Physics

The Main Branches of Physics

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Introduction

Physics

This article is about the field of science. For other uses, see Physics (disambiguation).

Not to be confused with Physical science.

Further information: Outline of physics

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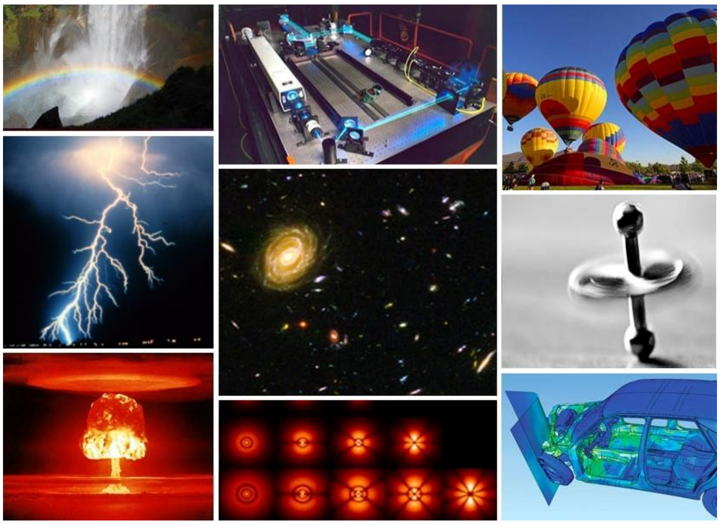
Physics (from Ancient Greek: φυσική (ἐπιστήμη) *phusikḗ (epistḗmē)* "knowledge of nature", from φύσις *phúsis* "nature"[1]) is the natural science that involves the study of matter[2] and its motion through space and time, along with related concepts such as energy and force.[3] One of the most fundamental scientific disciplines, the main goal of physics is to understand how the universe behaves.[4][5][6][7]



Various examples of physical phenomena.

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, biology, and certain branches of mathematics, but during the scientific revolution in the 17th century, the natural sciences emerged as unique research programs in their own right.[8] 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 that 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.

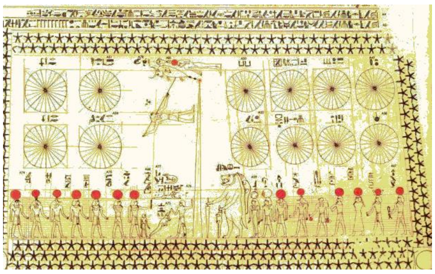
History

Main article: History of physics

Ancient astronomy

Main article: History of astronomy

Astronomy is the oldest of the natural sciences. The earliest civilizations dating back to beyond 3000 BCE, such as the Sumerians, ancient Egyptians, and the Indus Valley Civilization, all had a predictive knowledge and a basic understanding of the motions of the Sun, Moon, and stars. The stars and planets were often a target of worship, believed to represent their gods. While the explanations for these phenomena were often unscientific and lacking in evidence, these early observations laid the foundation for later astronomy.



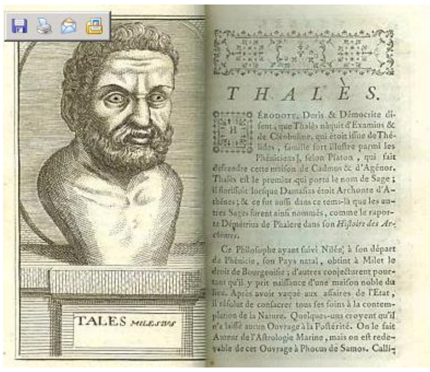
Ancient Egyptian astronomy is evident in monuments like the ceiling of Senemut's tomb from the Eighteenth Dynasty of Egypt.

According to Asger Aaboe, the origins of Western astronomy can be found in Mesopotamia, and all Western efforts in the exact sciences are descended from late Babylonian astronomy. Egyptian astronomers left monuments showing knowledge of the constellations and the motions of the celestial bodies, while Greek poet Homer wrote of various celestial objects in his *Iliad* and *Odyssey*; later Greek astronomers provided names, which are still used today, for most constellations visible from the northern hemisphere.

Natural philosophy

Main article: Natural philosophy

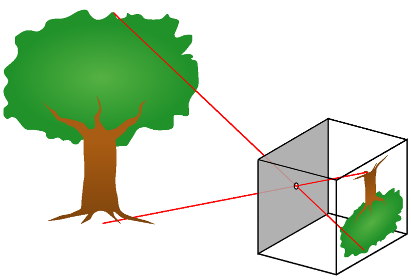
Natural philosophy has its origins in Greece during the Archaic period, (650 BCE – 480 BCE), when Pre-Socratic philosophers like Thales rejected non-naturalistic explanations for natural phenomena and proclaimed that every event had a natural cause. They proposed ideas verified by reason and observation, and many of their hypotheses proved successful in experiment; for example, atomism was found to be correct approximately 2000 years after it was first proposed by Leucippus and his pupil Democritus.



Physics in the medieval Islamic world

Main article: Physics in the medieval Islamic world

Islamic scholarship had inherited Aristotelian physics from the Greeks and during the Islamic Golden Age developed it further, especially placing emphasis on observation and *a priori* reasoning, developing early forms of the scientific method.

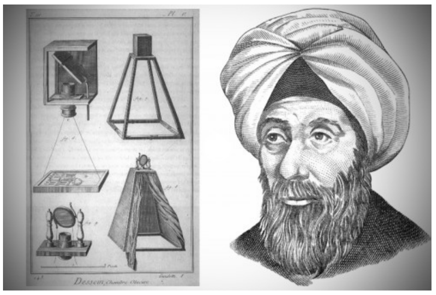


The basic way a pinhole camera works

The most notable innovations were in the field of Optics and vision, which came from the works of many scientists like Ibn Sahl, Al-Kindi, Ibn Al-Haitham, Al-Farisi and Avicenna. The most notable work, was *The Book of Optics* (also known as Kitāb al-Manāẓir) written by Ibn Al-Haitham, in which he was not only the first to disprove the ancient

Greek idea about vision, but also came up with a new theory.[9] In the book, he was also the first to study the phenomenon of the pinhole camera and delved further into the way the eye itself works. Using dissections and the knowledge of previous scholars, he was able to begin to explain how light enters the eye, is focused, and is projected to the back of the eye: and built then the world's first obscura camera hundreds of years before the modern development of photography.

The seven-volume Book of Optics (Kitab al-Manathir) hugely influenced thinking across disciplines from the theory of visual perception to the nature of perspective in medieval art, in both the East and the West, for more than 600 years. Many later European scholars and fellow polymaths, from Robert Grosseteste and Leonardo da Vinci to René Descartes, Johannes Kepler and Isaac Newton, were in his debt. Indeed, the influence of Ibn al-Haytham's Optics ranks alongside that of Newton's work of the same title, published 700 years later.



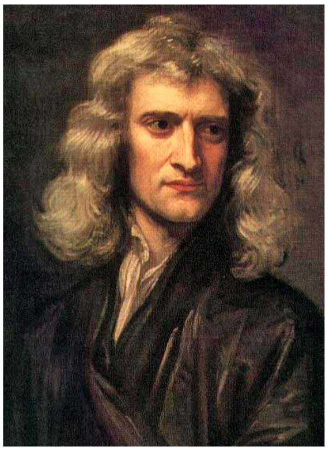
Ibn Al Haytham, The Father of Optics

The translation of *The Book of Optics* had a huge impact on Europe. From it, later European scholars were able to build the same devices as what Ibn Al Haytham did, and understand the way light works. From this, such important things as eyeglasses, magnifying glasses, telescopes, and cameras were developed.

Classical physics

Main article: Classical physics

Physics became a separate science when early modern Europeans used experimental and quantitative methods to discover what are now considered to be the laws of physics.



Sir Isaac Newton (1643–1727), whose laws of motion and universal gravitation were major milestones in classical physics

Major developments in this period include the replacement of the geocentric model of the solar system with the heliocentric Copernican model, the laws governing the motion of planetary bodies determined by Johannes Kepler between 1609 and 1619, pioneering work on telescopes and observational astronomy by Galileo Galilei in the 16th and 17th Centuries, and Isaac Newton's discovery and unification of the laws of motion and universal gravitation that would come to bear his name. Newton also developed calculus,[10] the mathematical study of change, which provided new mathematical methods for solving physical problems.

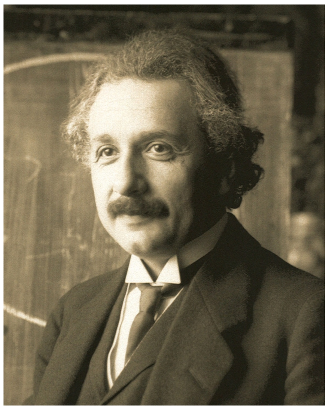
The discovery of new laws in thermodynamics, chemistry, and electromagnetics resulted from greater research efforts during the Industrial Revolution as energy needs increased. The laws comprising classical physics remain very widely used for objects on everyday scales travelling at non-relativistic speeds, since they provide a very close approximation in such situations, and theories such as quantum mechanics and the theory of relativity simplify to their classical equivalents at such scales. However, inaccuracies in classical mechanics for very small objects and very high velocities led to the development of modern physics in the 20th century.

Modern physics

Main article: Modern physics

See also: History of special relativity and History of quantum mechanics

Modern physics began in the early 20th century with the work of Max Planck in quantum theory and Albert Einstein's theory of relativity. Both of these theories came about due to inaccuracies in classical mechanics in certain situations. Classical mechanics predicted a varying speed of light, which could not be resolved with the constant speed predicted by Maxwell's equations of electromagnetism; this discrepancy was corrected by Einstein's theory of special relativity, which replaced classical mechanics for fast-moving bodies and allowed for a constant speed of light. Black body radiation provided another problem for classical physics, which was corrected when Planck proposed that light comes in individual packets known as photons; this, along with the photoelectric effect and a complete theory predicting discrete energy levels of electron orbitals, led to the theory of quantum mechanics taking over from classical physics at very small scales.



Albert Einstein (1879–1955), whose work on the photoelectric effect and the theory of relativity led to a revolution in 20th century physics

Quantum mechanics would come to be pioneered by Werner Heisenberg, Erwin Schrödinger and Paul Dirac. From this early work, and work in related fields, the Standard Model of particle physics was derived. Following the discovery of a particle with properties consistent with the Higgs boson at CERN in 2012, all fundamental particles predicted by the standard model, and no others, appear to exist; however, physics beyond the Standard Model, with theories such as supersymmetry, is an active area of research.[11] Areas of mathematics in general are important to this field, such as study of probabilities.

Philosophy

Main article: Philosophy of physics

In many ways, physics stems from ancient Greek philosophy. From Thales' first attempt to characterize matter, to Democritus' deduction that matter ought to reduce to an invariant state, the Ptolemaic astronomy of a crystalline firmament, and Aristotle's book *Physics* (an early book on physics, which attempted to analyze and define motion from a philosophical point of view), various Greek philosophers advanced their own theories of nature. Physics was known as natural philosophy until the late 18th century.[12]

By the 19th century, physics was realized as a discipline distinct from philosophy and the other sciences. Physics, as with the rest of science, relies on philosophy of science and its "scientific method" to advance our knowledge of the physical world. The scientific method employs *a priori reasoning* as well as *a posteriori* reasoning and the use of Bayesian inference to measure the validity of a given theory.

The development of physics has answered many questions of early philosophers, but has also raised new questions. Study of the philosophical issues surrounding physics, the philosophy of physics, involves issues such as the nature of space and time, determinism, and metaphysical outlooks such as empiricism, naturalism and realism.

Many physicists have written about the philosophical implications of their work, for instance Laplace, who championed causal determinism, and Erwin Schrödinger, who wrote on quantum mechanics. The mathematical physicist Roger Penrose has been called a Platonist by Stephen Hawking,[13] a view Penrose discusses in his book, *The Road to Reality*. Hawking refers to himself as an "unashamed reductionist" and takes issue with Penrose's views.

Core theories

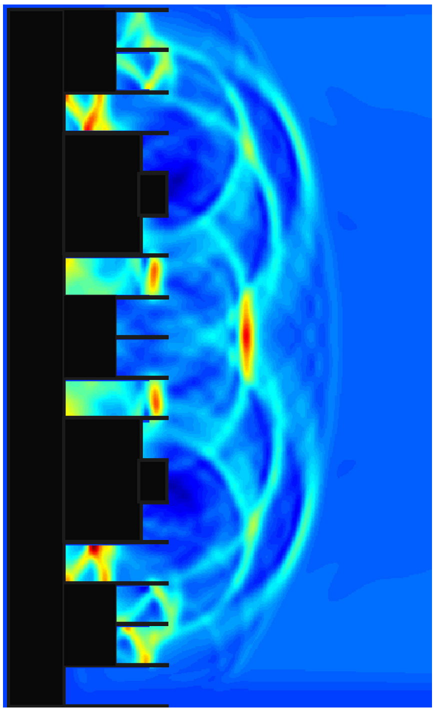
Further information: Branches of physics and Outline of physics

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 to be an adequate approximation of nature. 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 today. Chaos theory, a remarkable aspect of classical mechanics was discovered in the 20th century, three centuries after the original formulation of classical mechanics by Isaac Newton (1642–1727).

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

Classical physics

Main article: Classical physics



Classical physics implemented in an acoustic engineering model of sound reflecting from an acoustic diffuser

Classical physics includes the traditional branches and topics that were recognised 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 not subject to an acceleration), 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 include 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

Main article: Modern physics

Modern physics
Schrödinger equation
History of modern physics
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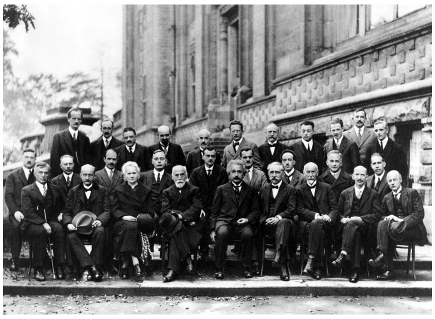
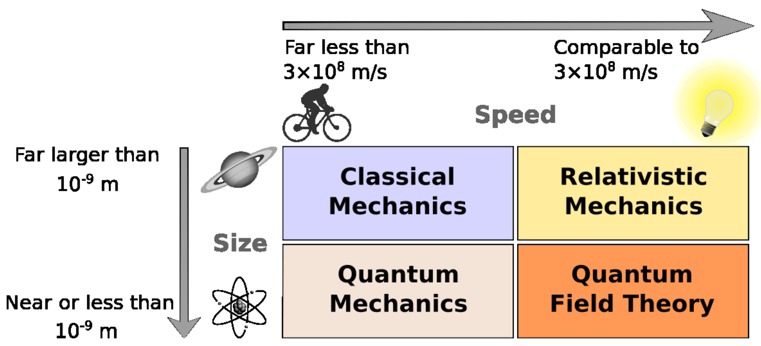


Solvay Conference of 1927, with prominent physicists such as Albert Einstein, Werner Heisenberg, Max Planck, Hendrik Lorentz, Niels Bohr, Marie Curie, Erwin Schrödinger and Paul Dirac.

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 a 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 since 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 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. Classical mechanics approximates nature as continuous, while quantum theory is concerned with the discrete 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



The basic domains of 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 predictions provided by classical mechanics. Albert Einstein contributed the framework of special relativity, which replaced notions of absolute time and space with spacetime and allowed an accurate description of systems whose components have speeds approaching the speed of light. Max Planck, Erwin Schrödinger, 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 spacetime, 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.

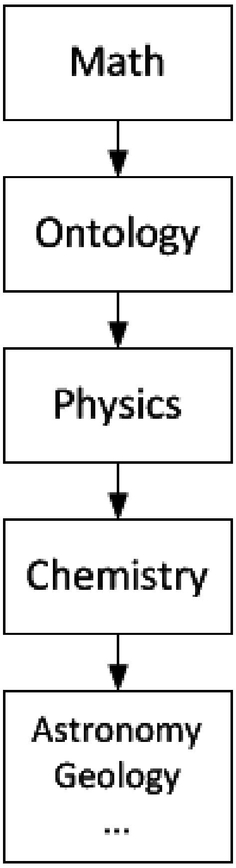
Relation to other fields

Prerequisites

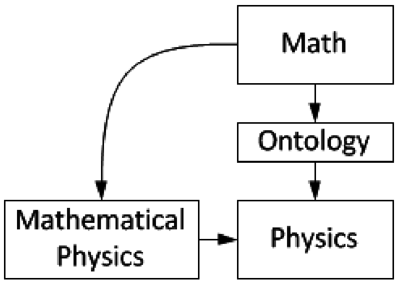
Mathematics provides a compact and exact language used to describe of the order in nature. This was noted and advocated by Pythagoras, Plato,[15] Galileo,[16] and Newton.

Physics uses mathematics to organize and formulate experimental results. From those results, precise or estimated solutions, quantitative results from which new predictions can be made and experimentally confirmed or negated. The results from physics experiments are numerical measurements. Technologies based on mathematics, like computation have made computational physics an active area of research.


This parabola-shaped lava flow illustrates the application of mathematics in physics—in this case, Galileo's law of falling bodies.



Mathematics and ontology are used in physics. Physics is used in chemistry and cosmology.



The distinction between mathematics and physics is clear-cut, but not always obvious, especially in mathematical physics.

Ontology is a prerequisite for physics, but not for mathematics. It means physics is ultimately concerned with descriptions of the real world, while mathematics is concerned with abstract patterns, even beyond the real world. Thus physics statements are synthetic, while mathematical statements are analytic. Mathematics contains hypotheses, while physics contains theories. Mathematics statements have to be only logically true, while predictions of physics statements must match observed and experimental data.

The distinction is clear-cut, but not always obvious. For example, mathematical physics is the application of mathematics in physics. Its methods are mathematical, but its subject is physical. The problems in this field start with a "mathematical model of a physical situation" (system) and a "mathematical description of a physical law" that will be applied to that system. Every mathematical statement used for solution has a hard-to-find physical meaning. The final mathematical solution has an easier-to-find meaning, because it is what the solver is looking for.Wikipedia:Please clarify

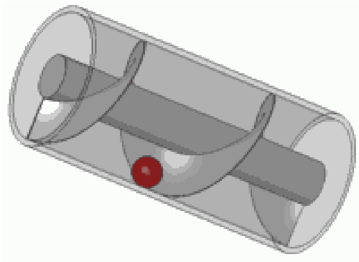
Physics is a branch of fundamental science, not practical science.[17] Physics is also called "the fundamental science" because the subject of study of all branches of natural science like chemistry, astronomy, geology and biology are constrained by laws of physics,[18] similar to how chemistry is often called the central science because of its role in linking the physical sciences. For example, chemistry studies properties, structures, and reactions of matter (chemistry's focus on the atomic scale distinguishes it from physics). Structures are formed because particles exert electrical forces on each other, properties include physical characteristics of given substances, and reactions are bound by laws of physics, like conservation of energy, mass and charge.

Physics is applied in industries like engineering and medicine.

Application and influence

Main article: Applied physics

Applied physics is a general term for physics research which is intended for a particular use. An applied physics curriculum usually contains a few classes in an applied discipline, like geology or electrical engineering. It usually differs from engineering in that an applied physicist may not be designing something in particular, but rather is using physics or conducting physics research with the aim of developing new technologies or solving a problem.



Archimedes' screw, a simple machine for lifting

The approach is similar to that of applied mathematics. Applied physicists use physics in scientific research. For instance, people working on accelerator physics might seek to build better particle detectors for research in theoretical physics.

Physics is used heavily in engineering. For example, statics, a subfield of mechanics, is used in the building of bridges and other static structures. The understanding and use of acoustics results in sound control and better concert halls; similarly, the use of optics creates better optical devices. An understanding of physics makes for more realistic flight simulators, video games, and movies, and is often critical in forensic investigations.

The application of physical laws in lifting liquids

With the standard consensus that the laws of physics are universal and do not change with time, physics can be used to study things that would ordinarily be mired in uncertainty. For example, in the study of the origin of the earth, one can reasonably model earth's mass, temperature, and rate of rotation, as a function of time allowing one to extrapolate forward or backward in time and so predict future or prior events. It also allows for simulations in engineering which drastically speed up the development of a new technology.

But there is also considerable interdisciplinarity in the physicist's methods, so many other important fields are influenced by physics (e.g., the fields of econophysics and sociophysics).

Research

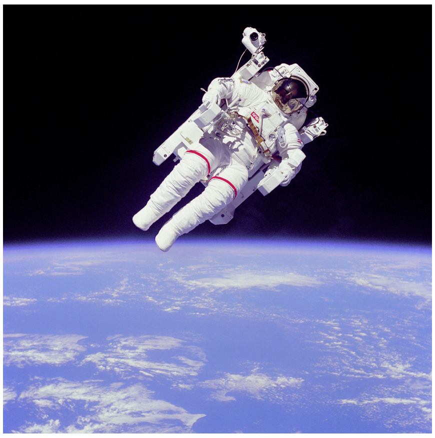
Scientific method

Physicists use the scientific method to test the validity of a physical theory. By using a methodical approach to compare the implications of a theory with the conclusions drawn from its related experiments and observations, physicists are better able to test the validity of a theory in a logical, unbiased, and repeatable way. To that end, experiments are performed and observations are made in order to determine the validity or invalidity of the theory.

A scientific law is a concise verbal or mathematical statement of a relation which expresses a fundamental principle of some theory, such as Newton's law of universal gravitation.

Theory and experiment

Main articles: Theoretical physics and Experimental physics



The astronaut and Earth are both in free-fall

Theorists seek to develop mathematical models that both agree with existing experiments and successfully predict future experimental results, while experimentalists devise and perform experiments to test theoretical predictions and explore new phenomena. Although theory and experiment are developed separately, they are strongly dependent upon each other. Progress in physics frequently comes about when experimentalists make a discovery that existing theories cannot explain, or when new theories generate experimentally testable predictions, which inspire new experiments.

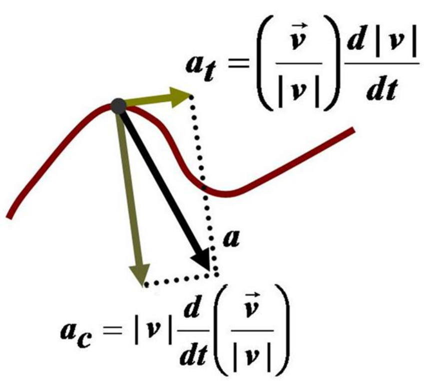
Physicists who work at the interplay of theory and experiment are called phenomenologists, who study complex phenomena observed in experiment and work to relate them to a fundamental theory.

Lightning is an electric current

Theoretical physics has historically taken inspiration from philosophy; electromagnetism was unified this way.[19] Beyond the known universe, the field of theoretical physics also deals with hypothetical issues,[20] such as parallel universes, a multiverse, and higher dimensions. Theorists invoke these ideas in hopes of solving particular problems with existing theories. They then explore the consequences of these ideas and work toward making testable predictions.

Experimental physics expands, and is expanded by, engineering and technology. Experimental physicists involved in basic research design and perform experiments with equipment such as particle accelerators and lasers, whereas those involved in applied research often work in industry developing technologies such as magnetic resonance imaging (MRI) and transistors. Feynman has noted that experimentalists may seek areas which are not well-explored by theorists.[21]

Scope and aims



Physics involves modeling the natural world with theory, usually quantitative. Here, the path of a particle is modeled with the mathematics of calculus to explain its behavior: the purview of the branch of physics known as mechanics.

