愿意接见你。

行动之前，一定要与导师进行沟通确认（建议沟通的时候采取委婉的方式），如果得到确认，即可去见。如果导师表示不方便，则最好不要去见了。

**83. 导师愿意接见我，有没有必要带土特产？**

礼多人不怪！

如果导师都答应见你了，空着手去总不是一件好吧，送礼，人之常情嘛，当然，有就带，没有就不带，礼不在贵而富有家乡特色就好。

**84. 给导师送礼物就一定能保证被录取吗？**

这个很难说，也不好说。

**85. 联系导师时有哪些忌讳的地方**

1) 忌讳之一：过分向导师了解某些信息。

导师能理解考生迫切的求学心情，但决不能容忍过分的要求，尤其不要表现的急功近利。

一些初试合格的学生，会通过电话、邮件、乃至导师的同事、熟人来了解复试的内容、复试导师的组成等等。绝大多数导师对此是反感的，因为这不利于了解考生的正确情况、不利于选择自己所需要的学生、干扰了正常的招生工作。据了解，大部分导师不但不会泄漏复试内容，反而对这些考生会有一些抵触反感情绪。

2) 忌讳之二：过于频繁地联系导师。

虽然考生确实有必要与导师联系，但提醒考生一定要注意频率。如果反复打电话与导师联系，可能影响导师的教学科研工作的进行，乃至影响导师的正常工作与生活，效果可能会适得其反。

3) 忌讳之三：询问毕业后就业问题。

就业是学生的大事，但不是导师的头等大事。作为导师，更关心考生对学术的追求，因为他们是知识传授者而非工作介绍者。不要因为一个不是现在的问题，让导师对你失去兴趣。

4) 忌讳之四：探听导师隐私并让导师知晓

了解导师的信息，决不是要探寻导师的隐私。让人知道你在探听他的隐私，那么他会怀疑你的品德，因而会留下极其负面的影响。

5) 忌讳之五：第一次接触不太成功后的消极自我暗示。

有些考生在第一次与导师接触后，感觉导师不够热情，或者觉得自己表现不好，给导师留下了不好的印象，便消极悲观，这是片面的、不科学的。导师第一次和陌生学生接触时，不会表现出强烈的感情倾向，因此不必过于在意导师的热情程度。切记，第一印象固然重要，但即使第一次接触不顺利，在进一步的联系中还可修复第一次的不足表现。