Physics covers a wide range of phenomena, from elementary particles (such as quarks, neutrinos, and electrons) to the largest superclusters of galaxies. Included in these phenomena are the most basic objects composing all other things. Therefore, physics is sometimes called the "fundamental science". Physics aims to describe the various phenomena that occur in nature in terms of simpler phenomena. Thus, physics aims to both connect the things observable to humans to root causes, and then connect these causes together.

For example, the ancient Chinese observed that certain rocks (lodestone and magnetite) were attracted to one another by an invisible force. This effect was later called magnetism, which was first rigorously studied in the 17th century. But even before the Chinese discovered magnetism, the ancient Greeks knew of other objects such as amber, that when rubbed with fur would cause a similar invisible attraction between the two. This was also first studied rigorously in the 17th century, and came to be called electricity. Thus, physics had come to understand two observations of nature in terms of some root cause (electricity and magnetism). However, further work in the 19th century revealed that these two forces were just two different aspects of one force—electromagnetism. This process of "unifying" forces continues today, and electromagnetism and the weak nuclear force are now considered to be two aspects of the electroweak interaction. Physics hopes to find an ultimate reason (Theory of Everything) for why nature is as it is (see section *Current research* below for more information).

Research fields

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

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), who worked in multiple fields of physics, are now very rare.[22]

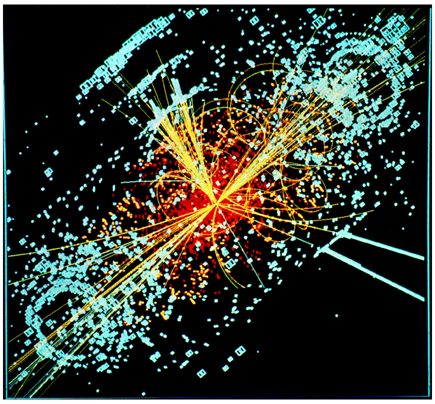
The major fields of physics, along with their subfields and the theories and concepts they employ, are shown in the following table.

Field	Subfields	Major theories	Concepts
Particle physics	Nuclear physics, Nuclear astrophysics, Particle astrophysics, Particle physics phenomenology	Standard Model, Quantum field theory, Quantum electrodynamics, Quantum chromodynamics, Electroweak theory, Effective field theory, Lattice field theory, Lattice gauge theory, Gauge theory, Supersymmetry, Grand unification theory, Superstring theory, M-theory	Fundamental force (gravitational, electromagnetic, weak, strong), Elementary particle, Spin, Antimatter, Spontaneous symmetry breaking, Neutrino oscillation, Seesaw mechanism, Brane, String, Quantum gravity, Theory of everything, Vacuum energy
Atomic, molecular, and optical physics	Atomic physics, Molecular physics, Atomic and Molecular astrophysics, Chemical physics, Optics, Photonics	Quantum optics, Quantum chemistry, Quantum information science	Photon, Atom, Molecule, Diffraction, Electromagnetic radiation, Laser, Polarization (waves), Spectral line, Casimir effect

Condensed matter physics	Solid state physics, High pressure physics, Low-temperature physics, Surface Physics, Nanoscale and Mesoscopic physics, Polymer physics	BCS theory, Bloch wave, Density functional theory, Fermi gas, Fermi liquid, Many-body theory, Statistical Mechanics	Phases (gas, liquid, solid), Bose-Einstein condensate, Electrical conduction, Phonon, Magnetism, Self-organization, Semiconductor, superconductor, superfluid, Spin,
Astrophysics	Astronomy, Astrometry, Cosmology, Gravitation physics, High-energy astrophysics, Planetary astrophysics, Plasma physics, Solar physics, Space physics, Stellar astrophysics	Big Bang, Cosmic inflation, General relativity, Newton's law of universal gravitation, Lambda-CDM model, Magnetohydrodynamics	Black hole, Cosmic background radiation, Cosmic string, Cosmos, Dark energy, Dark matter, Galaxy, Gravity, Gravitational radiation, Gravitational singularity, Planet, Solar System, Star, Supernova, Universe
Applied Physics	Accelerator physics, Acoustics, Agrophysics, Biophysics, Chemical Physics, Communication Physics, Econophysics, Engineering physics, Fluid dynamics, Geophysics, Laser Physics, Materials physics, Medical physics, Nanotechnology, Optics, Optoelectronics, Photonics, Photovoltaics, Physical chemistry, Physics of computation, Plasma physics, Solid-state devices, Quantum chemistry, Quantum electronics, Quantum information science, Vehicle dynamics		

Particle physics

Main articles: Particle physics and Nuclear physics



A simulated event in the CMS detector of the Large Hadron Collider, featuring a possible appearance of the Higgs boson.

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, an integral part of a Higgs mechanism.

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.

Atomic, molecular, and optical physics

Main article: 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 their relevant energy scales. 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).

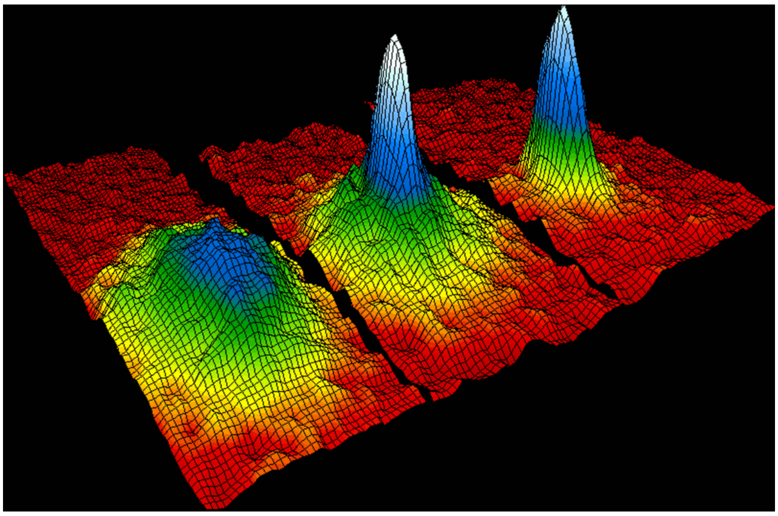
Atomic physics studies the electron shells of atoms. Current research focuses on activities in quantum control, cooling and trapping of atoms and ions,[23] low-temperature collision dynamics and the effects of electron correlation on structure and dynamics. Atomic physics is influenced by the nucleus (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.

Condensed matter physics

Main article: 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.



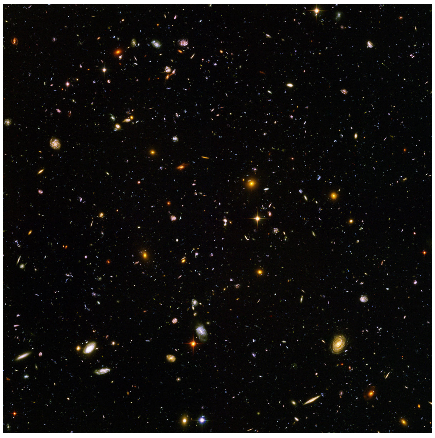
Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate

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 superfluid 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 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.

Astrophysics

Main articles: Astrophysics and Physical cosmology



The deepest visible-light image of the universe, the Hubble Ultra Deep Field

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 is 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 nucleosynthesis 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. Cosmologists have recently established the ΛCDM model of the evolution of the universe, which includes cosmic inflation, dark energy, and dark matter.

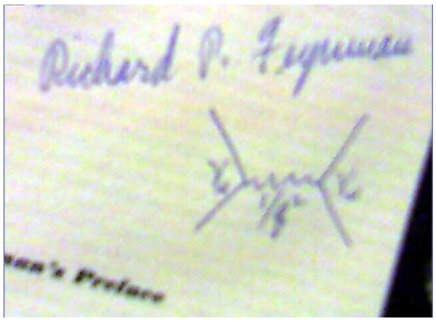
Numerous possibilities and discoveries are anticipated to emerge from new data from the Fermi Gamma-ray Space Telescope over the upcoming decade and vastly revise or clarify existing models of the universe.[24] In particular, the potential for a tremendous discovery surrounding dark matter is possible over the next several years. Fermi will search for evidence that dark matter is composed of weakly interacting massive particles, complementing similar experiments with the Large Hadron Collider and other underground detectors.

IBEX is already yielding new astrophysical discoveries: "No one knows what is creating the ENA (energetic neutral atoms) ribbon" along the termination shock of the solar wind, "but everyone agrees that it means the textbook picture of the heliosphere—in which the Solar System's enveloping pocket filled with the solar wind's charged particles is plowing through the onrushing 'galactic wind' of the interstellar medium in the shape of a comet—is wrong."

Current research

Further information: List of unsolved problems in physics

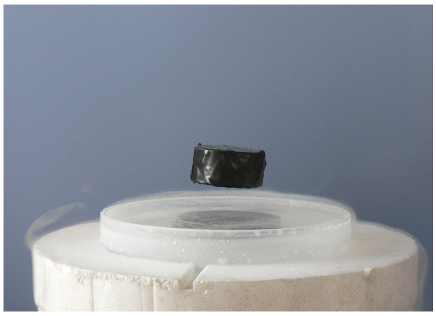
Research in physics is continually progressing on a large number of fronts.



Feynman diagram signed by R. P. Feynman.

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 Higgs boson and supersymmetric particles.[25]


A typical event described by physics: a magnet levitating above a superconductor demonstrates the Meissner effect.

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 sandpiles, nodes in trickling water, the shape of water droplets, mechanisms of surface tension catastrophes, and self-sorting in shaken heterogeneous collections.[26]

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. In the 1932 *Annual Review of Fluid Mechanics*, Horace Lamb said:

> I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.

Notes

[1] , ,

[2] At the start of *The Feynman Lectures on Physics*, Richard Feynman offers the atomic hypothesis as the single most prolific scientific concept: "If, in some cataclysm, all [] scientific knowledge were to be destroyed [save] one sentence [...] what statement would contain the most information in the fewest words? I believe it is [...] that *all things are made up of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another* ..."

[3] "Physical science is that department of knowledge which relates to the order of nature, or, in other words, to the regular succession of events."

[4] The term 'universe' is defined as everything that physically exists: the entirety of space and time, all forms of matter, energy and momentum, and the physical laws and constants that govern them. However, the term 'universe' may also be used in slightly different contextual senses, denoting concepts such as the cosmos or the philosophical world.

[5] "Physics is one of the most fundamental of the sciences. Scientists of all disciplines use the ideas of physics, including chemists who study the structure of molecules, paleontologists who try to reconstruct how dinosaurs walked, and climatologists who study how human activities affect the atmosphere and oceans. Physics is also the foundation of all engineering and technology. No engineer could design a flat-screen TV, an interplanetary spacecraft, or even a better mousetrap without first understanding the basic laws of physics. (...) You will come to see physics as a towering achievement of the human intellect in its quest to understand our world and ourselves.

[6] "Physics is an experimental science. Physicists observe the phenomena of nature and try to find patterns that relate these phenomena."

[7] "Physics is the study of your world and the world and universe around you."

[8] Francis Bacon's 1620 *Novum Organum* was critical in the development of scientific method.

[9] Dallal, Ahmad. *Islam, Science, and the Challenge of History*. New Haven:Yale University Press. pg 39

[10] Calculus was independently developed at around the same time by Gottfried Wilhelm Leibniz; while Leibniz was the first to publish his work, and developed much of the notation used for calculus today, Newton was the first to develop calculus and apply it to physical problems. See also Leibniz–Newton calculus controversy

[11] See, for example, John Womersley, Beyond the standard model (http://www.symmetrymagazine.org/sites/default/files/legacy/pdfs/200502/beyond_the_standard_model.pdf)

[12] Noll notes that some universities still use this title —Walter Noll (23 Jun 2006), "On the Past and Future of Natural Philosophy" (http://www.math.cmu.edu/~wn0g/noll/PFNP.pdf) *Journal of Elasticity* July 2006, **84**(1) pp 1-11

[13] "I think that Roger is a Platonist at heart but he must answer for himself."

[14] http://en.wikipedia.org/w/index.php?title=Template:Modern_physics&action=edit

[15] "Although usually remembered today as a philosopher, Plato was also one of ancient Greece's most important patrons of mathematics. Inspired by Pythagoras, he founded his Academy in Athens in 387 BC, where he stressed mathematics as a way of understanding more about reality. In particular, he was convinced that geometry was the key to unlocking the secrets of the universe. The sign above the Academy entrance read: 'Let no-one ignorant of geometry enter here.'"

[16] "Philosophy is written in that great book which ever lies before our eyes. I mean the universe, but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. This book is written in the mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is humanly impossible to comprehend a single word of it, and without which one wanders in vain through a dark labyrinth." – Galileo (1623), *The Assayer*, as quoted in

[17] American Association for the Advancement of Science, Science. 1917. Page 645

[18] ; see also reductionism and special sciences

[19] See, for example, the influence of Kant and Ritter on Ørsted.

[20] Concepts which are denoted *hypothetical* can change with time. For example, the atom of nineteenth century physics was denigrated by some, including Ernst Mach's critique of Ludwig Boltzmann's formulation of statistical mechanics. By the end of World War II, the atom was no longer deemed hypothetical.

[21] "In fact experimenters have a certain individual character. They ... very often do their experiments in a region in which people know the theorist has not made any guesses."

[22] Yet, universalism is encouraged in the culture of physics. For example, the World Wide Web, which was innovated at CERN by Tim Berners-Lee, was created in service to the computer infrastructure of CERN, and was/is intended for use by physicists worldwide. The same might be said for arXiv.org

[23] For example, AMO research groups at

[24] See also Nasa – Fermi Science (http://www.nasa.gov/mission_pages/GLAST/science/index.html) and NASA – Scientists Predict Major Discoveries for GLAST (http://www.nasa.gov/mission_pages/GLAST/science/unidentified_sources.html).

[25] finds a mass of 5.774 GeV for the UNIQ-math-0-6958cb99112e10e1-QINU

[26] See the work of Ilya Prigogine, on 'systems far from equilibrium', and others, e.g., Heinrich M. Jaeger, Andrea J. Liu (24 Sep 2010) "Far-From-Equilibrium Physics: An Overview" (http://jfi.uchicago.edu/~jaeger/group/JaegerGroupPapers/other/FarFromEquilPhys.pdf) http://arxiv.org/abs/1009.4874

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Wikibooks has a book on the topic of: ***Physics Study Guide***

Wikibooks has a book on the topic of: ***FHSST Physics***

Wikisource has original works on the topic: ***Physics***

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General

- Encyclopedia of Physics (http://www.scholarpedia.org/article/Encyclopedia_of_physics) at Scholarpedia
- de Haas, Paul, Historic Papers in Physics (20th Century) (https://web.archive.org/web/20090826083339/http://home.tiscali.nl/physis/HistoricPaper/) at the Wayback Machine (archived August 26, 2009)
- PhysicsCentral (http://www.physicscentral.com/) – Web portal run by the American Physical Society (http://www.aps.org/)
- Physics.org (http://www.physics.org/) – Web portal run by the Institute of Physics (http://www.iop.org/)
- *The Skeptic's Guide to Physics* (http://musr.physics.ubc.ca/~jess/hr/skept/)
- Usenet Physics FAQ (http://math.ucr.edu/home/baez/physics/) – A FAQ compiled by sci.physics and other physics newsgroups
- Website of the Nobel Prize in physics (http://nobelprize.org/nobel_prizes/physics/)
- World of Physics (http://scienceworld.wolfram.com/physics/) An online encyclopedic dictionary of physics
- *Nature*: Physics (http://www.nature.com/naturephysics)
- Physics (http://physics.aps.org/) announced 17 July 2008 by the American Physical Society
- Physics/Publications (https://www.dmoz.org//Science/Physics/Publications/) at DMOZ
- Physicsworld.com (http://physicsworld.com/) – News website from Institute of Physics Publishing (http://publishing.iop.org/)
- Physics Central (http://physlib.com/) – includes articles on astronomy, particle physics, and mathematics.
- The Vega Science Trust (http://www.vega.org.uk/) – science videos, including physics

- Video: Physics "Lightning" Tour with Justin Morgan (https://archive.org/details/JustinMorganPhysicsLightningTour/)
- 52-part video course: The Mechanical Universe...and Beyond (http://www.learner.org/resources/series42.html) Note: also available at 01 – Introduction (http://web.archive.org/web/20140915031418/https://video.google.com/videoplay?docid=-6774539130229106025) at Google Videos
- HyperPhysics website (http://hyperphysics.phy-astr.gsu.edu/Hbase/hframe.html) – HyperPhysics, a physics and astronomy mind-map from Georgia State University

Organizations

- AIP.org (http://www.aip.org/index.html) – Website of the American Institute of Physics
- APS.org (http://www.aps.org/) – Website of the American Physical Society
- IOP.org (http://www.iop.org/) – Website of the Institute of Physics
- PlanetPhysics.org (http://planetphysics.org/)
- Royal Society (http://www.royalsoc.ac.uk/) – Although not exclusively a physics institution, it has a strong history of physics
- SPS National (http://www.spsnational.org/) – Website of the Society of Physics Students

Main Branches of Physics

Classical Mechanics

For the textbooks, see Classical Mechanics (Goldstein book) and Classical Mechanics (Kibble and Berkshire book).

Classical mechanics
Second law of motion
• **History** • **Timeline**
• v • t • e [1]

In physics, **classical mechanics** and quantum mechanics are the two major sub-fields of mechanics. Classical mechanics is concerned with the set of physical laws describing the motion of bodies under the influence 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. It is also widely known as **Newtonian mechanics**.

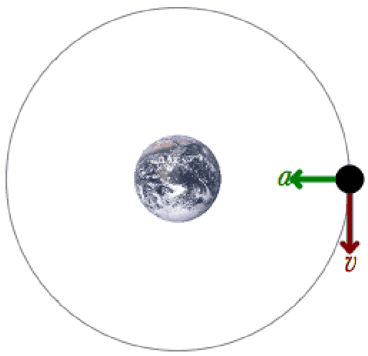


Diagram of orbital motion of a satellite around the earth, showing perpendicular velocity and acceleration (force) vectors.

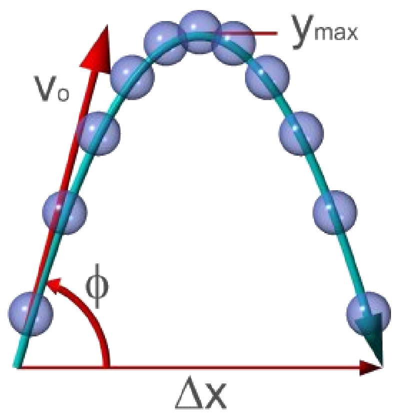
Classical mechanics describes the motion of macroscopic objects, from projectiles to parts of machinery, as well as astronomical objects, such as spacecraft, planets, stars, and galaxies. Within classical mechanics are fields of study that describe the behavior of solids, liquids and gases and other specific sub-topics. Classical mechanics also 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 examined are sufficiently small, it becomes necessary to introduce the other major sub-field of mechanics, quantum mechanics, which adjusts the laws of physics of macroscopic objects for the atomic nature of matter by including the wave–particle duality of atoms and molecules. When both quantum mechanics and classical mechanics cannot apply, such as at the quantum level with high speeds, quantum field theory (QFT) becomes applicable.

The term *classical mechanics* was coined in the early 20th century to describe the system of physics begun by Isaac Newton and many contemporary 17th century natural philosophers, and is built upon the earlier astronomical theories of Johannes Kepler, which in turn were based on the precise observations of Tycho Brahe and the studies of terrestrial projectile motion of Galileo. Since these aspects of physics were developed long before the emergence of quantum physics and relativity, some sources exclude Einstein's theory of relativity from this category. However, a number of modern sources *do* include relativistic mechanics, which in their view represents *classical mechanics* in its most developed and most accurate form.[2]

The earliest 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, Leibniz, 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.

Description of the theory

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. Each of these parameters is discussed in turn.



The analysis of projectile motion is a part of classical mechanics.

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: a baseball can spin while it is moving, for example. However, the results for point particles can be used to study such objects by treating them as composite objects, made of a large number of collectively acting 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.

Position and its derivatives

Main article: Kinematics

The SI derived "mechanical" (that is, not electromagnetic or thermal) units with kg, m and s	
position	m
angular position/angle	unitless (radian)
velocity	$m \cdot s^{-1}$
angular velocity	s^{-1}
acceleration	$m \cdot s^{-2}$
angular acceleration	s^{-2}
jerk	$m \cdot s^{-3}$
"angular jerk"	s^{-3}
specific energy	$m^2 \cdot s^{-2}$

absorbed dose rate	$m^2 \cdot s^{-3}$
moment of inertia	$kg \cdot m^2$
momentum	$kg \cdot m \cdot s^{-1}$
angular momentum	$kg \cdot m^2 \cdot s^{-1}$
force	$kg \cdot m \cdot s^{-2}$
torque	$kg \cdot m^2 \cdot s^{-2}$
energy	$kg \cdot m^2 \cdot s^{-2}$
power	$kg \cdot m^2 \cdot s^{-3}$
pressure and energy density	$kg \cdot m^{-1} \cdot s^{-2}$
surface tension	$kg \cdot s^{-2}$
spring constant	$kg \cdot s^{-2}$
irradiance and energy flux	$kg \cdot s^{-3}$
kinematic viscosity	$m^2 \cdot s^{-1}$
dynamic viscosity	$kg \cdot m^{-1} \cdot s^{-1}$
density (mass density)	$kg \cdot m^{-3}$
density (weight density)	$kg \cdot m^{-2} \cdot s^{-2}$
number density	m^{-3}
action	$kg \cdot m^2 \cdot s^{-1}$

The *position* of a point particle is defined with respect to an arbitrary fixed some convenient reference point in space called the origin **O**, in space, to which is attached a coordinate system. A simple coordinate system might describe the position of a point **P** by means of an arrow designated as **r** (in classical mechanics called a vector), pointing from the origin **O** to the point particle. In general, the point particle need not be stationary relative to **O**, such that **r** is a function of *t*, the time. In pre-Einstein relativity (known as Galilean relativity), time is considered an absolute, i.e., the time interval that is observed to elapse between any given pair of events is the same for all observers.[3] In addition to relying on absolute time, classical mechanics assumes Euclidean geometry for the structure of space.[4]

Velocity and speed

Main articles: 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. For example, if one car traveling east at 60 km/h passes another car traveling east at 50 km/h, then from the perspective of the slower car, the faster car is traveling east at 60 − 50 = 10 km/h. Whereas, from the perspective of the faster car, the slower car is moving 10 km/h to the west. Velocities are directly additive as vector quantities; they must be dealt with using vector analysis.

Mathematically, if the velocity of the first object in the previous discussion is denoted by the vector **u** = *u***d** and the velocity of the second object by the vector **v** = *v***e**, where *u* is the speed of the first object, *v* is the speed of the second object, and **d** and **e** are unit vectors in the directions of motion of each particle respectively, then the velocity of the first object as seen by the second object is

Similarly,

When both objects are moving in the same direction, this equation can be simplified to

Or, by ignoring direction, the difference can be given in terms of speed only:

Acceleration

Main article: 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 represents the velocity's change over time: either of the velocity's magnitude or direction, 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.

Frames of reference

Main articles: Inertial frame of reference and Galilean transformation

While the position, velocity and acceleration of a particle can be described with respect 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 one that when an object that has no force interactions (an idealized situation) is viewed from that frame, 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 lawsWikipedia:Please clarify originate from identifiable sources caused by fields, such as electro-static field (caused by static electrical charges), electro-magnetic field (caused by moving charges), gravitational field (caused by mass), and so forth. A non-inertial reference frame is one that is accelerating with respect to an inertial frame, and in such a non-inertial frame a particle appears to be acted on by other forces not explained by existing fields. Such other forces are called variously fictitious forces, inertia forces, pseudo-forces. Hence, there appears to be other forces that enter the equations of motion solely as a result of the observed accelerations. A key concept of inertial frames is the method for identifying them. For practical purposes, reference frames that are unaccelerated with respect to the distant stars (an extremely distant point) are regarded as good approximations to inertial frames.

Consider two reference frames S and S'. For observers in each of the reference frames an event has space-time coordinates of (x,y,z,t) in frame S and (x',y',z',t') in frame S'. Assuming time is measured the same in all reference frames, and if we require $x = x'$ when $t = 0$, then the relation between the space-time coordinates of the same event observed from the reference frames S' and S, which are moving at a relative velocity of u in the x direction is:

$$x' = x - u \cdot t$$

$$y' = y$$

$$z' = z$$

$$t' = t.$$

This set of formulas defines a group transformation known as the Galilean transformation (informally, the *Galilean transform*). This group is a limiting case of the Poincaré group used in special relativity. The limiting case applies when the velocity u is very small compared to c, the speed of light.

The transformations have the following consequences:

- $\mathbf{v}' = \mathbf{v} - \mathbf{u}$ (the velocity $\mathbf{v}'$ of a particle from the perspective of S' is slower by $\mathbf{u}$ than its velocity $\mathbf{v}$ from the perspective of S)
- $\mathbf{a}' = \mathbf{a}$ (the acceleration of a particle is the same in any inertial reference frame)
- $\mathbf{F}' = \mathbf{F}$ (the force on a particle is the same in any inertial reference frame)
- the speed of light is not a constant in classical mechanics, nor does the special position given to the speed of light in relativistic mechanics have a counterpart in classical mechanics.

For some problems, it is convenient to use rotating coordinates (reference frames). Thereby one can either keep a mapping to a convenient inertial frame, or introduce additionally a fictitious centrifugal force and Coriolis force.

Forces; Newton's second law

Main articles: Force and Newton's laws of motion

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.Wikipedia:Citation needed Either interpretation has the same mathematical consequences, historically known as "Newton's Second Law":

The quantity $m\mathbf{v}$ is called the (canonical) momentum. The net force on a particle is thus equal to the rate of change of the momentum of the particle with time. Since the definition of acceleration is $\mathbf{a} = d\mathbf{v}/dt$, the second law can be written in the simplified and more familiar form:

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*.

As an example, assume that friction is the only force acting on the particle, and that it may be modeled as a function of the velocity of the particle, for example:

where λ is a positive constant, the negative sign states that the force is opposite the sense of the velocity. Then the equation of motion is

This can be integrated to obtain

where $\mathbf{v}_0$ is the initial velocity. This means that the velocity of this particle decays exponentially to zero as time progresses. In this case, an equivalent viewpoint is that the kinetic energy of the particle is absorbed by friction (which converts it to heat energy in accordance with the conservation of energy), and the particle is slowing down. This expression can be further integrated to obtain the position $\mathbf{r}$ of the particle as a function of time.

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.Wikipedia:Please clarify

Work and energy

Main articles: Work (physics), kinetic energy and potential energy

If a constant force **F** is applied to a particle that makes a displacement $\Delta\mathbf{r}$,[5] 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

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

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 as it moves 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:

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

The decrease in the potential energy is equal to the increase in the kinetic energy

This result is known as *conservation of energy* and states that the total energy,

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

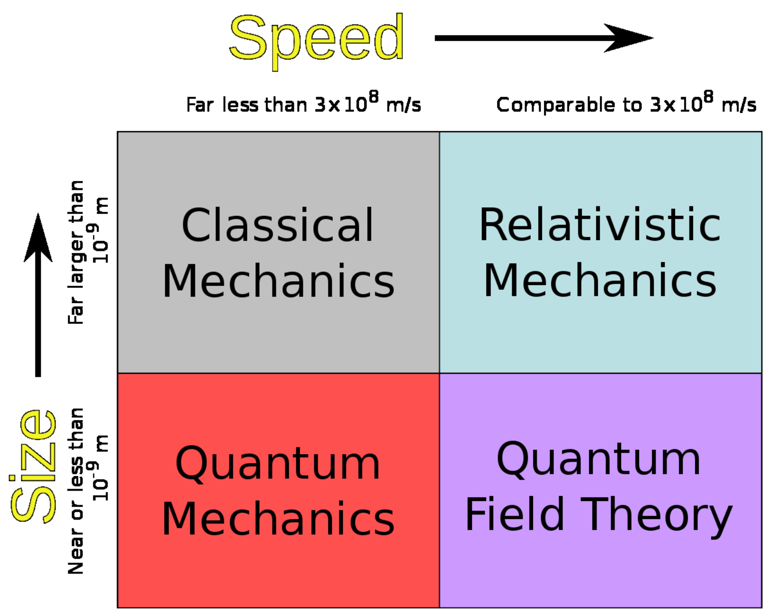
Beyond Newton's laws

Classical mechanics also describes the more complex motions of extended non-pointlike objects. Euler's laws provide extensions to Newton's laws in this area. The concepts of angular momentum rely on the same calculus used to describe one-dimensional motion. The rocket equation extends the notion of rate of change of an object's momentum to include the effects of an object "losing mass".

There are two important alternative formulations of classical mechanics: Lagrangian mechanics and Hamiltonian mechanics. These, and other modern formulations, usually bypass the concept of "force", instead referring to other physical quantities, such as energy, speed and momentum, for describing mechanical systems in generalized coordinates.

The expressions given above for momentum and kinetic energy are only valid when there is no significant electromagnetic contribution. In electromagnetism, Newton's second law for current-carrying wires breaks down unless one includes the electromagnetic field contribution to the momentum of the system as expressed by the Poynting vector divided by c^2, where c is the speed of light in free space.

Limits of validity



Domain of validity for Classical Mechanics

Many branches of classical mechanics are simplifications or approximations of more accurate forms; two of the most accurate being general relativity and relativistic statistical mechanics. Geometric optics is an approximation to the quantum theory of light, and does not have a superior "classical" form.

When both quantum mechanics and classical mechanics cannot apply, such as at the quantum level with many degrees of freedom, quantum field theory (QFT) is of use. QFT deals with small distances and large speeds with many degrees of freedom as well as the possibility of any change in the number of particles throughout the interaction. When treating large degrees of freedom at the macroscopic level, statistical mechanics becomes useful. Statistical mechanics describes the behavior of large (but countable) numbers of particles and their interactions as a whole at the macroscopic level. Statistical mechanics is mainly used in thermodynamics for systems that lie outside the bounds of the assumptions of classical thermodynamics. 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 Newtonian approximation to special relativity

In special relativity, the momentum of a particle is given by

where m is the particle's rest mass, **v** its velocity, and c is the speed of light.

If v is very small compared to c, v^2/c^2 is approximately zero, and so

Thus the Newtonian equation $\mathbf{p} = m\mathbf{v}$ is an approximation of the relativistic equation for bodies moving with low speeds compared to the speed of light.

For example, the relativistic cyclotron frequency of a cyclotron, gyrotron, or high voltage magnetron is given by

where f_c is the classical frequency of an electron (or other charged particle) with kinetic energy T and (rest) mass m_0 circling in a magnetic field. The (rest) mass of an electron is 511 keV. So the frequency correction is 1% for a magnetic vacuum tube with a 5.11 kV direct current accelerating voltage.

The classical approximation to quantum mechanics

The ray approximation of classical mechanics breaks down when the de Broglie wavelength is not much smaller than other dimensions of the system. For non-relativistic particles, this wavelength is

where h is Planck's constant and p is the momentum.

Again, this happens with electrons before it happens with heavier particles. For example, the electrons used by Clinton Davisson and Lester Germer in 1927, accelerated by 54 volts, had a wavelength of 0.167 nm, which was long enough to exhibit a single diffraction side lobe when reflecting from the face of a nickel crystal with atomic spacing of 0.215 nm. With a larger vacuum chamber, it would seem relatively easy to increase the angular resolution from around a radian to a milliradian and see quantum diffraction from the periodic patterns of integrated circuit computer memory.

More practical examples of the failure of classical mechanics on an engineering scale are conduction by quantum tunneling in tunnel diodes and very narrow transistor gates in integrated circuits.

Classical mechanics is the same extreme high frequency approximation as geometric optics. It is more often accurate because it describes particles and bodies with rest mass. These have more momentum and therefore shorter De Broglie wavelengths than massless particles, such as light, with the same kinetic energies.

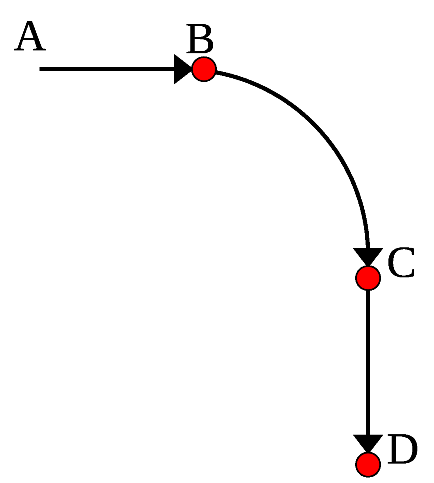
History

Main article: History of classical mechanics

See also: Timeline of classical mechanics

Some Greek philosophers of antiquity, among them Aristotle, founder of Aristotelian physics, may have been the first to maintain the idea that "everything happens for a reason" and that theoretical principles can assist in the understanding of nature. While to a modern reader, many of these preserved ideas come forth as eminently reasonable, there is a conspicuous lack of both mathematical theory and controlled experiment, as we know it. These latter became decisive factors in forming modern science, and their early application came to be known as classical mechanics.

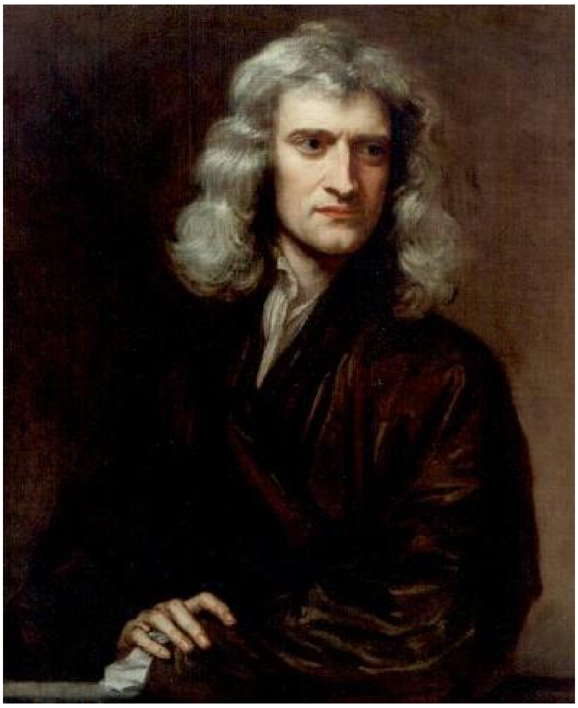
In his *Elementa super demonstrationem ponderum*, medieval mathematician Jordanus de Nemore introduced the concept of "positional gravity" and the use of component forces.



Three stage Theory of impetus according to Albert of Saxony.

The first published causal explanation of the motions of planets was Johannes Kepler's *Astronomia nova* published in 1609. He concluded, based on Tycho Brahe's observations of the orbit of Mars, that the orbits were ellipses. This break with ancient thought was happening around the same time that Galileo was proposing abstract mathematical laws for the motion of objects. He may (or may not) have performed the famous experiment of dropping two cannonballs of different weights from the tower of Pisa, showing that they both hit the ground at the same time. The reality of this experiment is disputed, but, more importantly, he did carry out quantitative experiments by rolling balls on an inclined plane. His theory of accelerated motion derived from the results of such experiments, and forms a cornerstone of classical mechanics.

Newton founded his principles of natural philosophy on three proposed laws of motion: the law of inertia, his second law of acceleration (mentioned above), and the law of action and reaction; and hence laid the foundations for classical mechanics. Both Newton's second and third laws were given the proper scientific and mathematical treatment in Newton's *Philosophiæ Naturalis Principia Mathematica*, which distinguishes them from earlier attempts at explaining similar phenomena, which were either incomplete, incorrect, or given little accurate mathematical expression. Newton also enunciated the principles of conservation of momentum and angular momentum. In mechanics, Newton was also the first to provide the first correct scientific and mathematical formulation of gravity in Newton's law of universal gravitation. The combination of Newton's laws of motion and gravitation provide the fullest and most accurate description of classical mechanics. He demonstrated that these laws apply to everyday objects as well as to celestial objects. In particular, he obtained a theoretical explanation of Kepler's laws of motion of the planets.



Sir Isaac Newton (1643–1727), an influential figure in the history of physics and whose three laws of motion form the basis of classical mechanics

Newton had previously invented the calculus, of mathematics, and used it to perform the mathematical calculations. For acceptability, his book, the *Principia*, was formulated entirely in terms of the long-established geometric methods, which were soon eclipsed by his calculus. However, it was Leibniz who developed the notation of the derivative and integral preferred[6] today.

Hamilton's greatest contribution is perhaps the reformulation of Newtonian mechanics, now called Hamiltonian mechanics.

Newton, and most of his contemporaries, with the notable exception of Huygens, worked on the assumption that classical mechanics would be able to explain all phenomena, including light, in the form of geometric optics. Even when discovering the so-called Newton's rings (a wave interference phenomenon) he maintained his own corpuscular theory of light.

After Newton, classical mechanics became a principal field of study in mathematics as well as physics. Several re-formulations progressively allowed finding solutions to a far greater number of problems. The first notable re-formulation was in 1788 by Joseph Louis Lagrange. Lagrangian mechanics was in turn re-formulated in 1833 by William Rowan Hamilton.

Some difficulties were discovered in the late 19th century that could only be resolved by more modern physics. Some of these difficulties related to compatibility with electromagnetic theory, and the famous Michelson–Morley experiment. The resolution of these problems led to the special theory of relativity, often included in the term classical mechanics.

A second set of difficulties were related to thermodynamics. When combined with thermodynamics, classical mechanics leads to the Gibbs paradox of classical statistical mechanics, in which entropy is not a well-defined quantity. Black-body radiation was not explained without the introduction of quanta. As experiments reached the atomic level, classical mechanics failed to explain, even approximately, such basic things as the energy levels and sizes of atoms and the photo-electric effect. The effort at resolving these problems led to the development of quantum mechanics.

Since the end of the 20th century, the place of classical mechanics in physics has been no longer that of an independent theory. Instead, classical mechanics is now considered an approximate theory to the more general quantum mechanics. Emphasis has shifted to understanding the fundamental forces of nature as in the Standard model and its more modern extensions into a unified theory of everything.[7] Classical mechanics is a theory useful for the study of the motion of non-quantum mechanical, low-energy particles in weak gravitational fields. In the 21st century classical mechanics has been extended into the complex domain and complex classical mechanics exhibits behaviors very similar to quantum mechanics.[8]

Branches

Classical mechanics was traditionally divided into three main branches:

- Statics, the study of equilibrium and its relation to forces
- Dynamics, the study of motion and its relation to forces
- Kinematics, dealing with the implications of observed motions without regard for circumstances causing them

Another division is based on the choice of mathematical formalism:

- Newtonian mechanics
- Lagrangian mechanics
- Hamiltonian mechanics

Alternatively, a division can be made by region of application:

- Celestial mechanics, relating to stars, planets and other celestial bodies
- Continuum mechanics, for materials modelled as a continuum, e.g., solids and fluids (i.e., liquids and gases).
- Relativistic mechanics (i.e. including the special and general theories of relativity), for bodies whose speed is close to the speed of light.
- Statistical mechanics, which provides a framework for relating the microscopic properties of individual atoms and molecules to the macroscopic or bulk thermodynamic properties of materials.

Notes

[1] http://en.wikipedia.org/w/index.php?title=Template:Classical_mechanics&action=edit
[2] .

The notion of "classical" may be somewhat confusing, insofar as this term usually refers to the era of classical antiquity in European history. While many discoveries within the mathematics of that period are applicable today and of great use, much of the science that emerged then has since been superseded by more accurate models. This in no way detracts from the science of that time because most of modern physics is built directly upon those developments. The emergence of classical mechanics was a decisive stage in the development of science, in the modern sense of the term. Above all, what characterizes it is its insistence that the descriptions of the behavior of bodies be placed on a more exacting basis that could only be provided by a mathematical treatment and its reliance on experiment, rather than speculation. Classical mechanics established the means of predicting in a quantitative manner the behavior of objects, and how to test them by carefully designed measurement. The emerging globally cooperative endeavor increasingly provided for much closer scrutiny and testing, both of theory and experiment. This was, and remains, a key factor in establishing certain knowledge, and in bringing it to the service of society. History shows how closely the health and wealth of a society depends on nurturing this investigative and critical approach.

[3] Mughal, Muhammad Aurang Zeb. 2009. Time, absolute (http://dro.dur.ac.uk/10920/1/10920.pdf). Birx, H. James (ed.), *Encyclopedia of Time: Science, Philosophy, Theology, and Culture*, Vol. 3. Thousand Oaks, CA: Sage, pp. 1254-1255.

[4] MIT physics 8.01 lecture notes (page 12) (http://ocw.mit.edu/courses/physics/8-01-physics-i-fall-2003/lecture-notes/binder1.pdf) (PDF)

[5] The displacement $\Delta\mathbf{r}$ is the difference of the particle's initial and final positions: $\Delta\mathbf{r} = \mathbf{r}_{\text{final}} - \mathbf{r}_{\text{initial}}$.

[6] Jesseph, Douglas M. (1998). "Leibniz on the Foundations of the Calculus: The Question of the Reality of Infinitesimal Magnitudes". Perspectives on Science. 6.1&2: 6–40. Retrieved 31 December 2011.

[7] Page 2-10 of the *Feynman Lectures on Physics* says "For already in classical mechanics there was indeterminability from a practical point of view." The past tense here implies that classical physics is no longer fundamental.

[8] Complex Elliptic Pendulum (http://arxiv.org/abs/1001.0131), Carl M. Bender, Daniel W. Hook, Karta Kooner in Asymptotics in Dynamics, Geometry and PDEs; Generalized Borel Summation vol. I (http://dx.doi.org/10.1007/978-88-7642-379-6_1)

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External links

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- Crowell, Benjamin. Newtonian Physics (http://www.lightandmatter.com/area1book1.html) (an introductory text, uses algebra with optional sections involving calculus)
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- Kinematic Models for Design Digital Library (KMODDL) (http://kmoddl.library.cornell.edu/index.php) Movies and photos of hundreds of working mechanical-systems models at Cornell University. Also includes an e-book library (http://kmoddl.library.cornell.edu/e-books.php) of classic texts on mechanical design and engineering.
- MIT OpenCourseWare 8.01: Classical Mechanics (http://ocw.mit.edu/courses/physics/8-01sc-physics-i-classical-mechanics-fall-2010/) Free videos of actual course lectures with links to lecture notes, assignments and exams.
- Alejandro A. Torassa, On Classical Mechanics (http://torassa.tripod.com/paper.htm)

Electromagnetism

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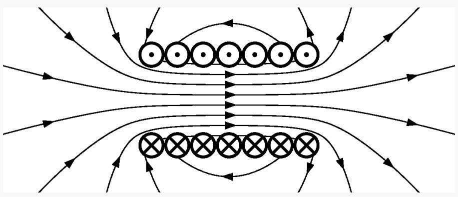
"Electromagnetic" redirects here. Electromagnetic may also refer to the use of an electromagnet.

Electromagnetism



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Electromagnetism is a branch of physics which involves the study of the **electromagnetic force**, a type of physical interaction that occurs between electrically charged particles. The electromagnetic force usually shows electromagnetic fields, such as electric fields, magnetic fields, and light. The electromagnetic force is one of the four fundamental interactions in nature. The other three fundamental interactions are the strong interaction, the weak interaction, and gravitation.


Lightning is an electrostatic discharge that travels between two charged regions.

The word *electromagnetism* is a compound form of two Greek terms, ἤλεκτρον, *ēlektron*, "amber", and μαγνῆτις λίθος *magnētis lithos*, which means "magnesian stone", a type of iron ore. 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 plays a major role in determining the internal properties of most objects encountered in daily life. 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 Faraday'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.

Although electromagnetism is considered one of the four fundamental forces, at high energy the weak force and electromagnetism are unified. In the history of the universe, during the quark epoch, the electroweak force split into the electromagnetic and weak forces.

History of the theory

See also: History of electromagnetic theory

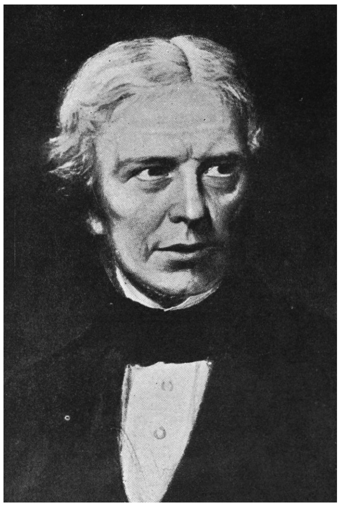

Hans Christian Ørsted.

Originally, electricity and magnetism were thought of as two separate forces. This view changed, however, with the publication of James Clerk Maxwell's 1873 *A Treatise on Electricity and Magnetism* in which the interactions of positive and negative charges were shown to be regulated by one force. There are four main effects resulting from these interactions, all of which have been clearly demonstrated by experiments:

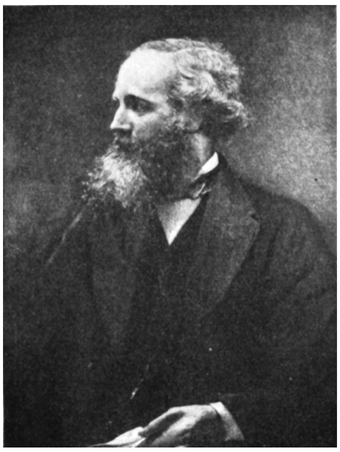
1. Electric charges attract or repel one another with a force inversely proportional to the square of the distance between them: unlike charges attract, like ones repel.
2. Magnetic poles (or states of polarization at individual points) attract or repel one another in a similar way and always come in pairs: every north pole is yoked to a south pole.
3. An electric current inside a wire creates a corresponding circular magnetic field outside the wire. Its direction (clockwise or counter-clockwise) depends on the direction of the current in the wire.
4. A current is induced in a loop of wire when it is moved toward or away from a magnetic field, or a magnet is moved towards or away from it; the direction of current depends on that of the movement.


André-Marie Ampère

While preparing for an evening lecture on 21 April 1820, Hans Christian Ørsted made a surprising observation. As he was setting up his materials, he noticed a compass needle deflected away from magnetic north when the electric current from the battery he was using was switched on and off. This deflection convinced him that magnetic fields radiate from all sides of a wire carrying an electric current, just as light and heat do, and that it confirmed a direct relationship between electricity and magnetism.


Michael Faraday

At the time of discovery, Ørsted did not suggest any satisfactory explanation of the phenomenon, nor did he try to represent the phenomenon in a mathematical framework. However, three months later he began more intensive investigations. Soon thereafter he published his findings, proving that an electric current produces a magnetic field as it flows through a wire. The CGS unit of magnetic induction (oersted) is named in honor of his contributions to the field of electromagnetism.