**二、院校与专业选择**

**86. 你为什么考我们这个学校？**

这是在考查你对目标院校的了解情况。

答案要点：兴趣+该校该专业名气和实力+该专业老师的实力。

**87. 为什么会报考这个专业，以及今后的打算。**

建议事先了解所报专业的研究领域与方向，然后稍微准备一个小型的研究计划（不成熟也没关系），最后你准备的与所报专业的研究方向是一致的。

**88. 你认为自己本科专业和现在所考的专业有什么互补性或者借鉴性？**

本科是学习，是基础，而硕士是研究。

**89. 你认为跨专业的优势和劣势是什么？**

以上两个问题的建议：如果你是跟专业的，在复试前需好好思考根据自己所学专业 and 所考专业之间展开论述。最好整理出了一篇腹稿，至少要有回答的提纲。

### 三、专业相关问题

**90. 复试中，专业课到底考哪方面的内容？**

有的学校有参考书目，有的学校没有，如果复试新的参考书目，以新的参考书目为主，如果没有，可以咨询往届考生，或者以初试的参考书目为主。

**91. 专业面试会问到哪些内容？**

专业课的基础知识永远少不了，时间允许的话，招生院校以及导师老师的一些专著，以及本专业的核心期刊都看一下。

**92. 专业面试会问一些热点的话题吗？**

有可能会，也有可能不会。适当关注一下很有必要。一方面是看你了解不了解当前的动态，另一方面是看你分析问题的能力，剖析问题的能力。

**93. 我的专业很差，导师会不会为难我？**

这个不用担心，复试的目的在于择优录取，而不是在于为难学生，如果导师是在为难学生，那么他将很难判断谁优谁劣。一般情况都只是在引导你。

**94. 本校的学生会有优势吗？**

这是必须的，他们有得天独厚的优势。

**95. 跨专业考试，受歧视？**

这得看什么方向，看什么样的老师了，有些老师还喜欢跨专业的学生。

**96. 非名校学生受歧视吗？**

这是“人之常情”，在复试的时候虽然不说，但实际会存在。

但你要相信自己的能力，以自己能力和潜力来征服评委。

建议：适当表达你对自己院校和专业的热爱，并会将这种热爱转移到新的院校与专业上。

**97. 你对目标专业的研究方向有什么了解，谈谈你的看法？**

建议：

1) 切实了解你所报考专业的情况，对所报考导师的学术观点、论文、专著应有较深的了解。

2) 了解其它院校相关专业的情况，最好进行一些比较。

3) 看一些相关专业领域的一些权威期刊。对整个行业研究有个大体的了解。

**98. 你为何换专业？**

对于跨专业考入的学生，要特别注意思考这一点。要提前准备好相关问题的答案。

**99. 如何在复试面试中体现自己的专业知识？**

复试的重要内容之一便是对专业课知识的考察。无论是跨专业还是非跨专业的考生，在面对专业课问题的提问时（具体形式可能是口述或者笔写）要有意识体现自己思路的独创新鲜性，因为导师作为学术带头人，其学术习惯很自然地会促使他们愿意多方听取新鲜思路和独创见解，并乐意招纳具备创新开拓精神的学生。考生在提出自己个人见解时，态度要谦虚谨慎，不妨可先简要陈述对该问题的一般性见解，然后在对此肯定的基础上再详细提出自己的新想法，新思路。

**100. 请你简单说说你的毕业论文（毕业设计）。**

这需要你简要的概括一下你的毕业论文的核心内容，但须要注意的是，这不只是在让你做概括题。建议做如下的准备：

- 1) 500 字左右的概括内容
- 2) 可以适当显示你的研究能力（可以谈谈你在写论文时的研究方法）。
- 3) 如果你是跨专业的考生，可以适当结合你本科的学习与研究，对所报专业的研究的支持作用。

建议：精心准备这部分内容，要清晰明了，尽量不出现让评委追问的情况。

#### 四、发表论文及著作

##### 101. 你在本科期间有论文发表吗？

尤其对于同等学力考生来说，可能是必须的，因此对于论文和著作这方面，也是有必要准备的。

【建议】有论文和著作的，可以提前复印一下当面给老师留下。

没有的话，实话实说就可以了。如果评委追问有什么研究兴趣，则可以围绕自己对科研的设想具体讲述一下。

# 考研复试英语面试复习资料

Good morning. I am very glad to be here for this interview.

2.姓名, 英文名, 毕业院校, 毕业专业, 毕业学院

First let me introduce myself. My name is LiShuai, and my English name is Jacky Lee. I've finished my undergraduate education in Xidian University, Majoring in Electronic Science and Technology in the college of Technical Physics.

3.性格, 爱好, 实践经验

I am open-minded, willing and have broad interests like basketball, reading and especially in engineering such as software programming, website design, hardware design. For example, during the past four years, I have accomplished two websites: one is the website of our school, and the other is the website of the doctor forum of china 2007. Furthermore, I am interested in C plus plus programming language and have written some application programs. In July in the last year, I finished my graduate project with flying colors, which was a software application about Image Process. In addition, I have also finished some projects about embedded system by using MCU when I was a junior.

4.为什么想读研,将来愿意从事的方向,读研时的打算

Although I have broad interests in many aspects and grasp the essential knowledge of the major, but I think at present, I can do many things in a superficial level, but not be competent to do things professionally owing to lack of ample knowledge and ability. So I think further study is still urgent for me to realize self-value. 徐州人才网

The major that I hope pursue for my further education is IC design. Because I find integrated circuits are playing a more and more important role in our modern society. And nowadays in China, with the recognition by the government, our domestic integrated circuits industry is growing rapidly and that may provide a lot of chances to us. 徐州招聘网

I plan to concentrate on study and research in this field in my graduate time. And I hope I can form a systematic view of micro electronics and IC design technology and make a solid foundation for future profession after three years study here. 徐州招聘

5.结束语

OK, that's all. Thank you very much.