James Clerk Maxwell

His findings resulted in intensive research throughout the scientific community in electrodynamics. They influenced French physicist André-Marie Ampère's developments of a single mathematical form to represent the magnetic forces between current-carrying conductors. Ørsted's discovery also represented a major step toward a unified concept of energy.

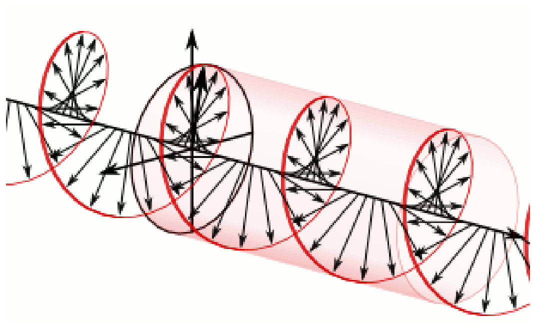
This unification, which was observed by Michael Faraday, extended by James Clerk Maxwell, and partially reformulated by Oliver Heaviside and Heinrich Hertz, is one of the key accomplishments of 19th century mathematical physics. It had far-reaching consequences, one of which was the understanding of the nature of light. Unlike what was proposed in Electromagnetism, light and other electromagnetic waves are at the present seen as taking the form of quantized, self-propagating oscillatory electromagnetic field disturbances which have been called photons. Different frequencies of oscillation give rise to the different forms of electromagnetic radiation, from radio waves at the lowest frequencies, to visible light at intermediate frequencies, to gamma rays at the highest frequencies.

Ørsted was not the only person to examine the relationship between electricity and magnetism. In 1802, Gian Domenico Romagnosi, an Italian legal scholar, deflected a magnetic needle using electrostatic charges. Actually, no galvanic current existed in the setup and hence no electromagnetism was present. An account of the discovery was published in 1802 in an Italian newspaper, but it was largely overlooked by the contemporary scientific community.

Fundamental forces

The electromagnetic force is one of the four known fundamental forces. The other fundamental forces are:

- the weak nuclear force, which binds to all known particles in the Standard Model, and causes certain forms of radioactive decay. (In particle physics though, the electroweak interaction is the unified description of two of the four known fundamental interactions of nature: electromagnetism and the weak interaction);
- the strong nuclear force, which binds quarks to form nucleons, and binds nucleons to form nuclei
- the gravitational force.



Representation of the electric field vector of a wave of circularly polarized electromagnetic radiation.

All other forces (e.g., friction) are derived from these four fundamental forces (including momentum which is carried by the movement of particles).

The electromagnetic force is the one responsible for practically all the phenomena one encounters in daily life above the nuclear scale, with the exception of gravity. Roughly speaking, all the forces involved in interactions between atoms can be explained by the electromagnetic force acting on the electrically charged atomic nuclei and electrons inside and around the atoms, together with how these particles carry momentum by their movement. This includes the forces we experience in "pushing" or "pulling" ordinary material objects, which come from the intermolecular forces between the individual molecules in our bodies and those in the objects. It also includes all forms of chemical phenomena.

A necessary part of understanding the intra-atomic to intermolecular forces is the effective force generated by the momentum of the electrons' movement, and that electrons move between interacting atoms, carrying momentum with them. As a collection of electrons becomes more confined, their minimum momentum necessarily increases due to the Pauli exclusion principle. The behaviour of matter at the molecular scale including its density is determined by the balance between the electromagnetic force and the force generated by the exchange of momentum carried by the electrons themselves.

Classical electrodynamics

Main article: Classical electrodynamics

The scientist William Gilbert proposed, in his *De Magnete* (1600), that electricity and magnetism, while both capable of causing attraction and repulsion of objects, were distinct effects. Mariners had noticed that lightning strikes had the ability to disturb a compass needle, but the link between lightning and electricity was not confirmed until Benjamin Franklin's proposed experiments in 1752. One of the first to discover and publish a link between man-made electric current and magnetism was Romagnosi, who in 1802 noticed that connecting a wire across a voltaic pile deflected a nearby compass needle. However, the effect did not become widely known until 1820, when Ørsted performed a similar experiment. Ørsted's work influenced Ampère to produce a theory of electromagnetism that set the subject on a mathematical foundation.

A theory of electromagnetism, known as classical electromagnetism, was developed by various physicists over the course of the 19th century, culminating in the work of James Clerk Maxwell, who unified the preceding developments into a single theory and discovered the electromagnetic nature of light. In classical electromagnetism, the electromagnetic field obeys a set of equations known as Maxwell's equations, and the electromagnetic force is given by the Lorentz force law.

One of the peculiarities of classical electromagnetism is that it is difficult to reconcile with classical mechanics, but it is compatible with special relativity. According to Maxwell's equations, the speed of light in a vacuum is a universal constant, dependent only on the electrical permittivity and magnetic permeability of free space. This violates Galilean invariance, a long-standing cornerstone of classical mechanics. One way to reconcile the two theories (electromagnetism and classical mechanics) is to assume the existence of a luminiferous aether through which the light propagates. However, subsequent experimental efforts failed to detect the presence of the aether. After important contributions of Hendrik Lorentz and Henri Poincaré, in 1905, Albert Einstein solved the problem with the introduction of special relativity, which replaces classical kinematics with a new theory of kinematics that is compatible with classical electromagnetism. (For more information, see History of special relativity.)

In addition, relativity theory shows that in moving frames of reference a magnetic field transforms to a field with a nonzero electric component and vice versa; thus firmly showing that they are two sides of the same coin, and thus the term "electromagnetism". (For more information, see Classical electromagnetism and special relativity and Covariant formulation of classical electromagnetism.

Quantum mechanics

Photoelectric effect

Main article: Photoelectric effect

In another paper published in 1905, Albert Einstein undermined the very foundations of classical electromagnetism. In his theory of the photoelectric effect (for which he won the Nobel prize in physics) and inspired by the idea of Max Planck's "quanta", he posited that light could exist in discrete particle-like quantities as well, which later came to be known as photons. Einstein's theory of the photoelectric effect extended the insights that appeared in the solution of the ultraviolet catastrophe presented by Max Planck in 1900. In his work, Planck showed that hot objects emit electromagnetic radiation in discrete packets ("quanta"), which leads to a finite total energy emitted as black body radiation. Both of these results were in direct contradiction with the classical view of light as a continuous wave. Planck's and Einstein's theories were progenitors of quantum mechanics, which, when formulated in 1925, necessitated the invention of a quantum theory of electromagnetism. This theory, completed in the 1940s-1950s, is known as quantum electrodynamics (or "QED"), and, in situations where perturbation theory is applicable, is one of the most accurate theories known to physics.

Quantum electrodynamics

Main article: Quantum electrodynamics

All electromagnetic phenomena are underpinned by quantum mechanics, specifically by quantum electrodynamics (which includes classical electrodynamics as a limiting case) and this accounts for almost all physical phenomena observable to the unaided human senses, including light and other electromagnetic radiation, all of chemistry, most of mechanics (excepting gravitation), and, of course, magnetism and electricity.

Electroweak interaction

Main article: Electroweak interaction

The **electroweak interaction** is the unified description of two of the four known fundamental interactions of nature: electromagnetism and the weak interaction. Although these two forces appear very different at everyday low energies, the theory models them as two different aspects of the same force. Above the unification energy, on the order of 100 GeV, they would merge into a single **electroweak force**. Thus if the universe is hot enough (approximately 10^{15} K, a temperature exceeded until shortly after the Big Bang) then the electromagnetic force and weak force merge into a combined electroweak force. During the electroweak epoch, the electroweak force separated from the strong force. During the quark epoch, the electroweak force split into the electromagnetic and weak force.

Quantities and units

See also: List of physical quantities and List of electromagnetism equations

Electromagnetic units are part of a system of electrical units based primarily upon the magnetic properties of electric currents, the fundamental SI unit being the ampere. The units are:

- ampere (electric current)
- coulomb (electric charge)
- farad (capacitance)
- henry (inductance)
- ohm (resistance)
- siemens (conductance)
- tesla (magnetic flux density)
- volt (electric potential)
- watt (power)
- weber (magnetic flux)

In the electromagnetic cgs system, electric current is a fundamental quantity defined via Ampère's law and takes the permeability as a dimensionless quantity (relative permeability) whose value in a vacuum is unity. As a consequence, the square of the speed of light appears explicitly in some of the equations interrelating quantities in this system.

SI electromagnetism units				
Symbol	**Name of Quantity**	**Derived Units**	**Unit**	**Base Units**
I	electric current	ampere (SI base unit)	A	A (= W/V = C/s)
Q	electric charge	coulomb	C	A·s
U, ΔV, $\Delta\varphi$; E	potential difference; electromotive force	volt	V	$\mathrm{kg{\cdot}m^2{\cdot}s^{-3}{\cdot}A^{-1}}$ (= J/C)
R; Z; X	electric resistance; impedance; reactance	ohm	Ω	$\mathrm{kg{\cdot}m^2{\cdot}s^{-3}{\cdot}A^{-2}}$ (= V/A)
ϱ	resistivity	ohm metre	Ω·m	$\mathrm{kg{\cdot}m^3{\cdot}s^{-3}{\cdot}A^{-2}}$
P	electric power	watt	W	$\mathrm{kg{\cdot}m^2{\cdot}s^{-3}}$ (= V·A)
C	capacitance	farad	F	$\mathrm{kg^{-1}{\cdot}m^{-2}{\cdot}s^4{\cdot}A^2}$ (= C/V)
$\mathbf{E}$	electric field strength	volt per metre	V/m	$\mathrm{kg{\cdot}m{\cdot}s^{-3}{\cdot}A^{-1}}$ (= N/C)
$\mathbf{D}$	electric displacement field	coulomb per square metre	$\mathrm{C/m^2}$	$\mathrm{A{\cdot}s{\cdot}m^{-2}}$
ε	permittivity	farad per metre	F/m	$\mathrm{kg^{-1}{\cdot}m^{-3}{\cdot}s^4{\cdot}A^2}$

χ_e	electric susceptibility	(dimensionless)	–	–
G; Y; B	conductance; admittance; susceptance	siemens	S	$kg^{-1}·m^{-2}·s^{3}·A^{2}$ (= Ω^{-1})
κ, γ, σ	conductivity	siemens per metre	S/m	$kg^{-1}·m^{-3}·s^{3}·A^{2}$
B	magnetic flux density, magnetic induction	tesla	T	$kg·s^{-2}·A^{-1}$ (= Wb/m^{2} = $N·A^{-1}·m^{-1}$)
	magnetic flux	weber	Wb	$kg·m^{2}·s^{-2}·A^{-1}$ (= V·s)
H	magnetic field strength	ampere per metre	A/m	$A·m^{-1}$
L, M	inductance	henry	H	$kg·m^{2}·s^{-2}·A^{-2}$ (= Wb/A = V·s/A)
μ	permeability	henry per metre	H/m	$kg·m·s^{-2}·A^{-2}$
χ	magnetic susceptibility	(dimensionless)	–	–

Formulas for physical laws of electromagnetism (such as Maxwell's equations) need to be adjusted depending on what system of units one uses. This is because there is no one-to-one correspondence between electromagnetic units in SI and those in CGS, as is the case for mechanical units. Furthermore, within CGS, there are several plausible choices of electromagnetic units, leading to different unit "sub-systems", including Gaussian, "ESU", "EMU", and Heaviside–Lorentz. Among these choices, Gaussian units are the most common today, and in fact the phrase "CGS units" is often used to refer specifically to CGS-Gaussian units.

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External links

Library resources about **Electromagnetism**
• Resources in your library (http://tools.wmflabs.org/ftl/cgi-bin/ftl?st=wp&su=Electromagnetism)

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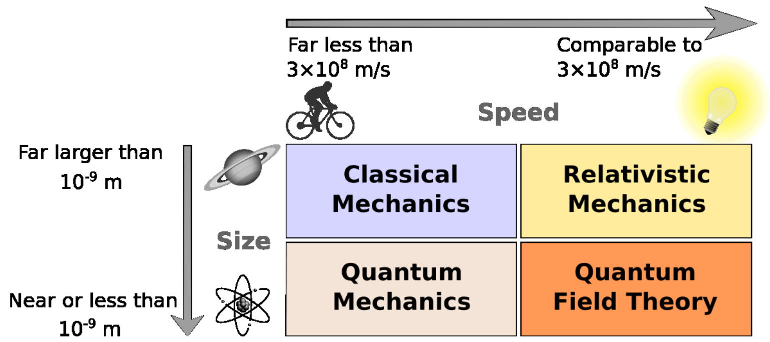
- The Deflection of a Magnetic Compass Needle by a Current in a Wire (video) (https://www.youtube.com/watch?v=HcPDc23ZLEs) on YouTube

- Electromagnetism abridged (http://www.gcsescience.com/pme.htm)

Modern Physics

Modern physics is an effort to understand the underlying processes of the interactions of matter utilizing the tools of science & engineering. It implies that nineteenth century descriptions of phenomena are not sufficient to describe nature as observed with modern instruments. It is generally assumed that a consistent description of these observations will incorporate elements of quantum mechanics & relativity.



Classical physics is usually concerned with everyday conditions: speeds much lower than the speed of light, and sizes much greater than that of atoms. Modern physics is usually concerned with high velocities and small distances.

Small velocities and large distances is usually the realm of classical physics. Modern physics often involves extreme conditions; in practice, quantum effects typically involve distances comparable to atoms (roughly 10^{-9} m), while relativistic effects typically involve velocities comparable to the speed of light (roughly 10^{8} m/s). Wikipedia:Disputed statement

Overview

Modern physics
Schrödinger equation
History of modern physics
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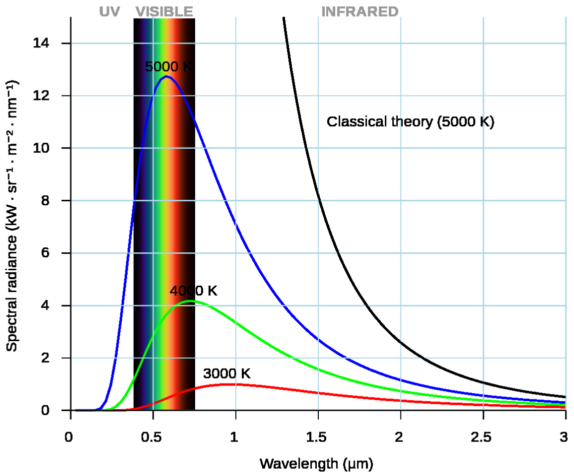
In a literal sense, the term *modern physics*, means up-to-date physics. In this sense, a significant portion of so-called *classical physics* is modern. However, since roughly 1890, new discoveries have caused significant paradigm shifts: the advent of quantum mechanics (QM), and of Einsteinian relativity (ER). Physics that incorporates elements of either QM or ER (or both) is said to be *modern physics*. It is in this latter sense that the term is generally used.

Modern physics is often encountered when dealing with extreme conditions. Quantum mechanical effects tend to appear when dealing with "lows" (low temperatures, small distances), while relativistic effects tend to appear when dealing with "highs" (high velocities, large distances), the "middles" being classical behaviour. For example, when analysing the behaviour of a gas at room temperature, most phenomena will involve the (classical) Maxwell–Boltzmann distribution. However near absolute zero, the Maxwell–Boltzmann distribution fails to account for the observed behaviour of the gas, and the (modern) Fermi–Dirac or Bose–Einstein distributions have to be used instead.

German physicist Max Planck, founder of quantum theory.

Very often, it is possible to find – or "retrieve" – the classical behaviour from the modern description by analysing the modern description at low speeds and large distances (by taking a limit, or by making an approximation). When doing so, the result is called the *classical limit*.



Classical physics (Rayleigh–Jeans law, black line) failed to explain black body radiation – the so-called ultraviolet catastrophe. The quantum description (Planck's law, colored lines) is said to be *modern physics*.

> "The term "modern physics," taken literally, means of course, the *sum total* of knowledge under the head of present-day physics. In this sense, the physics of 1890 is still modern; very few statements made in a good physics text of 1890 would need to be deleted today as untrue...
> On the other hand... there have been enormous advances in physics, and some of these advances have brought into question, or have directly contradicted, certain theories that had seemed to be strongly supported by the experimental evidence.
> For example, few, if any physicists in 1890 questioned the wave theory of light. Its triumphs over the old corpuscular theory seemed to be final and complete, particularly after the brilliant experiments of Hertz, in 1887, which demonstrated, beyond doubt, the fundamental soundness of Maxwell's electromagnetic theory of light. And yet... these very experiments of Hertz brought to light a new phenomenon—the photoelectric effect—which played an important part in establishing the quantum theory. The latter theory... is diametrically opposed to the wave theory of light; indeed, the reconciliation of these two theories... was one of the great problems of the first quarter of the twentieth century."

— F.K. Richtmyer, E.H. Kennard, T. Lauritsen, *Introduction to Modern Physics*, 5th edition (1955)

Hallmarks of modern physics

Main articles: History of quantum mechanics and History of relativity

These are generally considered to be the topics regarded as the "core" of the foundation of modern physics:

- Atomic theory and the evolution of the atomic model in general
- Black-body radiation
- Franck–Hertz experiment
- Geiger–Marsden experiment (Rutherford's experiment)
- Gravitational lensing
- Michelson–Morley experiment
- Photoelectric effect
- Quantum thermodynamics
- Radioactive phenomena in general
- Perihelion precession of Mercury
- Stern–Gerlach experiment
- Wave–particle duality
- Solid State Physics

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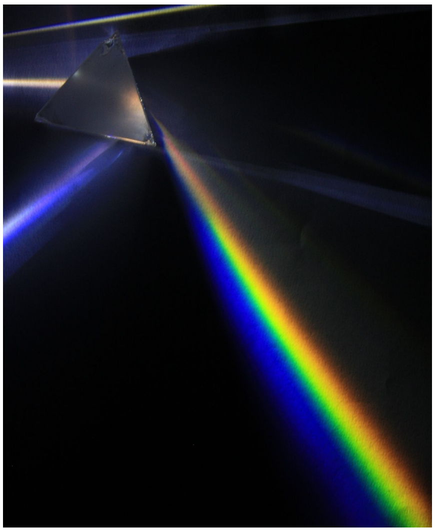
Optics

This article is about the branch of physics. For the book by Sir Isaac Newton, see Opticks. For other uses, see Optic (disambiguation).


Optics includes study of dispersion of light.

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.

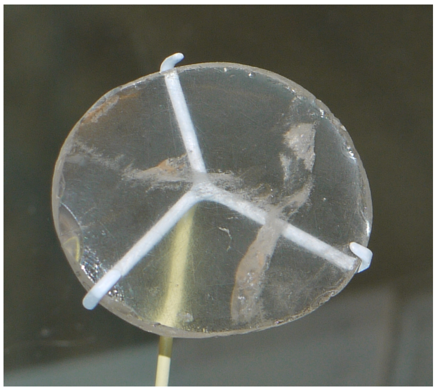
Some phenomena depend on the fact that light has both wave-like and particle-like properties. Explanation of these effects requires quantum mechanics. When considering light's particle-like properties, the light is modelled as a collection of particles called "photons". Quantum optics deals with the application of quantum mechanics to optical systems.

Optical science is relevant to and studied in many related disciplines including astronomy, various engineering fields, photography, and medicine (particularly ophthalmology and optometry). Practical applications of optics are found in a variety of technologies and everyday objects, including mirrors, lenses, telescopes, microscopes, lasers, and fibre optics.

History

Main article: History of optics

See also: Timeline of electromagnetism and classical optics



The Nimrud lens

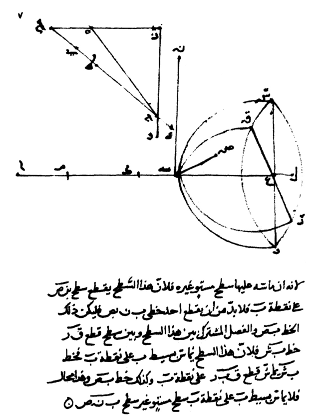
Optics began with the development of lenses by the ancient Egyptians and Mesopotamians. The earliest known lenses, made from polished crystal, often quartz, date from as early as 700 BC for Assyrian lenses such as the Layard/Nimrud lens. The ancient Romans and Greeks filled glass spheres with water to make lenses. These practical developments were followed by the development of theories of light and vision by ancient Greek and Indian philosophers, and the development of geometrical optics in the Greco-Roman world. The word *optics* comes from the ancient Greek word ὀπτική (*optikē*), meaning "appearance, look".

Greek philosophy on optics broke down into two opposing theories on how vision worked, the "intromission theory" and the "emission theory".[1] The intro-mission approach saw vision as coming from objects casting off copies of themselves (called eidola) that were captured by the eye. With many propagators including Democritus, Epicurus, Aristotle and their followers, this theory seems to have some contact with modern theories of what vision really is, but it remained only speculation lacking any experimental foundation.

Plato first articulated the emission theory, the idea that visual perception is accomplished by rays emitted by the eyes. He also commented on the parity reversal of mirrors in *Timaeus*. Some hundred years later, Euclid wrote a treatise entitled *Optics* where he linked vision to geometry, creating *geometrical optics*. He based his work on Plato's emission theory wherein he described the mathematical rules of perspective and described the effects of refraction qualitatively, although he questioned that a beam of light from the eye could instantaneously light up the stars every time someone blinked. Ptolemy, in his treatise *Optics*, held an extramission-intromission theory of vision: the rays (or flux) from the eye formed a cone, the vertex being within the eye, and the base defining the visual field. The rays were sensitive, and conveyed information back to the observer's intellect about the distance and orientation of surfaces. He summarised much of Euclid and went on to describe a way to measure the angle of refraction, though he failed to notice the empirical relationship between it and the angle of incidence.

Alhazen (Ibn al-Haytham), "the father of Optics"

During the Middle Ages, Greek ideas about optics were resurrected and extended by writers in the Muslim world. One of the earliest of these was Al-Kindi (c. 801–73) who wrote on the merits of Aristotelian and Euclidean ideas of optics, favouring the emission theory since it could better quantify optical phenomenon.[2] In 984, the Persian mathematician Ibn Sahl wrote the treatise "On burning mirrors and lenses", correctly describing a law of refraction equivalent to Snell's law. He used this law to compute optimum shapes for lenses and curved mirrors. In the early 11th century, Alhazen (Ibn al-Haytham) wrote the *Book of Optics* (*Kitab al-manazir*) in which he explored reflection and refraction and proposed a new system for explaining vision and light based on observation and experiment. He rejected the "emission theory" of Ptolemaic optics with its rays being emitted by the eye, and instead put forward the idea that light reflected in all directions in straight lines from all points of the objects being viewed and then entered the eye, although he was unable to correctly explain how the eye captured the rays. Alhazen's work was largely ignored in the Arabic world but it was anonymously translated into Latin around 1200 A.D. and further summarised and expanded on by the Polish monk Witelo making it a standard text on optics in Europe for the next 400 years.[3]



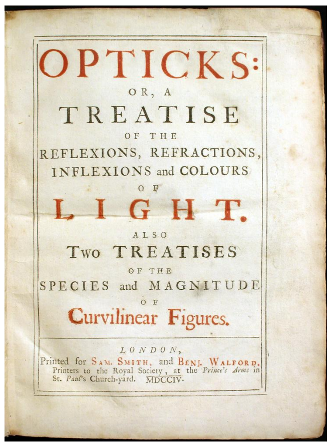
Reproduction of a page of Ibn Sahl's manuscript showing his knowledge of the law of refraction.

In the 13th century medieval Europe the English bishop Robert Grosseteste wrote on a wide range of scientific topics discussing light from four different perspectives: an epistemology of light, a metaphysics or cosmogony of light, an etiology or physics of light, and a theology of light,[4] basing it on the works Aristotle and Platonism. Grosseteste's most famous disciple, Roger Bacon, wrote works citing a wide range of recently translated optical and philosophical works, including those of Alhazen, Aristotle, Avicenna, Averroes, Euclid, al-Kindi, Ptolemy, Tideus, and Constantine the African. Bacon was able to use parts of glass spheres as magnifying glasses to demonstrate that light reflects from objects rather than being released from them.

The first wearable eyeglasses were invented in Italy around 1286. This was the start of the optical industry of grinding and polishing lenses for these "spectacles", first in Venice and Florence in the thirteenth century,[5] and later in the spectacle making centres in both the Netherlands and Germany. Spectacle makers created improved types of lenses for the correction of vision based more on empirical knowledge gained from observing the effects of the lenses rather than using the rudimentary optical theory of the day (theory which for the most part could not even adequately explain how spectacles worked). This practical development, mastery, and experimentation with lenses led directly to the invention of the compound optical microscope around 1595, and the refracting telescope in 1608, both of which appeared in the spectacle making centres in the Netherlands.[6]

In the early 17th century Johannes Kepler expanded on geometric optics in his writings, covering lenses, reflection by flat and curved mirrors, the principles of pinhole cameras, inverse-square law governing the intensity of light, and the optical explanations of astronomical phenomena such as lunar and solar eclipses and astronomical parallax. He was also able to correctly deduce the role of the retina as the actual organ that recorded images, finally being able to scientifically quantify the effects of different types of lenses that spectacle makers had been observing over the previous 300 years. After the invention of the telescope Kepler set out the theoretical basis on how they worked and described an improved version, known as the *Keplerian telescope*, using two convex lenses to produce higher magnification.[7]

Optical theory progressed in the mid-17th century with treatises written by philosopher René Descartes, which explained a variety of optical phenomena including reflection and refraction by assuming that light was emitted by objects which produced it. This differed substantively from the ancient Greek emission theory. In the late 1660s and early 1670s, Isaac Newton expanded Descartes' ideas into a corpuscle theory of light, famously determining that white light was a mix of colours which can be separated into its component parts with a prism. In 1690, Christiaan Huygens proposed a wave theory for light based on suggestions that had been made by Robert Hooke in 1664. Hooke himself publicly criticised Newton's theories of light and the feud between the two lasted until Hooke's death. In 1704, Newton published *Opticks* and, at the time, partly because of his success in other areas of physics, he was generally considered to be the victor in the debate over the nature of light.



Cover of the first edition of Newton's *Opticks*

Newtonian optics was generally accepted until the early 19th century when Thomas Young and Augustin-Jean Fresnel conducted experiments on the interference of light that firmly established light's wave nature. Young's famous double slit experiment showed that light followed the law of superposition, which is a wave-like property not predicted by Newton's corpuscle theory. This work led to a theory of diffraction for light and opened an entire area of study in physical optics. Wave optics was successfully unified with electromagnetic theory by James Clerk Maxwell in the 1860s.

The next development in optical theory came in 1899 when Max Planck correctly modelled blackbody radiation by assuming that the exchange of energy between light and matter only occurred in discrete amounts he called *quanta*.[8] In 1905 Albert Einstein published the theory of the photoelectric effect that firmly established the quantization of light itself.[9] In 1913 Niels Bohr showed that atoms could only emit discrete amounts of energy, thus explaining the discrete lines seen in emission and absorption spectra.[10] The understanding of the interaction between light and matter which followed from these developments not only formed the basis of quantum optics but also was crucial for the development of quantum mechanics as a whole. The ultimate culmination, the theory of quantum electrodynamics, explains all optics and electromagnetic processes in general as the result of the exchange of real and virtual photons.

Quantum optics gained practical importance with the inventions of the maser in 1953 and of the laser in 1960. Following the work of Paul Dirac in quantum field theory, George Sudarshan, Roy J. Glauber, and Leonard Mandel applied quantum theory to the electromagnetic field in the 1950s and 1960s to gain a more detailed understanding of photodetection and the statistics of light.

Classical optics

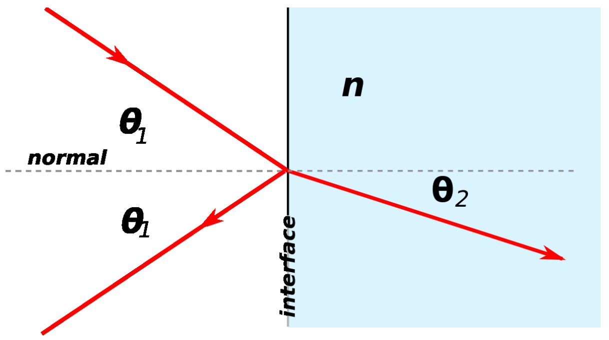
Classical optics is divided into two main branches: geometrical (or ray) optics and physical (or wave) optics. In geometrical optics, light is considered to travel in straight lines, while in physical optics, light is considered as an electromagnetic wave.

Geometrical optics can be viewed as an approximation of physical optics that applies when the wavelength of the light used is much smaller than the size of the optical elements in the system being modelled.

Geometrical optics

Main article: 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. These laws were discovered empirically as far back as 984 AD and have been used in the design of optical components and instruments from then until the present day. They can be summarised as follows:



Geometry of reflection and refraction of light rays

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:

,

where *n* is a constant for any two materials and a given colour of light. If the first material is air or vacuum, *n* is the refractive index of the second material.

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.*

Approximations

Geometric optics is often simplified by making the paraxial approximation, or "small angle approximation". The mathematical behaviour then becomes linear, allowing optical components and systems to be described by simple matrices. This leads to the techniques of Gaussian optics and *paraxial ray tracing*, which are used to find basic properties of optical systems, such as approximate image and object positions and magnifications.

Reflections

Main article: Reflection (physics)

Reflections can be divided into two types: specular reflection and diffuse reflection. Specular reflection describes the gloss of surfaces such as mirrors, which reflect light in a simple, predictable way. This allows for production of reflected images that can be associated with an actual (real) or extrapolated (virtual) location in space. Diffuse reflection describes non-glossy materials, such as paper or rock. The reflections from these surfaces can only be described statistically, with the exact distribution of the reflected light depending on the microscopic structure of the material. Many diffuse reflectors are described or can be approximated by Lambert's cosine law, which describes surfaces that have equal luminance when viewed from any angle. Glossy surfaces can give both specular and diffuse reflection.

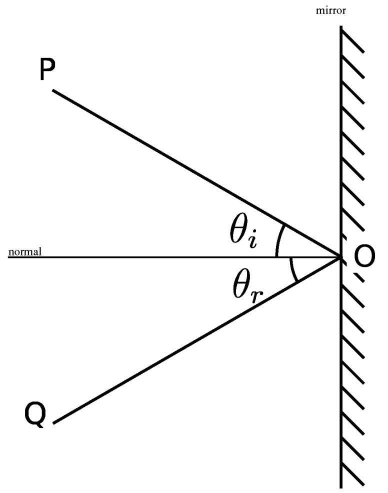


Diagram of specular reflection

In specular reflection, the direction of the reflected ray is determined by the angle the incident ray makes with the surface normal, a line perpendicular to the surface at the point where the ray hits. The incident and reflected rays and the normal lie in a single plane, and the angle between the reflected ray and the surface normal is the same as that between the incident ray and the normal. This is known as the Law of Reflection.

For flat mirrors, the law of reflection implies that images of objects are upright and the same distance behind the mirror as the objects are in front of the mirror. The image size is the same as the object size. The law also implies that mirror images are parity inverted, which we perceive as a left-right inversion. Images formed from reflection in two (or any even number of) mirrors are not parity inverted. Corner reflectors retroreflect light, producing reflected rays that travel back in the direction from which the incident rays came.

Mirrors with curved surfaces can be modelled by ray-tracing and using the law of reflection at each point on the surface. For mirrors with parabolic surfaces, parallel rays incident on the mirror produce reflected rays that converge at a common focus. Other curved surfaces may also focus light, but with aberrations due to the diverging shape causing the focus to be smeared out in space. In particular, spherical mirrors exhibit spherical aberration. Curved mirrors can form images with magnification greater than or less than one, and the magnification can be negative, indicating that the image is inverted. An upright image formed by reflection in a mirror is always virtual, while an inverted image is real and can be projected onto a screen.

Refractions

Main article: Refraction

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 index of refraction . In such situations, Snell's Law describes the resulting deflection of the light ray:

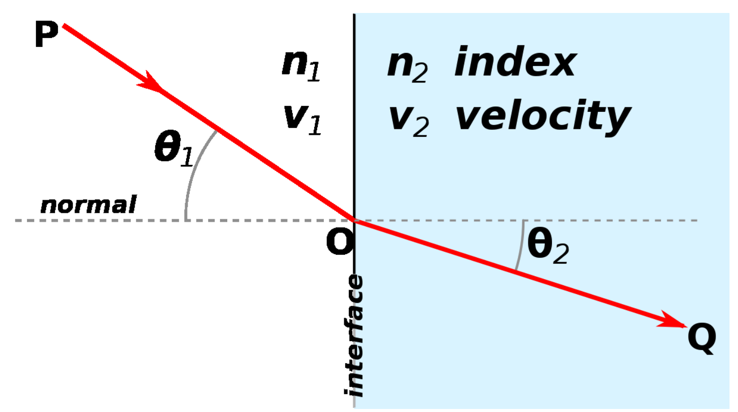


Illustration of Snell's Law for the case $n_1 < n_2$, such as air/water interface

where and are the angles between the normal (to the interface) and the incident and refracted waves, respectively.

The index of refraction of a medium is related to the speed, *v*, of light in that medium by

,

where *c* is the speed of light in vacuum.

Snell's Law can be used to predict the deflection of light rays as they pass through linear media as long as the indexes of refraction and the geometry of the media are known. For example, the propagation of light through a prism results in the light ray being deflected depending on the shape and orientation of the prism. In most materials, the index of refraction varies with the frequency of the light. Taking this into account, Snell's Law can be used to predict how a prism will disperse light into a spectrum. The discovery of this phenomenon when passing light through a prism is famously attributed to Isaac Newton.

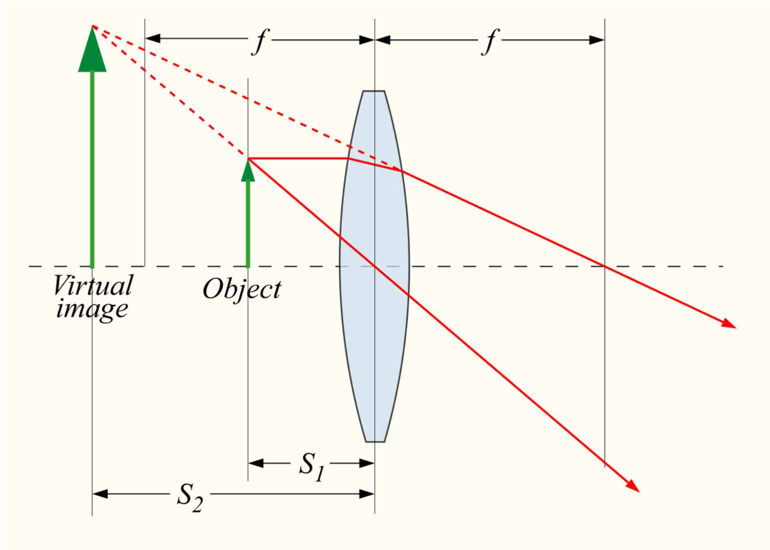
Some media have an index of refraction which varies gradually with position and, thus, light rays in the medium are curved. This effect is responsible for mirages seen on hot days: a change in index of refraction air with height causes light rays to bend, creating the appearance of specular reflections in the distance (as if on the surface of a pool of water). Optical materials with varying index of refraction are called gradient-index (GRIN) materials. Such materials are used to make gradient-index optics.

For light rays travelling from a material with a high index of refraction to a material with a low index of refraction, Snell's law predicts that there is no when is large. In this case, no transmission occurs; all the light is reflected. This phenomenon is called total internal reflection and allows for fibre optics technology. As light travels down an optical fibre, it undergoes total internal reflection allowing for essentially no light to be lost over the length of the cable.

Lenses

Main article: Lens (optics)

A device which produces converging or diverging light rays due to refraction is known as a *lens*. Lenses are characterized by their focal length: a converging lens has positive focal length, while a diverging lens has negative focal length. Smaller focal length indicates that the lens has a stronger converging or diverging effect. The focal length of a simple lens in air is given by the lensmaker's equation.[11]



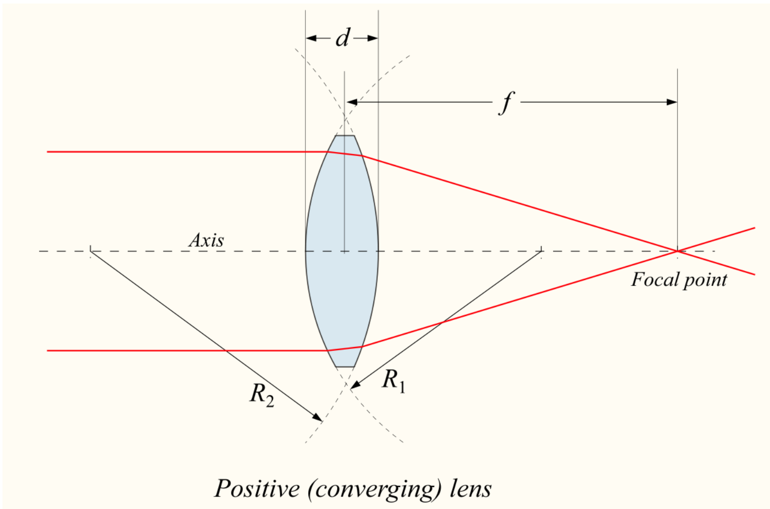
A ray tracing diagram for a converging lens.

Ray tracing can be used to show how images are formed by a lens. For a thin lens in air, the location of the image is given by the simple equation

,

where is the distance from the object to the lens, is the distance from the lens to the image, and is the focal length of the lens. In the sign convention used here, the object and image distances are positive if the object and image are on opposite sides of the lens.

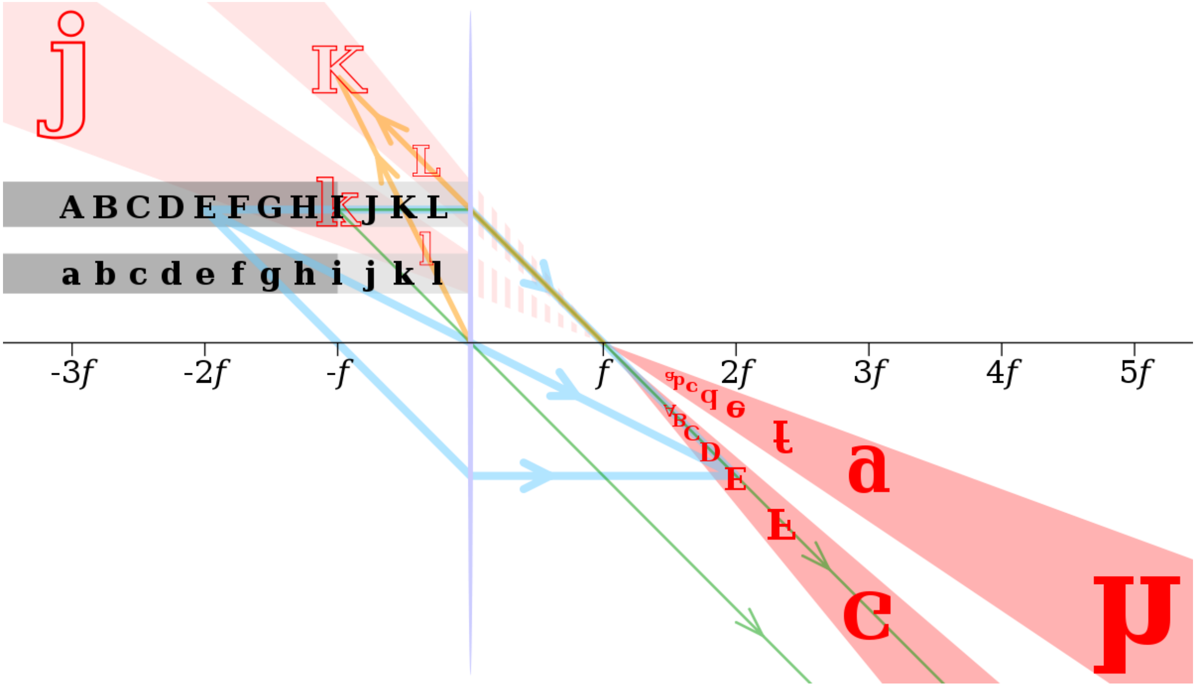
Incoming parallel rays are focused by a converging lens onto a spot one focal length from the lens, on the far side of the lens. This is called the rear focal point of the lens. Rays from an object at finite distance are focused further from the lens than the focal distance; the closer the object is to the lens, the further the image is from the lens.



Positive (converging) lens

With diverging lenses, incoming parallel rays diverge after going through the lens, in such a way that they seem to have originated at a spot one focal length in front of the lens. This is the lens's front focal point. Rays from an object at finite distance are associated with a virtual image that is closer to the lens than the focal point, and on the same side of the lens as the object. The closer the object is to the lens, the closer the virtual image is to the lens. As with mirrors, upright images produced by a single lens are virtual, while inverted images are real.

Lenses suffer from aberrations that distort images. *Monochromatic aberrations* occur because the geometry of the lens does not perfectly direct rays from each object point to a single point on the image, while chromatic aberration occurs because the index of refraction of the lens varies with the wavelength of the light.



Images of black letters in a thin convex lens of focal length *f* are shown in red. Selected rays are shown for letters **E**, **I** and **K** in blue, green and orange, respectively. Note that **E** (at 2*f*) has an equal-size, real and inverted image; **I** (at *f*) has its image at infinity; and **K** (at *f*/2) has a double-size, virtual and upright image.

Physical optics

Main article: Physical optics

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

The wave model can be used to make predictions about how an optical system will behave without requiring an explanation of what is "waving" in what medium. Until the middle of the 19th century, most physicists believed in an "ethereal" medium in which the light disturbance propagated.[12] 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.[13] Light waves are now generally treated as electromagnetic waves except when quantum mechanical effects have to be considered.

Modelling and design of optical systems using physical optics

Many simplified approximations are available for analysing 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.[14] 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. Examples of the application of Huygens–Fresnel principle can be found in the sections on diffraction and Fraunhofer diffraction.

More rigorous models, involving the modelling 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 behaviour 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 polarised light.

Numerical modeling techniques such as the finite element method, the boundary element method and the transmission-line matrix method can be used to model the propagation of light in systems which cannot be solved analytically. Such models are computationally demanding and are normally only used to solve small-scale problems that require accuracy beyond that which can be achieved with analytical solutions.

All of the results from geometrical optics can be recovered using the techniques of Fourier optics which apply many of the same mathematical and analytical techniques used in acoustic engineering and signal processing.

Gaussian beam propagation is a simple paraxial physical optics model for the propagation of coherent radiation such as laser beams. This technique partially accounts for diffraction, allowing accurate calculations of the rate at which a laser beam expands with distance, and the minimum size to which the beam can be focused. Gaussian beam propagation thus bridges the gap between geometric and physical optics.[15]

Superposition and interference

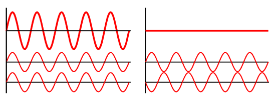
Main articles: Superposition principle and Interference (optics)

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. See below for an illustration of this effect.[]

combined waveform

wave 1

wave 2



Two waves in phase **Two waves 180° out of phase**

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.


When oil or fuel is spilled, colourful patterns are formed by thin-film interference.

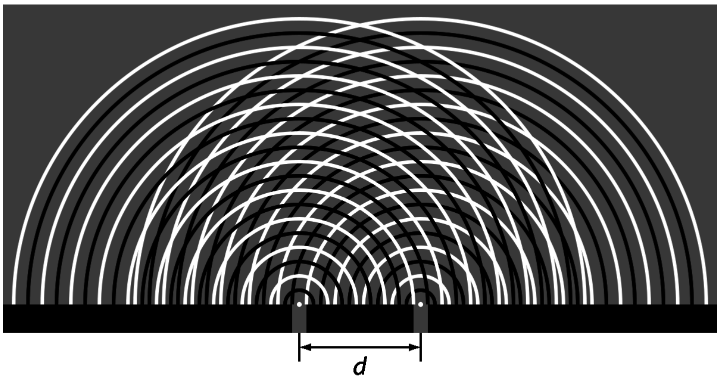
The appearance of thin films and coatings is directly affected by interference effects. Antireflective coatings use destructive interference to reduce the reflectivity of the surfaces they coat, and can be used to minimise glare and unwanted reflections. The simplest case is a single layer with thickness one-fourth the wavelength of incident light. The reflected wave from the top of the film and the reflected wave from the film/material interface are then exactly 180° out of phase, causing destructive interference. The waves are only exactly out of phase for one wavelength, which would typically be chosen to be near the centre of the visible spectrum, around 550 nm. More complex designs using multiple layers can achieve low reflectivity over a broad band, or extremely low reflectivity at a single wavelength.

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 colour separation in colour television cameras. This interference effect is also what causes the colourful rainbow patterns seen in oil slicks.

Diffraction and optical resolution

Main articles: Diffraction and Optical resolution

Diffraction is the process by which light interference is most commonly observed. The effect was first described in 1665 by Francesco Maria Grimaldi, who also coined the term from the Latin *diffringere*, 'to break into pieces'. Later that century, Robert Hooke and Isaac Newton also described phenomena now known to be diffraction in Newton's rings while James Gregory recorded his observations of diffraction patterns from bird feathers.



Diffraction on two slits separated by distance . The bright fringes occur along lines where black lines intersect with black lines and white lines intersect with white lines. These fringes are separated by angle and are numbered as order .

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

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

where is the separation between two wavefront sources (in the case of Young's experiments, it was two slits), is the angular separation between the central fringe and the th order fringe, where the central maximum is .[16]

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 and being twice the spacing between atoms.

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 (as described in diffraction-limited optics) 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 a disk is given by

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

For astronomical imaging, the atmosphere prevents optimal resolution from being achieved in the visible spectrum due to the atmospheric scattering and dispersion which cause stars to twinkle. Astronomers refer to this effect as the quality of astronomical seeing. Techniques known as adaptive optics have been used to eliminate the atmospheric disruption of images and achieve results that approach the diffraction limit.[17]

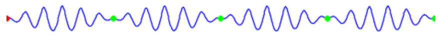
Dispersion and scattering

Main articles: Dispersion (optics) 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 while the similar process for scattering by particles that are similar or larger in wavelength is known as Mie scattering with the Tyndall effect being a commonly observed result. A small proportion of light scattering from atoms or molecules may undergo Raman scattering, wherein the frequency changes due to excitation of the atoms and molecules. Brillouin scattering occurs when the frequency of light changes due to local changes with time and movements of a dense material.

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



Dispersion: two sinusoids propagating at different speeds make a moving interference pattern. The red dot moves with the phase velocity, and the green dots propagate with the group velocity. In this case, the phase velocity is twice the group velocity. The red dot overtakes two green dots, when moving from the left to the right of the figure. In effect, the individual waves (which travel with the phase velocity) escape from the wave packet (which travels with the group velocity).