## 考研复试英语面试

### 自我介绍 (self-introduce)

Good morning. I am glad to be here for this interview. First let me introduce myself. My name is \*\*\*, 24. I come from \*\*\*, the capital of \*\*\*Province. I graduated from the \*\*\* department of \*\*\*University in July, 2001. In the past two years I have been preparing for the postgraduate examination while I have been teaching \*\*\* in NO. \*\*\* middle School and I was a head-teacher of a class in junior grade two. Now all my hard work has got a result since I have a chance to be interviewed by you.

I am open-minded, quick in thought and very fond of history. In my spare time, I have broad interests like many other youngsters. I like reading books, especially those \*\*\*. Frequently I exchange with other people by making comments in the forum on line. In addition, during my college years, I was once a Net-bar technician. So, I have a comparative good command of network application. I am able to operate the computer well. I am skillful in searching for information in Internet. I am a football fan for years. Italian team is my favorite. Anyway, I feel great pity for our country's team.

I always believe that one will easily lag behind unless he keeps on learning .Of course, if I am given a chance to study \*\*\*\*\* in this famous University, I will spare no effort to master a good command of advance \*\*\*\*\*.

Hello, my professors. It's a fine day today, and i'm very pleased to meet you here. First of all, i'd like to introduce myself to you. My name is \*\*\*, my hometown is \*\*\*, which is a really beautiful city. Even when i was a young boy, i was very interested in biology science. Every one may have a dream, and i still remember that my dream is to be a biology scientist (just like ZHU KE ZHEN). I liked to make wonders just like, where are we from? Where are we going in the universe? And then i would find the answers in book by myself. Still today i think that interest is the best teacher in one's whole life (and knowledge comes from practice).

Second, i will introduce my major in the university. My major is Biological Engineering in \*\*\* University. It has a great relationship with biology science. Their relationship can be shown with an example: Just like a river, biology science, which often finds new discoveries and theories, is at the head of the river. And my major, which lays more stress on practical use, seems to be at the end of it. When both of them interact well enough, the discoveries and theories in biology science can be soon turned into

products in all of the modern industry.

Four years' university education gives me a lot of things to learn, a lot of chances to try, and a lot of practices to improve myself. It teaches me not only what to study and how to think, but also to see the importance of practical ability (such as doing experiment as much as possible). In the university life, I have made many good friends. They help me improve my study and research ability, do everything just like a man, and often give me good example to follow.

Besides what I have introduced myself above, I also have many interests in my spare time. I like playing football, which is an effective way I think to improve my body health, and it can teach me how to join in a group and deal with other people. Drawing and writing is another favor to me.

Above all, I choose the major in order to broaden my view in biology science, and enhance my research ability. I will do my best to join the new group and be good at postgraduate study.

### **考研英语复试英语 75 个经典提问总结**

**考研英语面试中，在自我介绍完了老师就会开始问你问题这里列出一些常见的问题，可以认真准备。注意在准备的过程中，要结合自己的经历和见解来准备答案，让自己回答的问题和整个的自我介绍融为一个整**



体。要不然很容易被考官抓住把柄，问个没完，很容易因紧张而露出马脚。

在每一年的面试中都会有很多相同的问题，这些问题看起来很平常，却有很多陷阱，一不小心就会被考官抓主小辫子了。回答这些常见的看起来很平常的问题，是很有艺术的。在这里一共提供了 75 个常见的各类问题，本文进行了详细的分析。

### 一、传统面试问题 (Sample Traditional Interview Questions)

1、What can you tell me about yourself? (关于你自己，你能告诉我些什么?)

这一问题如果面试没有安排自我介绍的时间的话。这是一个必问的问题。考官并不希望你大谈你的个人历史，他是在寻找有关你性格、资历、志向和生活动力的线索，来判断你是否适合读研或者 MBA。下面是一个积极正面回答的好例子：“在高中我参加各种竞争性体育活动，并一直努力提高各项运动的成绩。大学期间，我曾在一家服装店打工，我发现我能轻而易举地将东西推销出去。销售固然重要，但对我来说，更重要的是要确信顾客能够满意。不久便有顾客返回那家服装店点名让我为他们服务。我很有竞争意识，力求完美对我很重要。”

In high school I was involved in competitive sports and I always tried to improve in each sport I participated in. As a college student, I worked in a clothing store part-time and found that I could sell things easily. The sale was important, but for me, it was even more important to make sure that the customer was

satisfied. It was not long before customers came back to the store and specifically asked for me to help them. I 'm very competitive and it means a lot to me to be the best.

2、What would you like to be doing five years after graduation ?

(在毕业以后 5 年内你想做些什么 ? )

你要清楚你实际上能胜任什么。你可以事先和其他的 MBA 交流一番。问问他们在毕业后在公司的头 5 年都做了些什么。可以这样回答：“我希望能在我的职位上尽力做好工作，由于在同一领域工作的许多人都被提为区域负责人，所以我亦有此打算。”

I hope to do my best I can be at my job and because many in this line of work are promoted to area manager, I am planning on that also.

3. What is your greatest strength? (你最突出的优点是什么 ? )

这是很多面试考官喜欢问的一个问题，这是你“展示自己”的最佳机会，不要吹嘘自己或过于自负，但要让雇主知道你相信自己，你知道自己的优点。如可答：“我认为我最大的优点是能够执着地尽力把事情办好。当做完一件工作而其成果又正合我的预想时，我会有一种真正的成就感。我给自己定了一些高目标。比如说，我要成为出色的毕业生。尽管在大学一年级时我启动慢了些，但最终我以优等论文完成了学业。”

I feel that my strongest asset is my ability to stick to things to get them done. I feel a real sense of accomplishment when I finish a job and it turns out just as I 'd planned. I ' ve set some

high goals for myself. For example, I want to graduate with highest distinction. And even though I had a slow start in my freshman year, I made up for it by doing an honor 's thesis.

4. What is your greatest weakness? (你最大的弱点是什么?)

**你不应该说你没有任何弱点，以此来回避这个问题。每个人都有弱点，最佳策略是承认你的弱点，但同时表明你在予以改进，并有克服弱点的计划。可能的话，你可说出一项可能会给公司带来好处的弱点，如可说：“我是一个完美主义者。工作做得不漂亮，我是不会撒手的。”**

I 'm such a perfectionist that I will not stop until a job is well done.

5. How do you feel about your progress to date? “ (对于你至今所取得的进步你是怎样看的?)

**绝不要对你以前的所作所为表示内疚。如可答：“我认为我在学校表现不错。事实上，有好几门功课我的成绩居全班第一。在某公司实习时，我获得了该公司数年来给予其雇员的好几项最高评价。”**

I think I did well in school. In fact, in a number of courses I received the highest exam scores in the class. As an intern for the X Company, I received some of the highest evaluations that had been given in years.

## **二、其他常见问题**

6. Why did you choose peking university?

7. Why did you choose MBA?

8.What would you like to be doing five years after graduation ?

9.What has been your greatest accomplishment ?

10.Describe your greatest strengths and weaknesses.

11.What have you learned from the jobs you have held ?

**三、行为面试问题 (Sample Behavioral Interview Questions) :**

12.Describe the best/worst team of which you have been a member.

13Tell me about a time when your course load was heaviest. How did you get all of your work done ?

14.Give me a specific example of a time when you sold someone on an idea or concept.

15.Tell me about a time when you were creative in solving a problem.

16.Describe a time when you got co-workers or classmates who dislike each other to work together.

17.Tell me about a time when you made a bad decision.