Material dispersion is often characterised by the Abbe number, which gives a simple measure of dispersion based on the index of refraction at three specific wavelengths. Waveguide dispersion is dependent on the propagation constant. Both kinds of dispersion cause changes in the group characteristics of the wave, the features of the wave packet that change with the same frequency as the amplitude of the electromagnetic wave. "Group velocity dispersion" manifests as a spreading-out of the signal "envelope" of the radiation and can be quantified with a group dispersion delay parameter:

where is the group velocity. For a uniform medium, the group velocity is

where *n* is the index of refraction and *c* is the speed of light in a vacuum.[18] This gives a simpler form for the dispersion delay parameter:

If *D* is less than zero, the medium is said to have *positive dispersion* or normal dispersion. If *D* is greater than zero, the medium has *negative dispersion*. If a light pulse is propagated through a normally dispersive medium, the result is the higher frequency components slow down more than the lower frequency components. The pulse therefore becomes *positively chirped*, or *up-chirped*, increasing in frequency with time. This causes the spectrum coming out of a prism to appear with red light the least refracted and blue/violet light the most refracted. Conversely, if a pulse travels through an anomalously (negatively) dispersive medium, high frequency components travel faster than the lower ones, and the pulse becomes *negatively chirped*, or *down-chirped*, decreasing in frequency with time.

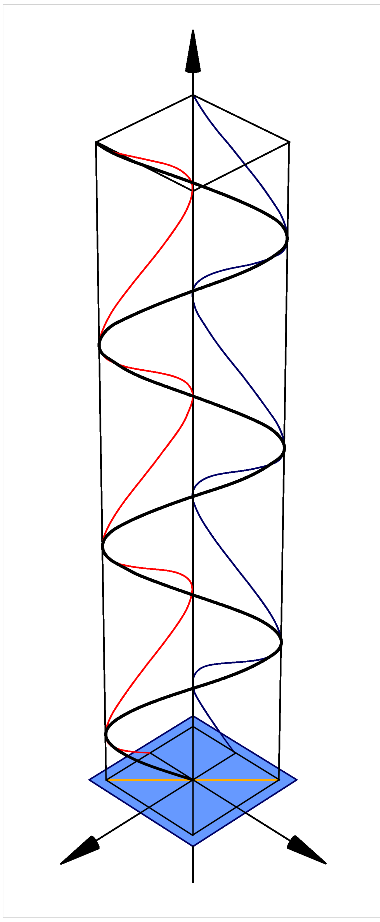
The result of group velocity dispersion, whether negative or positive, is ultimately temporal spreading of the pulse. This makes dispersion management extremely important in optical communications systems based on optical fibres, since if dispersion is too high, a group of pulses representing information will each spread in time and merge, making it impossible to extract the signal.

Polarization

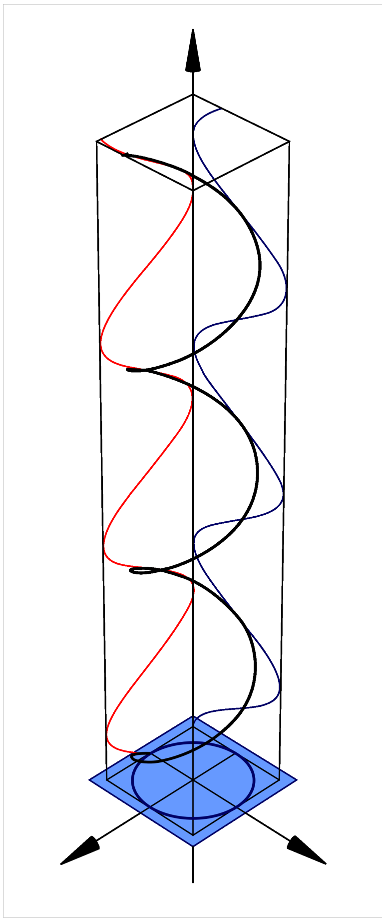
Main article: Polarization (waves)

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 polarised 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.[19]

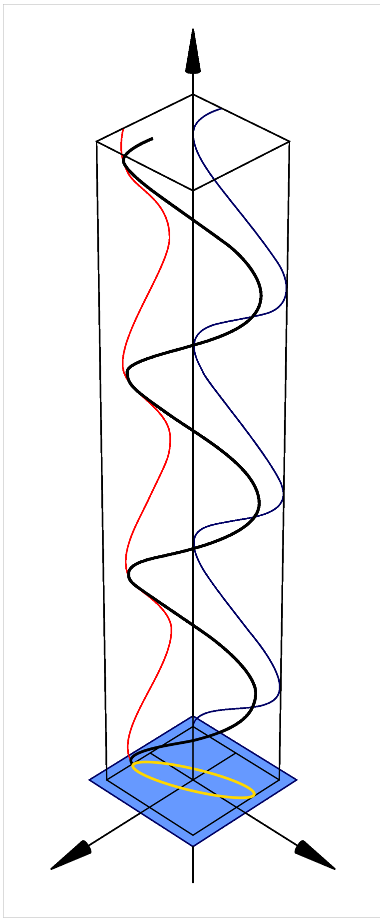
The typical way to consider polarization is to keep track of the orientation of the electric field vector as the electromagnetic wave propagates. The electric field vector of a plane wave may be arbitrarily divided into two perpendicular components labeled *x* and *y* (with **z** indicating the direction 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*. The following figures show some examples of the evolution of the electric field vector (blue), with time (the vertical axes), at a particular point in space, along with its *x* and *y* components (red/left and green/right), and the path traced by the vector in the plane (purple): The same evolution would occur when looking at the electric field at a particular time while evolving the point in space, along the direction opposite to propagation.



Linear



Circular



Elliptical polarization

In the leftmost figure above, the x and y components of the light wave are in phase. In this case, the ratio of their strengths is constant, so the direction of the electric vector (the vector sum of these two components) is constant. Since the tip of the vector traces out a single line in the plane, this special case is called linear polarization. The direction of this line depends on the relative amplitudes of the two components.

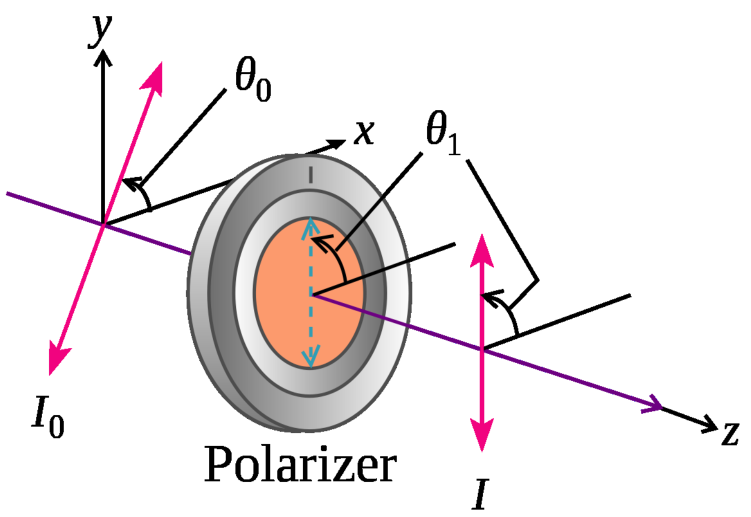
In the middle figure, the two orthogonal components have the same amplitudes and are 90° out of phase. In this case, one component is zero when the other component is at maximum or minimum amplitude. There are two possible phase relationships that satisfy this requirement: the x component can be 90° ahead of the y component or it can be 90° behind the y component. In this special case, the electric vector traces out a circle in the plane, so this polarization is called circular polarization. The rotation direction in the circle depends on which of the two phase relationships exists and corresponds to *right-hand circular polarization* and *left-hand circular polarization*.

In all other cases, where the two components either do not have the same amplitudes and/or their phase difference is neither zero nor a multiple of 90°, the polarization is called elliptical polarization because the electric vector traces out an ellipse in the plane (the *polarization ellipse*). This is shown in the above figure on the right. Detailed mathematics of polarization is done using Jones calculus and is characterised by the Stokes parameters.

Changing polarization

Media that have different indexes of refraction for different polarization modes are called *birefringent*. Well known manifestations of this effect appear in optical wave plates/retarders (linear modes) and in Faraday rotation/optical rotation (circular modes). If the path length in the birefringent medium is sufficient, plane waves will exit the material with a significantly different propagation direction, due to refraction. For example, this is the case with macroscopic crystals of calcite, which present the viewer with two offset, orthogonally polarised images of whatever is viewed through them. It was this effect that provided the first discovery of polarization, by Erasmus Bartholinus in

1669. In addition, the phase shift, and thus the change in polarization state, is usually frequency dependent, which, in combination with dichroism, often gives rise to bright colours and rainbow-like effects. In mineralogy, such properties, known as pleochroism, are frequently exploited for the purpose of identifying minerals using polarization microscopes. Additionally, many plastics that are not normally birefringent will become so when subject to mechanical stress, a phenomenon which is the basis of photoelasticity. Non-birefringent methods, to rotate the linear polarization of light beams, include the use of prismatic polarization rotators which use total internal reflection in a prism set designed for efficient collinear transmission.



A polariser changing the orientation of linearly polarised light.
In this picture, $\theta_1 - \theta_0 = \theta_i$.

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 "polarisers". Malus' law, which is named after Étienne-Louis Malus, says that when a perfect polariser is placed in a linear polarised beam of light, the intensity, *I*, of the light that passes through is given by

where

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

A beam of unpolarised light can be thought of as containing a uniform mixture of linear polarizations at all possible angles. Since the average value of is 1/2, the transmission coefficient becomes

In practice, some light is lost in the polariser and the actual transmission of unpolarised light will be somewhat lower than this, around 38% for Polaroid-type polarisers but considerably higher (>49.9%) for some birefringent prism types.

In addition to birefringence and dichroism in extended media, polarization effects can also occur at the (reflective) interface between two materials of different refractive index. These effects are treated by the Fresnel equations. Part of the wave is transmitted and part is reflected, with the ratio depending on angle of incidence and the angle of refraction. In this way, physical optics recovers Brewster's angle. When light reflects from a thin film on a surface, interference between the reflections from the film's surfaces can produce polarization in the reflected and transmitted light.

Natural light

The effects of a polarising filter on the sky in a photograph. Left picture is taken without polariser. For the right picture, filter was adjusted to eliminate certain polarizations of the scattered blue light from the sky.

Most sources of electromagnetic radiation contain a large number of atoms or molecules that emit light. The orientation of the electric fields produced by these emitters may not be correlated, in which case the light is said to be *unpolarised*. If there is partial correlation between the emitters, the light is *partially polarised*. If the polarization is consistent across the spectrum of the source, partially polarised light can be described as a superposition of a completely unpolarised component, and a completely polarised one. One may then describe the light in terms of the degree of polarization, and the parameters of the polarization ellipse.

Light reflected by shiny transparent materials is partly or fully polarised, except when the light is normal (perpendicular) to the surface. It was this effect that allowed the mathematician Étienne-Louis Malus to make the measurements that allowed for his development of the first mathematical models for polarised light. Polarization occurs when light is scattered in the atmosphere. The scattered light produces the brightness and colour in clear skies. This partial polarization of scattered light can be taken advantage of using polarizing filters to darken the sky in photographs. Optical polarization is principally of importance in chemistry due to circular dichroism and optical rotation ("*circular birefringence*") exhibited by optically active (chiral) molecules.

Modern optics

Main articles: Optical physics and Optical engineering

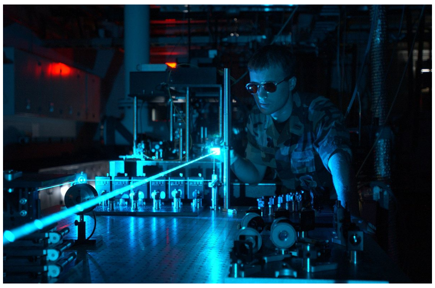
Modern optics encompasses the areas of optical science and engineering that became popular in the 20th century. These areas of optical science typically relate to the electromagnetic or quantum properties of light but do include other topics. A major subfield of modern optics, quantum optics, deals with specifically quantum mechanical properties of light. Quantum optics is not just theoretical; some modern devices, such as lasers, have principles of operation that depend on quantum mechanics. Light detectors, such as photomultipliers and channeltrons, respond to individual photons. Electronic image sensors, such as CCDs, exhibit shot noise corresponding to the statistics of individual photon events. Light-emitting diodes and photovoltaic cells, too, cannot be understood without quantum mechanics. In the study of these devices, quantum optics often overlaps with quantum electronics.[20]

Specialty areas of optics research include the study of how light interacts with specific materials as in crystal optics and metamaterials. Other research focuses on the phenomenology of electromagnetic waves as in singular optics, non-imaging optics, non-linear optics, statistical optics, and radiometry. Additionally, computer engineers have taken an interest in integrated optics, machine vision, and photonic computing as possible components of the "next generation" of computers.

Today, the pure science of optics is called optical science or optical physics to distinguish it from applied optical sciences, which are referred to as optical engineering. Prominent subfields of optical engineering include illumination engineering, photonics, and optoelectronics with practical applications like lens design, fabrication and testing of optical components, and image processing. Some of these fields overlap, with nebulous boundaries between the subjects terms that mean slightly different things in different parts of the world and in different areas of industry. A professional community of researchers in nonlinear optics has developed in the last several decades due to advances in laser technology.

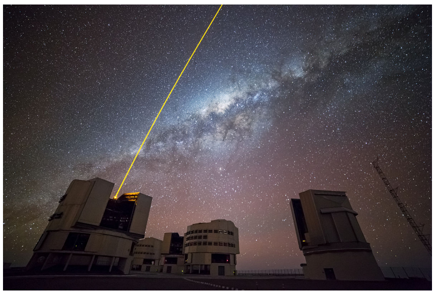
Lasers

Main article: Laser



Experiments such as this one with high-power lasers are part of the modern optics research.

A laser is a device that emits light (electromagnetic radiation) through a process called *stimulated emission*. The term *laser* is an acronym for *Light Amplification by Stimulated Emission of Radiation*. Laser light is usually spatially coherent, which means that the light either is emitted in a narrow, low-divergence beam, or can be converted into one with the help of optical components such as lenses. Because the microwave equivalent of the laser, the *maser*, was developed first, devices that emit microwave and radio frequencies are usually called *masers*.[21]



VLT's laser guided star.

The first working laser was demonstrated on 16 May 1960 by Theodore Maiman at Hughes Research Laboratories. When first invented, they were called "a solution looking for a problem". Since then, lasers have become a multibillion-dollar industry, finding utility in thousands of highly varied applications. The first application of lasers visible in the daily lives of the general population was the supermarket barcode scanner, introduced in 1974.[22] The laserdisc player, introduced in 1978, was the first successful consumer product to include a laser, but the compact disc player was the first laser-equipped device to become truly common in consumers' homes, beginning in 1982. These optical storage devices use a semiconductor laser less than a millimetre wide to scan the surface of the disc for data retrieval. Fibre-optic communication relies on lasers to transmit large amounts of information at the speed of light. Other common applications of lasers include laser printers and laser pointers. Lasers are used in medicine in areas such as bloodless surgery, laser eye surgery, and laser capture microdissection and in military applications such as missile defence systems, electro-optical countermeasures (EOCM), and lidar. Lasers are also used in holograms, bubblegrams, laser light shows, and laser hair removal.

Kapitsa–Dirac effect

The Kapitsa–Dirac effect causes beams of particles to diffract as the result of meeting a standing wave of light. Light can be used to position matter using various phenomena (see optical tweezers).

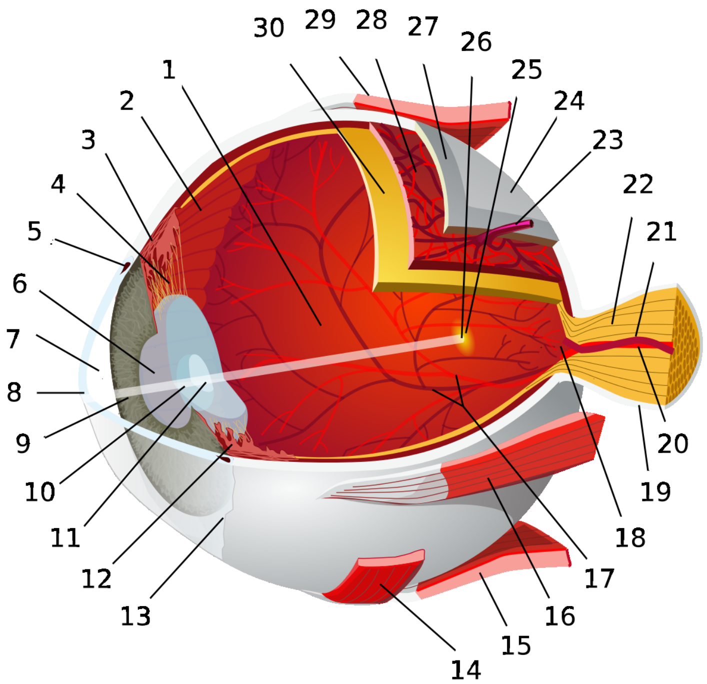
Applications

Optics is part of everyday life. The ubiquity of visual systems in biology indicates the central role optics plays as the science of one of the five senses. Many people benefit from eyeglasses or contact lenses, and optics are integral to the functioning of many consumer goods including cameras. Rainbows and mirages are examples of optical phenomena. Optical communication provides the backbone for both the Internet and modern telephony.

Human eye

Main articles: Human eye and Photometry (optics)

The human eye functions by focusing light onto a layer of photoreceptor cells called the retina, which forms the inner lining of the back of the eye. The focusing is accomplished by a series of transparent media. Light entering the eye passes first through the cornea, which provides much of the eye's optical power. The light then continues through the fluid just behind the cornea—the anterior chamber, then passes through the pupil. The light then passes through the lens, which focuses the light further and allows adjustment of focus. The light then passes through the main body of fluid in the eye—the vitreous humour, and reaches the retina. The cells in the retina line the back of the eye, except for where the optic nerve exits; this results in a blind spot.



Model of a human eye. Features mentioned in this article are 3. ciliary muscle, 6. pupil, 8. cornea, 10. lens cortex, 22. optic nerve, 26. fovea, 30. retina

There are two types of photoreceptor cells, rods and cones, which are sensitive to different aspects of light. Rod cells are sensitive to the intensity of light over a wide frequency range, thus are responsible for black-and-white vision. Rod cells are not present on the fovea, the area of the retina responsible for central vision, and are not as responsive as cone cells to spatial and temporal changes in light. There are, however, twenty times more rod cells than cone cells in the retina because the rod cells are present across a wider area. Because of their wider distribution, rods are responsible for peripheral vision.

In contrast, cone cells are less sensitive to the overall intensity of light, but come in three varieties that are sensitive to different frequency-ranges and thus are used in the perception of colour and photopic vision. Cone cells are highly concentrated in the fovea and have a high visual acuity meaning that they are better at spatial resolution than rod cells. Since cone cells are not as sensitive to dim light as rod cells, most night vision is limited to rod cells. Likewise, since cone cells are in the fovea, central vision (including the vision needed to do most reading, fine detail work such as sewing, or careful examination of objects) is done by cone cells.

Ciliary muscles around the lens allow the eye's focus to be adjusted. This process is known as accommodation. The near point and far point define the nearest and farthest distances from the eye at which an object can be brought into sharp focus. For a person with normal vision, the far point is located at infinity. The near point's location depends on how much the muscles can increase the curvature of the lens, and how inflexible the lens has become with age. Optometrists, ophthalmologists, and opticians usually consider an appropriate near point to be closer than normal reading distance—approximately 25 cm.

Defects in vision can be explained using optical principles. As people age, the lens becomes less flexible and the near point recedes from the eye, a condition known as presbyopia. Similarly, people suffering from hyperopia cannot decrease the focal length of their lens enough to allow for nearby objects to be imaged on their retina. Conversely, people who cannot increase the focal length of their lens enough to allow for distant objects to be imaged on the retina suffer from myopia and have a far point that is considerably closer than infinity. A condition known as astigmatism results when the cornea is not spherical but instead is more curved in one direction. This causes horizontally extended objects to be focused on different parts of the retina than vertically extended objects, and results in distorted images.

All of these conditions can be corrected using corrective lenses. For presbyopia and hyperopia, a converging lens provides the extra curvature necessary to bring the near point closer to the eye while for myopia a diverging lens provides the curvature necessary to send the far point to infinity. Astigmatism is corrected with a cylindrical surface lens that curves more strongly in one direction than in another, compensating for the non-uniformity of the cornea.

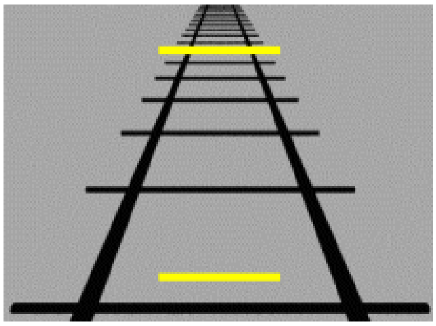
The optical power of corrective lenses is measured in diopters, a value equal to the reciprocal of the focal length measured in metres; with a positive focal length corresponding to a converging lens and a negative focal length corresponding to a diverging lens. For lenses that correct for astigmatism as well, three numbers are given: one for the spherical power, one for the cylindrical power, and one for the angle of orientation of the astigmatism.

Visual effects

Main articles: Optical illusions and Perspective (graphical)

For the visual effects used in film, video, and computer graphics, see visual effects.

Optical illusions (also called visual illusions) are characterized by visually perceived images that differ from objective reality. The information gathered by the eye is processed in the brain to give a percept that differs from the object being imaged. Optical illusions can be the result of a variety of phenomena including physical effects that create images that are different from the objects that make them, the physiological effects on the eyes and brain of excessive stimulation (e.g. brightness, tilt, colour, movement), and cognitive illusions where the eye and brain make unconscious inferences.



The Ponzo Illusion relies on the fact that parallel lines appear to converge as they approach infinity.

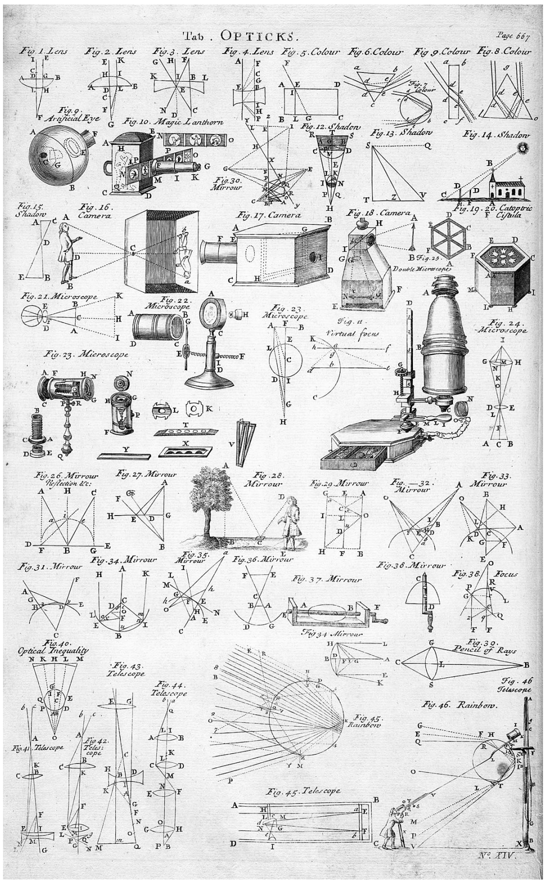
Cognitive illusions include some which result from the unconscious misapplication of certain optical principles. For example, the Ames room, Hering, Müller-Lyer, Orbison, Ponzo, Sander, and Wundt illusions all rely on the suggestion of the appearance of distance by using converging and diverging lines, in the same way that parallel light rays (or indeed any set of parallel lines) appear to converge at a vanishing point at infinity in two-dimensionally rendered images with artistic perspective.[23] This suggestion is also responsible for the famous moon illusion where the moon, despite having essentially the same angular size, appears much larger near the horizon than it does at zenith.[24] This illusion so confounded Ptolemy that he incorrectly attributed it to atmospheric refraction when he described it in his treatise, *Optics*.