**四、压力面试问题 (Sample Stress Interview Questions) :**

18.What kinds of people do you find it difficult to work with ?

19.What are some of the things you find difficult to do ?

20.How would you evaluate me as an interviewer ?

21.What interests you least about MBA ?

22.How do you handle rejection ?

23.What is the worst thing you have heard about our school ?

24.See this pen I 'm holding. Sell it to me.

## **五、案例面试问题 (Sample Case Interview Questions) :**

25. A chain of grocery stores currently receives its stock on a decentralized basis. Each store deals independently with its suppliers. The president of the chain is wondering whether the firm can benefit from a centralized warehouse. What are the key considerations in making this decision?

A magazine publisher is trying to decide how many magazines she should deliver to each individual distribution outlet in order to maximize profits. She has extensive historical sales volume data for each of the outlets. How should she determine delivery quantities?

## **六、非常规问题:**

26. It is the 15th Century. How do convince the Pope that the Earth is round?

27. If I gave you an elephant, where would you hide it?

28. Why are soda cans tapered on the top and bottom?

29. How much RAM does a PC need to run Windows95?

30. You are in a boat on a fresh water lake. In your hand is a rock. You throw the rock into the lake. How is the lake's water level affected?

31. If it rained music, what would grow?

32. Describe your best friend and what he or she does for a living.

33. In what ways are you similar or different from your best friend ?
34. What are your career 's strengths and how do you capitalize on them ?
35. Are you a happy person ?
36. According to JRM, Jr., a fast growing software company asked this question..... You have a wealthy aunt who weighs 300 pounds. Tell me how you would redesign her toilet.

**七、其他常见的英语面试问题：**

37. Would you please make a brief introduction about yourself ?
38. Why did you take the MBA examination ? Would you please say something about the currently MBA program in China ?
39. Why do you choose RENMIN University to study MBA ? Tell me a little about RENMIN University from your understanding.
40. How do the people around you review MBA ?
41. What 's the difference between MBA program at home and abroad ?
42. If you failed this time what will you do in the near future ?
43. Why do you want to be a part of MBA students ?
44. Why do you think you are qualified for MBA program ?
45. Do you have a career plan in 5 years ?
46. Do you have a study plan if you were accepted as a MBA student ?
47. What 's your opinion about the requirement that a MBA student

must have working experience ?

48. How do you define marketing or management ?

49. Do you think English is quite important in MBA study ? Why ?

50. Do you think MBA training courses will help you a lot in your future life ? Why ?

51. What do you want to do after your MBA study ?

52. What is the most important qualification that a MBA student should have ?

53. Say a little about teamwork.

54. Say a little about management.

55. How communication works in organizations ?

56. Tell me the relationship between the management and management theory.

57. What will you do if you can 't find a job ?

58. Do you think that the economy will get better ?

59. Who are you currently employed with ?

60. What kinds of opportunities are you looking for ?

61. What is your biggest accomplishment on the job ?

62. What joy did you enjoy the most and why ?

63. What would your former boss say about you ?

64. Why did you leave your last job ?

65. Please tell me a little about your working history ? What kind

of fields ?

66. Say a little about your educational background.

67. What are your strengths and weakness ?

68. What do you do in your spare time ?

69. What is your impression of Beijing ?

70. What is CFO ? If you were a CFO, what would you do ?

71. What is the difference between sales and marketing ?

72. What do you think is the most important as a manager ?

**在面试快结束的时候，一般考官都会问，你有没有什么要问的。除非你是最后一个面试者，你明显感到所有的考官都急切的想离开，一般不适合说 “I don ‘t have any question.” 可以问考官一两个你关心的问题 (Questions you should ask the recruiter) :**

73. What changes do you anticipate in our school ? **(你希望我们学校会有些什么样的变化)**

74. Which is the best course in our school ? **(什么课程是我们院最好的课程)**

75. does our school provide some guidance of job to MBA ?

**最后可以说:** Thank you for giving me the chance. I hope to see you again and soon. **(谢谢您给我机会，我希望很快能再见到)**