Another type of optical illusion exploits broken patterns to trick the mind into perceiving symmetries or asymmetries that are not present. Examples include the café wall, Ehrenstein, Fraser spiral, Poggendorff, and Zöllner illusions. Related, but not strictly illusions, are patterns that occur due to the superimposition of periodic structures. For example, transparent tissues with a grid structure produce shapes known as moiré patterns, while the superimposition of periodic transparent patterns comprising parallel opaque lines or curves produces line moiré patterns.

Optical instruments

Main article: Optical instruments

Single lenses have a variety of applications including photographic lenses, corrective lenses, and magnifying glasses while single mirrors are used in parabolic reflectors and rear-view mirrors. Combining a number of mirrors, prisms, and lenses produces compound optical instruments which have practical uses. For example, a periscope is simply two plane mirrors aligned to allow for viewing around obstructions. The most famous compound optical instruments in science are the microscope and the telescope which were both invented by the Dutch in the late 16th century.



Illustrations of various optical instruments from the 1728 *Cyclopaedia*

Microscopes were first developed with just two lenses: an objective lens and an eyepiece. The objective lens is essentially a magnifying glass and was designed with a very small focal length while the eyepiece generally has a longer focal length. This has the effect of producing magnified images of close objects. Generally, an additional source of illumination is used since magnified images are dimmer due to the conservation of energy and the spreading of light rays over a larger surface area. Modern microscopes, known as *compound microscopes* have many lenses in them (typically four) to optimize the functionality and enhance image stability. A slightly different variety of microscope, the comparison microscope, looks at side-by-side images to produce a stereoscopic binocular view that appears three dimensional when used by humans.

The first telescopes, called *refracting telescopes* were also developed with a single objective and eyepiece lens. In contrast to the microscope, the objective lens of the telescope was designed with a large focal length to avoid optical aberrations. The objective focuses an image of a distant object at its focal point which is adjusted to be at the focal point of an eyepiece of a much smaller focal length. The main goal of a telescope is not necessarily magnification, but rather collection of light which is determined by the physical size of the objective lens. Thus, telescopes are normally indicated by the diameters of their objectives rather than by the magnification which can be changed by switching eyepieces. Because the magnification of a telescope is equal to the focal length of the objective divided by the focal length of the eyepiece, smaller focal-length eyepieces cause greater magnification.

Since crafting large lenses is much more difficult than crafting large mirrors, most modern telescopes are *reflecting telescopes*, that is, telescopes that use a primary mirror rather than an objective lens. The same general optical considerations apply to reflecting telescopes that applied to refracting telescopes, namely, the larger the primary mirror, the more light collected, and the magnification is still equal to the focal length of the primary mirror divided by the focal length of the eyepiece. Professional telescopes generally do not have eyepieces and instead place an instrument (often a charge-coupled device) at the focal point instead.

Photography

Main article: Science of photography

The optics of photography involves both lenses and the medium in which the electromagnetic radiation is recorded, whether it be a plate, film, or charge-coupled device. Photographers must consider the reciprocity of the camera and the shot which is summarized by the relation

$$\text{Exposure} \propto \text{ApertureArea} \times \text{ExposureTime} \times \text{SceneLuminance}$$

In other words, the smaller the aperture (giving greater depth of focus), the less light coming in, so the length of time has to be increased (leading to possible blurriness if motion occurs). An example of the use of the law of reciprocity is the Sunny 16 rule which gives a rough estimate for the settings needed to estimate the proper exposure in daylight.

Photograph taken with aperture *f*/32

Photograph taken with aperture *f*/5

A camera's aperture is measured by a unitless number called the f-number or f-stop, *f*/#, often notated as , and given by

where is the focal length, and is the diameter of the entrance pupil. By convention, "*f*/#" is treated as a single symbol, and specific values of *f*/# are written by replacing the number sign with the value. The two ways to increase the f-stop are to either decrease the diameter of the entrance pupil or change to a longer focal length (in the case of a zoom lens, this can be done by simply adjusting the lens). Higher f-numbers also have a larger depth of field due to the lens approaching the limit of a pinhole camera which is able to focus all images perfectly, regardless of distance, but requires very long exposure times.

The field of view that the lens will provide changes with the focal length of the lens. There are three basic classifications based on the relationship to the diagonal size of the film or sensor size of the camera to the focal length of the lens:

- Normal lens: angle of view of about 50° (called *normal* because this angle considered roughly equivalent to human vision) and a focal length approximately equal to the diagonal of the film or sensor.
- Wide-angle lens: angle of view wider than 60° and focal length shorter than a normal lens.
- Long focus lens: angle of view narrower than a normal lens. This is any lens with a focal length longer than the diagonal measure of the film or sensor. The most common type of long focus lens is the telephoto lens, a design that uses a special *telephoto group* to be physically shorter than its focal length.

Modern zoom lenses may have some or all of these attributes.

The absolute value for the exposure time required depends on how sensitive to light the medium being used is (measured by the film speed, or, for digital media, by the quantum efficiency). Early photography used media that had very low light sensitivity, and so exposure times had to be long even for very bright shots. As technology has improved, so has the sensitivity through film cameras and digital cameras.

Other results from physical and geometrical optics apply to camera optics. For example, the maximum resolution capability of a particular camera set-up is determined by the diffraction limit associated with the pupil size and given, roughly, by the Rayleigh criterion.

Atmospheric optics

Main article: Atmospheric optics

The unique optical properties of the atmosphere cause a wide range of spectacular optical phenomena. The blue colour of the sky is a direct result of Rayleigh scattering which redirects higher frequency (blue) sunlight back into the field of view of the observer. Because blue light is scattered more easily than red light, the sun takes on a reddish hue when it is observed through a thick atmosphere, as during a sunrise or sunset. Additional particulate matter in the sky can scatter different colours at different angles creating colourful glowing skies at dusk and dawn. Scattering off of ice crystals and other particles in the atmosphere are responsible for halos, afterglows, coronas, rays of sunlight, and sun dogs. The variation in these kinds of phenomena is due to different particle sizes and geometries.

A colourful sky is often due to scattering of light off particulates and pollution, as in this photograph of a sunset during the October 2007 California wildfires.

Mirages are optical phenomena in which light rays are bent due to thermal variations in the refraction index of air, producing displaced or heavily distorted images of distant objects. Other dramatic optical phenomena associated with this include the Novaya Zemlya effect where the sun appears to rise earlier than predicted with a distorted shape. A spectacular form of refraction occurs with a temperature inversion called the Fata Morgana where objects on the horizon or even beyond the horizon, such as islands, cliffs, ships or icebergs, appear elongated and elevated, like "fairy tale castles".

Rainbows are the result of a combination of internal reflection and dispersive refraction of light in raindrops. A single reflection off the backs of an array of raindrops produces a rainbow with an angular size on the sky that ranges from 40° to 42° with red on the outside. Double rainbows are produced by two internal reflections with angular size of 50.5° to 54° with violet on the outside. Because rainbows are seen with the sun 180° away from the centre of the rainbow, rainbows are more prominent the closer the sun is to the horizon.

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Wikimedia Commons has media related to ***Optics***.

Relevant discussions

- Optics (http://www.bbc.co.uk/programmes/b00774t5) on *In Our Time* at the BBC. (listen now (http://www.bbc.co.uk/iplayer/console/b00774t5/In_Our_Time_Optics))

Textbooks and tutorials

- Optics (http://www.lightandmatter.com/area1book5.html) – an open-source optics textbook
- Optics2001 (http://www.optics2001.com) – Optics library and community
- Fundamental Optics (http://marketplace.idexop.com/store/SupportDocuments/Fundamental_Optics_OverviewWEB.pdf) – Melles Griot Technical Guide
- Physics of Light and Optics (http://optics.byu.edu/textbook.aspx) – Brigham Young University Undergraduate Book

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- Physics Study Guide/Optics
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Further reading

- Optics and photonics: Physics enhancing our lives (http://www.iop.org/publications/iop/2009/page_38205.html) by Institute of Physics publications (http://www.iop.org/publications/iop/index.html)

Societies

- European Optical Society – link (http://www.myeos.org)
- The Optical Society – link (http://www.osa.org)
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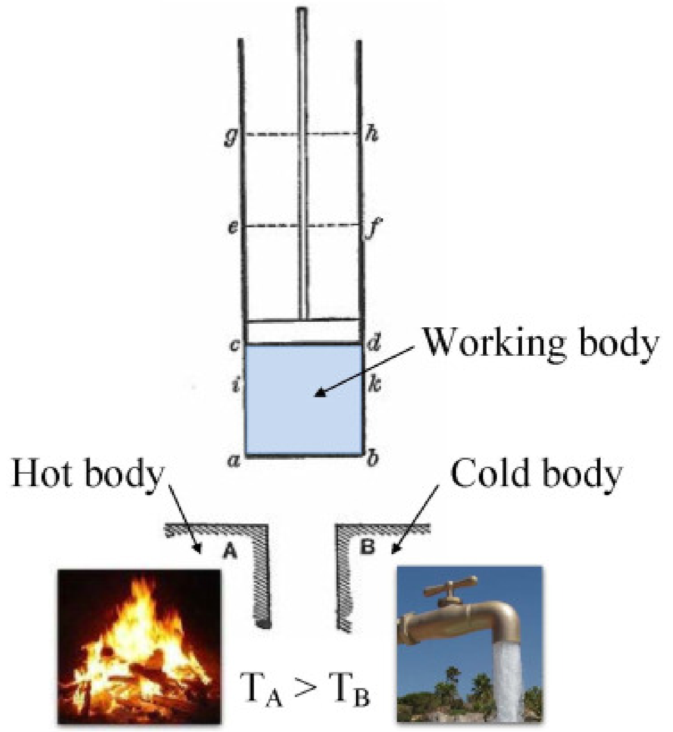
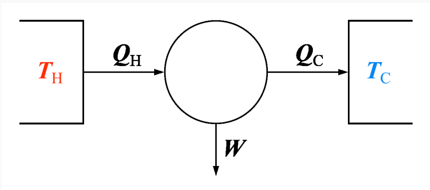
Thermodynamics



Annotated color version of the original 1824 Carnot heat engine showing the hot body (boiler), working body (system, steam), and cold body (water), the letter-labels indicate the stopping points in Carnot cycle

Thermodynamics



The classical Carnot heat engine

Book:Thermodynamics

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Thermodynamics is a branch of physics concerned with heat and temperature and their relation to energy and work. It defines macroscopic variables, such as internal energy, entropy, and pressure, that partly describe a body of matter or radiation. It states that the behavior of those variables is subject to general constraints, that are common to all materials, beyond the peculiar properties of particular materials. These general constraints are expressed in the four laws of thermodynamics. Thermodynamics describes the bulk behavior of the body, not the microscopic behaviors of the very large numbers of its microscopic constituents, such as molecules. The basic results of thermodynamics rely on the existence of idealized states of thermodynamic equilibrium. Its laws are explained by statistical mechanics, in terms of the microscopic constituents.

Thermodynamics applies to a wide variety of topics in science and engineering, especially physical chemistry, chemical engineering and mechanical engineering.

Historically, the distinction between heat and temperature was studied in the 1750s by Joseph Black. Characteristically thermodynamic thinking began in the work of Carnot (1824) who believed that the efficiency of heat engines was the key that could help France win the Napoleonic Wars. The Irish-born British physicist Lord Kelvin was the first to formulate a concise definition of thermodynamics in 1854:[2]

> 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, thermodynamics, as applied to heat engines, was concerned with the thermal properties of their 'working materials', such as steam, in an effort to increase the efficiency and power output of engines. Thermodynamics was later expanded to the study of energy transfers in chemical processes, such as the investigation, published in 1840, of the heats of chemical reactions[3] by Germain Hess, which was not originally explicitly concerned with the relation between energy exchanges by heat and work. From this evolved the study of chemical thermodynamics and the role of entropy in chemical reactions.[4][5][6][7]

Introduction

Historically, thermodynamics arose from the study of two distinct kinds of transfer of energy, as heat and as work, and the relation of those to the system's macroscopic variables of volume, pressure and temperature.[8][9] As it developed, thermodynamics began also to study transfers of matter.

The plain term 'thermodynamics' refers to a macroscopic description of bodies and processes.[10] Reference to atomic constitution is foreign to classical thermodynamics.[11] Usually the plain term 'thermodynamics' refers by default to equilibrium as opposed to non-equilibrium thermodynamics. The qualified term 'statistical thermodynamics' refers to descriptions of bodies and processes in terms of the atomic or other microscopic constitution of matter, using statistical and probabilistic reasoning.

Thermodynamic equilibrium is one of the most important concepts for thermodynamics.[12][13] The temperature of a thermodynamic system 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. Many important practical engineering cases, as in heat engines or refrigerators, can be approximated as systems consisting of many subsystems at different temperatures and pressures. If a physical process is too fast, the equilibrium thermodynamic variables, for example temperature, may not be well enough defined to provide a useful approximation.

Central to thermodynamic analysis are the definitions of the system, which is of interest, and of its surroundings.[14] 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 held at a prescribed temperature, regardless of how much heat might be drawn from it.

There are four fundamental kinds of physical entities in thermodynamics:

- states of a system, and the states of its surrounding systems
- walls of a system,[15][16][17][18]
- thermodynamic processes of a system, and

- thermodynamic operations.

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. Always associated with the material that constitutes a system, its working substance, are the walls that delimit the system, and connect it with its surroundings. The state variables chosen for the system should be appropriate for the natures of the walls and surroundings.[19]

A thermodynamic operation is an artificial physical manipulation that changes the definition of a system or its surroundings. Usually it is a change of the permeability of a wall of the system,[20] that allows energy (as heat or work) or matter (mass) to be exchanged with the environment. For example, the partition between two thermodynamic systems can be removed so as to produce a single system. A thermodynamic operation that increases the range of possible transfers usually leads to a thermodynamic process of transfer of mass or energy that changes the state of the system, and the transfer occurs in natural accord with the laws of thermodynamics. But if the operation simply reduces the possible range of transfers, in general it does not initiate a process. The states of the system's surrounding systems are assumed to be unchanging in time except when they are changed by a thermodynamic operation, whereupon a thermodynamic process can be initiated.

A thermodynamic system can also be defined in terms of the cyclic processes that it can undergo. A cyclic process is a cyclic sequence of thermodynamic operations and processes that can be repeated indefinitely often without changing the final state of the system.

For thermodynamics and statistical thermodynamics to apply to a physical system, it is necessary that its internal atomic mechanisms fall into one of two classes:

- those so rapid that, in the time frame of the process of interest, the atomic states rapidly bring system to its own state of internal thermodynamic equilibrium; and
- those so slow that, in the time frame of the process of interest, they leave the system unchanged.[21][22]

The rapid atomic mechanisms account for the internal energy of the system. They 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 equilibrium relations between macroscopic mechanical variables and temperature and internal energy. 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.[23][24][25][26]

The present article takes a gradual approach to the subject, starting with a focus on cyclic processes and thermodynamic equilibrium, and then gradually beginning to further consider non-equilibrium systems.

Thermodynamic facts can often be explained by viewing macroscopic objects as assemblies of very many microscopic or atomic objects that obey Hamiltonian dynamics.[27][28] 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 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.

History

The history of thermodynamics as a scientific discipline generally begins with Otto von Guericke who, in about 1650,[29] built and designed the world's first vacuum pump and demonstrated a vacuum using his Magdeburg hemispheres. Guericke was driven to make a vacuum in order to disprove Aristotle's long-held supposition that 'nature abhors a vacuum'. Shortly after Guericke, the physicist and chemist Robert Boyle had learned of Guericke's designs and, in 1656, in coordination with the scientist Robert Hooke, built an air pump. Using this pump, Boyle and Hooke noticed a correlation between pressure, temperature, and volume. In time, they formulated Boyle's Law, which states that for a gas at constant temperature, its pressure and volume are inversely proportional. In 1679, based on these concepts, an associate of Boyle's named Denis Papin built a steam digester, which was a closed vessel with a tightly fitting lid that confined steam until a high pressure was generated. Later versions of this design implemented a steam release valve that kept the machine from exploding. By watching the valve rhythmically move up and down, Papin conceived of the idea of a piston and a cylinder engine. He did not, however, follow through with his design. Nevertheless, in 1697, based on Papin's designs, the engineer Thomas Savery built the first engine, followed by Thomas Newcomen in 1712. Although these early engines were crude and inefficient, they attracted the attention of the leading scientists of the time.

The thermodynamicists representative of the original eight founding schools of thermodynamics. The schools with the most-lasting effect in founding the modern versions of thermodynamics are the Berlin school, particularly as established in Rudolf Clausius's 1865 textbook *The Mechanical Theory of Heat*, the Vienna school, while the statistical mechanics of Ludwig Boltzmann, and the Gibbsian school at Yale University, led by the American engineer Willard Gibbs' 1876 *On the Equilibrium of Heterogeneous Substances* launched chemical thermodynamics.

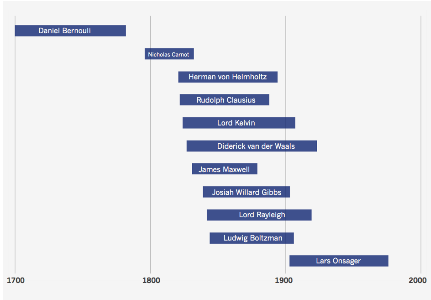
The concepts of heat capacity and latent heat, which were necessary for development of thermodynamics, were developed by Professor Joseph Black at the University of Glasgow, where James Watt worked as an instrument maker. Watt consulted with Black on tests of his steam engine, but it was Watt who conceived the idea of the external condenser, greatly raising the steam engine's efficiency.[30] All the previous work led Sadi Carnot, the "father of thermodynamics", to publish *Reflections on the Motive Power of Fire* (1824), a discourse on heat, power, energy, and engine efficiency. The paper outlined the basic energetic relations between the Carnot engine, the Carnot cycle, and motive power. It marked the start of thermodynamics as a modern science.

The first thermodynamic textbook was written in 1859 by William Rankine, originally trained as a physicist and a professor of civil and mechanical engineering at the University of Glasgow. The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolf Clausius, and William Thomson (Lord Kelvin).

The foundations of statistical thermodynamics were set out by physicists such as James Clerk Maxwell, Ludwig Boltzmann, Max Planck, Rudolf Clausius and J. Willard Gibbs.

From 1873 to '76, the American mathematical physicist Josiah Willard Gibbs published a series of three papers, the most famous being "On the equilibrium of heterogeneous substances". Gibbs showed how thermodynamic processes, including chemical reactions, could be graphically analyzed. By studying the energy, entropy, volume, chemical potential, temperature and pressure of the thermodynamic system, one can determine whether a process would occur spontaneously. Chemical thermodynamics was further developed by Pierre Duhem, Gilbert N. Lewis, Merle Randall, and E. A. Guggenheim, who applied the mathematical methods of Gibbs.

Etymology



The lifetimes of some of the most important contributors to thermodynamics

The etymology of *thermodynamics* has an intricate history. It was first spelled in a hyphenated form as an adjective (*thermo-dynamic*) in 1849 and from 1854 to 1859 as the hyphenated noun *thermo-dynamics* to represent the science of heat and motive power and thereafter as *thermodynamics*.

The components of the word *thermo-dynamic* are derived from the Greek words θέρμη *therme*, meaning "heat," and δύναμις *dynamis*, meaning "power" (Haynie claims that the word was coined around 1840).[31]

The term ***thermo-dynamic*** was first used in January 1849 by William Thomson, later Lord Kelvin, in the phrase *a perfect thermo-dynamic engine* to describe Sadi Carnot's heat engine.[:545] In April 1849, Thomson added an appendix to his paper and used the term ***thermodynamic*** in the phrase *the object of a thermodynamic engine*.[:569]

Pierre Perrot claims that the term *thermodynamics* was coined by James Joule in 1858 to designate the science of relations between heat and power. Joule, however, never used that term, but did use the term *perfect thermo-dynamic engine* in reference to Thomson's 1849 phraseology,[:545] and Thomson's note on Joules' 1851 paper *On the Air-Engine*.

In 1854, ***thermo-dynamics***, as a functional term to denote the general study of the action of heat, was first used by William Thomson in his paper "On the Dynamical Theory of Heat".

In 1859, the closed compound form ***thermodynamics*** was first used by William Rankine in *A Manual of the Steam Engine* in a chapter on the Principles of Thermodynamics.

Branches of description

Thermodynamic systems are theoretical constructions used to model physical systems that exchange matter and energy in terms of the laws of thermodynamics. The study of thermodynamical systems has developed into several related branches, each using a different fundamental model as a theoretical or experimental basis, or applying the principles to varying types of systems.

Classical thermodynamics

Classical thermodynamics accounts for the adventures of a thermodynamic system in terms, either of its time-invariant equilibrium states, or else of its continually repeated cyclic processes, but, formally, not both in the same account. It uses only time-invariant, or equilibrium, macroscopic quantities measurable in the laboratory, counting as time-invariant a long-term time-average of a quantity, such as a flow, generated by a continually repetitive process.[32][33] In classical thermodynamics, rates of change are not admitted as variables of interest. An equilibrium state stands endlessly without change over time, while a continually repeated cyclic process runs endlessly without a net change in the system over time.

In the account in terms of equilibrium states of a system, a state of thermodynamic equilibrium in a simple system is spatially homogeneous.

In the classical account solely in terms of a cyclic process, the spatial interior of the 'working body' of that process is not considered; the 'working body' thus does not have a defined internal thermodynamic state of its own because no assumption is made that it should be in thermodynamic equilibrium; only its inputs and outputs of energy as heat and work are considered.[34] It is common to describe a cycle theoretically as composed of a sequence of very many thermodynamic operations and processes. This creates a link to the description in terms of equilibrium states. The cycle is then theoretically described as a continuous progression of equilibrium states.

Classical thermodynamics was originally concerned with the transformation of energy in a cyclic process, and the exchange of energy between closed systems defined only by their equilibrium states. The distinction between transfers of energy as heat and as work was central.

As classical thermodynamics developed, the distinction between heat and work became less central. This was because there was more interest in open systems, for which the distinction between heat and work is not simple, and is beyond the scope of the present article. Alongside the amount of heat transferred as a fundamental quantity, entropy was gradually found to be a more generally applicable concept, especially when considering chemical reactions. Massieu in 1869 considered entropy as the basic dependent thermodynamic variable, with energy potentials and the reciprocal of the thermodynamic temperature as fundamental independent variables. Massieu functions can be useful in present-day non-equilibrium thermodynamics. In 1875, in the work of Josiah Willard Gibbs, entropy was considered a fundamental independent variable, while internal energy was a dependent variable.[35]

All actual physical processes are to some degree irreversible. Classical thermodynamics can consider irreversible processes, but its account in exact terms is restricted to variables that refer only to initial and final states of thermodynamic equilibrium, or to rates of input and output that do not change with time. For example, classical thermodynamics can consider time-average rates of flows generated by continually repeated irreversible cyclic processes. Also it can consider irreversible changes between equilibrium states of systems consisting of several phases (as defined below in this article), or with removable or replaceable partitions. But for systems that are described in terms of equilibrium states, it considers neither flows, nor spatial inhomogeneities in simple systems with no externally imposed force fields such as gravity. In the account in terms of equilibrium states of a system, descriptions of irreversible processes refer only to initial and final static equilibrium states; the time it takes to change thermodynamic state is not considered.[36][37]

Local equilibrium thermodynamics

Local equilibrium thermodynamics is concerned with the time courses and rates of progress of irreversible processes in systems that are smoothly spatially inhomogeneous. It admits time as a fundamental quantity, but only in a restricted way. Rather than considering time-invariant flows as long-term-average rates of cyclic processes, local equilibrium thermodynamics considers time-varying flows in systems that are described by states of local thermodynamic equilibrium, as follows.

For processes that involve only suitably small and smooth spatial inhomogeneities and suitably small changes with time, a good approximation can be found through the assumption of local thermodynamic equilibrium. Within the large or global region of a process, for a suitably small local region, this approximation assumes that a quantity known as the entropy of the small local region can be defined in a particular way. That particular way of definition of entropy is largely beyond the scope of the present article, but here it may be said that it is entirely derived from the concepts of classical thermodynamics; in particular, neither flow rates nor changes over time are admitted into the definition of the entropy of the small local region. It is assumed without proof that the instantaneous global entropy of a non-equilibrium system can be found by adding up the simultaneous instantaneous entropies of its constituent small local regions. Local equilibrium thermodynamics considers processes that involve the time-dependent production of entropy by dissipative processes, in which kinetic energy of bulk flow and chemical potential energy are converted into internal energy at time-rates that are explicitly accounted for. Time-varying bulk flows and specific diffusional flows are considered, but they are required to be dependent variables, derived only from material properties described only by static macroscopic equilibrium states of small local regions. The independent state variables of a small local region are only those of classical thermodynamics.

Generalized or extended thermodynamics

Like local equilibrium thermodynamics, generalized or extended thermodynamics also is concerned with the time courses and rates of progress of irreversible processes in systems that are smoothly spatially inhomogeneous. It describes time-varying flows in terms of states of suitably small local regions within a global region that is smoothly spatially inhomogeneous, rather than considering flows as time-invariant long-term-average rates of cyclic processes. In its accounts of processes, generalized or extended thermodynamics admits time as a fundamental quantity in a more far-reaching way than does local equilibrium thermodynamics. The states of small local regions are defined by macroscopic quantities that are explicitly allowed to vary with time, including time-varying flows. Generalized thermodynamics might tackle such problems as ultrasound or shock waves, in which there are strong spatial inhomogeneities and changes in time fast enough to outpace a tendency towards local thermodynamic equilibrium. Generalized or extended thermodynamics is a diverse and developing project, rather than a more or less completed subject such as is classical thermodynamics.[38][39]

For generalized or extended thermodynamics, the definition of the quantity known as the entropy of a small local region is in terms beyond those of classical thermodynamics; in particular, flow rates are admitted into the definition of the entropy of a small local region. The independent state variables of a small local region include flow rates, which are not admitted as independent variables for the small local regions of local equilibrium thermodynamics.

Outside the range of classical thermodynamics, the definition of the entropy of a small local region is no simple matter. For a thermodynamic account of a process in terms of the entropies of small local regions, the definition of entropy should be such as to ensure that the second law of thermodynamics applies in each small local region. It is often assumed without proof that the instantaneous global entropy of a non-equilibrium system can be found by adding up the simultaneous instantaneous entropies of its constituent small local regions. For a given physical process, the selection of suitable independent local non-equilibrium macroscopic state variables for the construction of a thermodynamic description calls for qualitative physical understanding, rather than being a simply mathematical problem concerned with a uniquely determined thermodynamic description. A suitable definition of the entropy of a small local region depends on the physically insightful and judicious selection of the independent local non-equilibrium macroscopic state variables, and different selections provide different generalized or extended thermodynamical accounts of one and the same given physical process. This is one of the several good reasons for considering entropy as an epistemic physical variable, rather than as a simply material quantity. According to a respected author: "There is no compelling reason to believe that the classical thermodynamic entropy is a measurable property of nonequilibrium phenomena, ..."[40]

Statistical thermodynamics

Statistical thermodynamics, also called statistical mechanics, emerged with the development of atomic and molecular theories in the second half of the 19th century and early 20th century. It provides an explanation of classical thermodynamics. It considers the microscopic interactions between individual particles and their collective motions, in terms of classical or of quantum mechanics. Its explanation is in terms of statistics that rest on the fact the system is composed of several species of particles or collective motions, the members of each species respectively being in some sense all alike.

Thermodynamic equilibrium

Equilibrium thermodynamics studies transformations of matter and energy in systems at or near thermodynamic equilibrium. In thermodynamic equilibrium, a system's properties are, by definition, unchanging in time. In thermodynamic equilibrium no macroscopic change is occurring or can be triggered; within the system, every microscopic process is balanced by its opposite; this is called the principle of detailed balance. A central aim in equilibrium thermodynamics is: given a system in a well-defined initial state, subject to specified constraints, to calculate what the equilibrium state of the system is.[41]

In theoretical studies, it is often convenient to consider the simplest kind of thermodynamic system. This is defined variously by different authors.[42][43][44][45] For the present article, the following definition is convenient, as abstracted from the definitions of various authors. A region of material with all intensive properties continuous in space and time is called a phase. A simple system is for the present article defined as one that consists of a single phase of a pure chemical substance, with no interior partitions.

Within a simple isolated thermodynamic system in thermodynamic equilibrium, in the absence of externally imposed force fields, all properties of the material of the system are spatially homogeneous.[46] Much of the basic theory of thermodynamics is concerned with homogeneous systems in thermodynamic equilibrium.[47]

Most systems found in nature or considered in engineering are not in thermodynamic equilibrium, exactly considered. They are changing or can be triggered to change over time, and are continuously and discontinuously subject to flux of matter and energy to and from other systems. For example, according to Callen, "in absolute thermodynamic equilibrium all radioactive materials would have decayed completely and nuclear reactions would have transmuted all nuclei to the most stable isotopes. Such processes, which would take cosmic times to complete, generally can be ignored.". Such processes being ignored, many systems in nature are close enough to thermodynamic equilibrium that for many purposes their behaviour can be well approximated by equilibrium calculations.

Quasi-static transfers between simple systems are nearly in thermodynamic equilibrium and are reversible

It very much eases and simplifies theoretical thermodynamical studies to imagine transfers of energy and matter between two simple systems that proceed so slowly that at all times each simple system considered separately is near enough to thermodynamic equilibrium. Such processes are sometimes called quasi-static and are near enough to being reversible.[48][49]

Natural processes are partly described by tendency towards thermodynamic equilibrium and are irreversible

If not initially in thermodynamic equilibrium, simple isolated thermodynamic systems, as time passes, tend to evolve naturally towards thermodynamic equilibrium. In the absence of externally imposed force fields, they become homogeneous in all their local properties. Such homogeneity is an important characteristic of a system in thermodynamic equilibrium in the absence of externally imposed force fields.

Many thermodynamic processes can be modeled by compound or composite systems, consisting of several or many contiguous component simple systems, initially not in thermodynamic equilibrium, but allowed to transfer mass and energy between them. Natural thermodynamic processes are described in terms of a tendency towards thermodynamic equilibrium within simple systems and in transfers between contiguous simple systems. Such natural processes are irreversible.[50]

Non-equilibrium thermodynamics

Non-equilibrium thermodynamics[51] is a branch of thermodynamics that deals with systems that are not in thermodynamic equilibrium; it is also called thermodynamics of irreversible processes.

Laws of thermodynamics

Main article: 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.*

This statement 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.[52] 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.[53] Empirical temperatures lead to calorimetry for heat transfer in terms of the mechanical properties of bodies, without reliance on mechanical concepts of energy.

The physical content of the zeroth law has long been recognized. For example, Rankine in 1853 defined temperature as follows: "Two portions of matter are said to have equal temperatures when neither tends to communicate heat to the other."[54] Maxwell in 1872 stated a "Law of Equal Temperatures".[55] He also stated: "All Heat is of the same kind."[56] Planck explicitly assumed and stated it in its customary present-day wording in his formulation of the first two laws.[57] By the time the desire arose to number it as a law, the other three had already been assigned numbers, and so it was designated the *zeroth law*.

- 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 the system:* $\Delta U = Q - W$ [58][59][60][61][62][63][64][65][66] (Note that due to the ambiguity of what constitutes positive work, some sources state that $\Delta U = Q + W$, in which case work done on the system is positive.)

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 (see Thermodynamic state) 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.[67][68][69][70]

- Second law of thermodynamics: *Heat cannot spontaneously flow from a colder location to a hotter location.*

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.

- Third law of thermodynamics: *As a system approaches absolute zero the entropy of the system approaches a minimum value.*

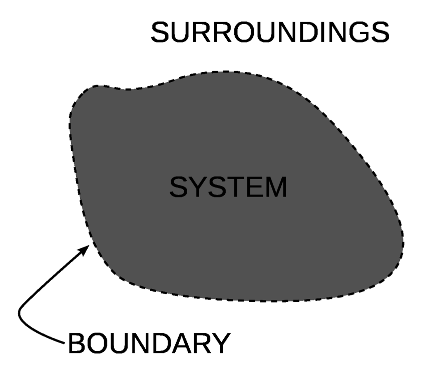
The third law of thermodynamics is a statistical law of nature regarding entropy and the impossibility of reaching absolute zero of temperature. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is the absolute entropy. Alternate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

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

System models

Types of transfers permitted

type of partition	type of transfer		
	Mass and energy	Work	Heat
permeable to matter	✓	✗	✗
permeable to energy but impermeable to matter	✗	✓	✓
adiabatic	✗	✓	✗
adynamic and impermeable to matter	✗	✗	✓
isolating	✗	✗	✗



A diagram of a generic thermodynamic system

The thermodynamic system is an important concept of thermodynamics. It is 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 actual, or merely notional and fictive, but by convention delimits a finite volume. Transfers of work, heat, or matter between the system and the surroundings take place across this boundary, which may or may not have properties that restrict what can be transferred across it. A system may have several distinct boundary sectors or partitions separating it from the surroundings, each characterized by how it restricts transfers, and being permeable to its characteristic transferred quantities.

The volume can be the region surrounding a single atom resonating energy, as Max Planck defined in 1900;Wikipedia:Citation needed it can be a body of steam or air in a steam engine, such as Sadi Carnot defined in 1824; it can be the body of a tropical cyclone, as Kerry Emanuel theorized in 1986 in the field of atmospheric thermodynamics; it could also be just one nuclide (i.e. a system of quarks) as hypothesized in quantum thermodynamics.

Anything that passes across the boundary needs to be accounted for in a proper transfer balance equation. Thermodynamics is largely about such transfers.

Boundary sectors are of various characters: rigid, flexible, fixed, moveable, actually restrictive, and fictive or not actually restrictive. For example, in an engine, a fixed boundary sector means the piston is locked at its position; then no pressure-volume work is done across it. In that same engine, a moveable boundary allows the piston to move in and out, permitting pressure-volume work. There is no restrictive boundary sector for the whole earth including its atmosphere, and so roughly speaking, no pressure-volume work is done on or by the whole earth system. Such a system is sometimes said to be diabatically heated or cooled by radiation.[71][72]

Thermodynamics distinguishes classes of systems by their boundary sectors.

- An **open** system has a boundary sector that is permeable to matter; such a sector is usually permeable also to energy, but the energy that passes cannot in general be uniquely sorted into heat and work components. Open system boundaries may be either actually restrictive, or else non-restrictive.
- A **closed** system has no boundary sector that is permeable to matter, but in general its boundary is permeable to energy. For closed systems, boundaries are totally prohibitive of matter transfer.
- An **adiabatically isolated** system has only adiabatic boundary sectors. Energy can be transferred as work, but transfers of matter and of energy as heat are prohibited.
- A **purely diathermically isolated** system has only boundary sectors permeable only to heat; it is sometimes said to be adynamically isolated and closed to matter transfer. A process in which no work is transferred is sometimes called adynamic.[73]
- An **isolated** system has only isolating boundary sectors. Nothing can be transferred into or out of it.

Engineering and natural processes are often described as composites of many different component simple systems, sometimes with unchanging or changing partitions between them. A change of partition is an example of a thermodynamic operation.

States and processes

There are four fundamental kinds of entity in thermodynamics—states of a system, walls between systems, thermodynamic processes, and thermodynamic operations. 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".[74][75][76] 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.[77] 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.[78][79]

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",[80] 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.[81]

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.[82][83]

An intensive variable is one that is unchanged with the thermodynamic operation of scaling of a system.

An extensive variable is one that simply scales with the scaling of a system, without the further requirement used just below here, of additivity even when there is inhomogeneity of the added systems.

Examples of extensive thermodynamic variables are total mass and total volume. Under the above definition, entropy is also regarded as an extensive variable. 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. Physical macroscopic variables can be mechanical, material, or thermal. Temperature is a thermal variable; according to Guggenheim, "the most important conception in thermodynamics is temperature."

Intensive variables have 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.[84] In other words, intensive variables are not altered by the thermodynamic operation of scaling.

For the immediately present account just below, an alternative definition of extensive variables is considered, that requires 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. Examples of extensive variables in this alternative definition are mass, volume, and internal energy. They depend on the total quantity of mass in the system.[85] In other words, although extensive variables scale with the system under the thermodynamic operation of scaling, nevertheless the present alternative definition of an extensive variable requires more than this: it requires also its additivity regardless of the inhomogeneity (or equality or inequality of the values of the intensive variables) of the component systems.

Though, when it can be properly defined, density of entropy is an intensive variable, for inhomogeneous systems, entropy itself does not fit into this alternative classification of state variables.[86][87] 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 immediately present definition of an extensive variable.

Being neither an intensive variable nor an extensive variable according to the immediately present 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.[88] 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.[89] 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. For the immediately present account, systems with multiple phases are not considered, though for many thermodynamic questions, multiphase systems are important.

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 between states of thermodynamic equilibrium

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.[90] 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.[91]

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.[92][93][94][95] Another example is in separation and mixing of gases, with use of chemically semi-permeable membranes.[96]

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. Such isentropic conduct of a process seems called for when the entropy of the system is considered as an independent variable, as for example when the internal energy is considered as a function of the entropy and volume of the system, the natural variables of the internal energy as studied by Gibbs.
- 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

It is sometimes of interest to study a process in which several variables are controlled, subject to some specified constraint. In a system in which a chemical reaction can occur, for example, in which the pressure and temperature can affect the equilibrium composition, a process might occur in which temperature is held constant but pressure is slowly altered, just so that chemical equilibrium is maintained all the way. There is a corresponding process at constant temperature in which the final pressure is the same but is reached by a rapid jump. Then it can be shown that the volume change resulting from the rapid jump process is smaller than that from the slow equilibrium process. The work transferred differs between the two processes.

Account in terms of cyclic processes

A cyclic process[] is a process that can be repeated indefinitely often without changing the final state of the system in which the process occurs. The only traces of the effects of a cyclic process are to be found in the surroundings of the system or in other systems. This is the kind of process that concerned early thermodynamicists such as Sadi Carnot, and in terms of which Kelvin defined absolute temperature,[97] before the use of the quantity of entropy by Rankine and its clear identification by Clausius.[98] For some systems, for example with some plastic working substances, cyclic processes are practically nearly unfeasible because the working substance undergoes practically irreversible changes.[99] This is why mechanical devices are lubricated with oil and one of the reasons why electrical devices are often useful.

A cyclic process of a system requires in its surroundings at least two heat reservoirs at different temperatures, one at a higher temperature that supplies heat to the system, the other at a lower temperature that accepts heat from the system. The early work on thermodynamics tended to use the cyclic process approach, because it was interested in machines that converted some of the heat from the surroundings into mechanical power delivered to the surroundings, without too much concern about the internal workings of the machine. Such a machine, while receiving an amount of heat from a higher temperature reservoir, always needs a lower temperature reservoir that accepts some lesser amount of heat. The difference in amounts of heat is equal to the amount of heat converted to work.[] Later, the internal workings of a system became of interest, and they are described by the states of the system. Nowadays, instead of arguing in terms of cyclic processes, some writers are inclined to derive the concept of absolute temperature from the concept of entropy, a variable of state.

Instrumentation

There are two types of thermodynamic instruments, the **meter** and the **reservoir**. A thermodynamic meter is any device that measures any parameter of a thermodynamic system. In some cases, the thermodynamic parameter is actually defined in terms of an idealized measuring instrument. For example, the zeroth law states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. This principle, as noted by James Maxwell in 1872, asserts that it is possible to measure temperature. An idealized thermometer is a sample of an ideal gas at constant pressure. From the ideal gas law $PV=nRT$, the volume of such a sample can be used as an indicator of temperature; in this manner it defines temperature. Although pressure is defined mechanically, a pressure-measuring device, called a barometer may also be constructed from a sample of an ideal gas held at a constant temperature. A calorimeter is a device that measures and define the internal energy of a system.

A thermodynamic reservoir is a system so large that it does not appreciably alter its state parameters when brought into contact with the test system. It is used to impose a particular value of a state parameter upon the system. For example, a pressure reservoir is a system at a particular pressure, which imposes that pressure upon any test system that it is mechanically connected to. The Earth's atmosphere is often used as a pressure reservoir.

Conjugate variables

Main article: 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:

Name	Symbol	Formula	Natural variables
Internal energy			
Helmholtz free energy			
Enthalpy			
Gibbs free energy			
Landau Potential (Grand potential)	,		

where is the temperature, the entropy, the pressure, the volume, the chemical potential, the number of particles in the system, and is the count of particles types in the system.

Thermodynamic potentials can be derived from the energy balance equation applied to a thermodynamic system. Other thermodynamic potentials can also be obtained through Legendre transformation.

Axiomatics

Most accounts of thermodynamics presuppose the law of conservation of mass, sometimes with,[100] and sometimes without,[101][102] explicit mention. Particular attention is paid to the law in accounts of non-equilibrium thermodynamics.[103][104] One statement of this law is "The total mass of a closed system remains constant." Another statement of it is "In a chemical reaction, matter is neither created nor destroyed."[105] Implied in this is that matter and energy are not considered to be interconverted in such accounts. The full generality of the law of conservation of energy is thus not used in such accounts.

In 1909, Constantin Carathéodory presented a purely mathematical axiomatic formulation, a description often referred to as *geometrical thermodynamics*, and sometimes said to take the "mechanical approach" to thermodynamics. The Carathéodory formulation is restricted to equilibrium thermodynamics and does not attempt to deal with non-equilibrium thermodynamics, forces that act at a distance on the system, or surface tension effects.[106] Moreover, Carathéodory's formulation does not deal with materials like water near 4 °C, which have a density extremum as a function of temperature at constant pressure.[107][108] Carathéodory used the law of conservation of energy as an axiom from which, along with the contents of the zeroth law, and some other assumptions including his own version of the second law, he derived the first law of thermodynamics. Consequently, one might also describe Carathėodory's work as lying in the field of energetics,[109] which is broader than thermodynamics. Carathéodory presupposed the law of conservation of mass without explicit mention of it.

Since the time of Carathėodory, other influential axiomatic formulations of thermodynamics have appeared, which like Carathéodory's, use their own respective axioms, different from the usual statements of the four laws, to derive the four usually stated laws.[110][111][112]

Many axiomatic developments assume the existence of states of thermodynamic equilibrium and of states of thermal equilibrium. States of thermodynamic equilibrium of compound systems allow their component simple systems to exchange heat and matter and to do work on each other on their way to overall joint equilibrium. Thermal equilibrium allows them only to exchange heat. The physical properties of glass depend on its history of being heated and cooled and, strictly speaking, glass is not in thermodynamic equilibrium.[113]

According to Herbert Callen's widely cited 1985 text on thermodynamics: "An essential prerequisite for the measurability of energy is the existence of walls that do not permit transfer of energy in the form of heat.".[114] According to Werner Heisenberg's mature and careful examination of the basic concepts of physics, the theory of heat has a self-standing place.[115]

From the viewpoint of the axiomatist, there are several different ways of thinking about heat, temperature, and the second law of thermodynamics. The Clausius way rests on the empirical fact that heat is conducted always down, never up, a temperature gradient. The Kelvin way is to assert the empirical fact that conversion of heat into work by cyclic processes is never perfectly efficient. A more mathematical way is to assert the existence of a function of state called the entropy that tells whether a hypothesized process occurs spontaneously in nature. A more abstract way is that of Carathéodory that in effect asserts the irreversibility of some adiabatic processes. For these different ways, there are respective corresponding different ways of viewing heat and temperature.

The Clausius–Kelvin–Planck way This way prefers ideas close to the empirical origins of thermodynamics. It presupposes transfer of energy as heat, and empirical temperature as a scalar function of state. According to Gislason and Craig (2005): "Most thermodynamic data come from calorimetry..."[116] According to Kondepudi (2008): "Calorimetry is widely used in present day laboratories."[117] In this approach, what is often currently called the zeroth law of thermodynamics is deduced as a simple consequence of the presupposition of the nature of heat and empirical temperature, but it is not named as a numbered law of thermodynamics. Planck attributed this point of view to Clausius, Kelvin, and Maxwell. Planck wrote (on page 90 of the seventh edition, dated 1922, of his treatise) that he thought that no proof of the second law of thermodynamics could ever work that was not based on the impossibility of a perpetual motion machine of the second kind. In that treatise, Planck makes no mention of the 1909 Carathéodory way, which was well known by 1922. Planck for himself chose a version of what is just above called the Kelvin way.[118] The development by Truesdell and Bharatha (1977) is so constructed that it can deal naturally with cases like that of water near 4 °C.

The way that assumes the existence of entropy as a function of state This way also presupposes transfer of energy as heat, and it presupposes the usually stated form of the zeroth law of thermodynamics, and from these two it deduces the existence of empirical temperature. Then from the existence of entropy it deduces the existence of absolute thermodynamic temperature.

The Carathéodory way This way presupposes that the state of a simple one-phase system is fully specifiable by just one more state variable than the known exhaustive list of mechanical variables of state. It does not explicitly name empirical temperature, but speaks of the one-dimensional "non-deformation coordinate". This satisfies the definition of an empirical temperature, that lies on a one-dimensional manifold. The Carathéodory way needs to assume moreover that the one-dimensional manifold has a definite sense, which determines the direction of irreversible adiabatic process, which is effectively assuming that heat is conducted from hot to cold. This way presupposes the often currently stated version of the zeroth law, but does not actually name it as one of its axioms. According to one author, Carathéodory's principle, which is his version of the second law of thermodynamics, does not imply the increase of entropy when work is done under adiabatic conditions (as was noted by Planck[119]). Thus Carathéodory's way leaves unstated a further empirical fact that is needed for a full expression of the second law of thermodynamics.[120]

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.[121]

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.[122][123][124] 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.[125][126]

Applied fields

- Atmospheric thermodynamics
- Biological thermodynamics
- Black hole thermodynamics
- Chemical thermodynamics
- Equilibrium thermodynamics
- Geology
- Industrial ecology (re: Exergy)
- Maximum entropy thermodynamics
- Non-equilibrium thermodynamics
- Philosophy of thermal and statistical physics
- Psychrometrics
- Quantum thermodynamics
- Statistical thermodynamics
- Thermoeconomics

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