Publisher's Note

Grey House Publishing is pleased to add *Principles of Physics* to its Salem Press collection, the second of four titles in a new *Principles of* series: Chemistry, Physics, Astronomy, and Computer Science. This new resource introduces students and researchers to the fundamentals of physics using easy-to-understand language, giving readers a solid start and deeper understanding and appreciation of this complex subject.

The 142 entries range from Aberrations to X-rays and are arranged in an A to Z order, making it easy to find the topic of interest. Entries include the following:

- Related fields of study to illustrate the connections between the various branches of physics, including acoustics, high energy physics, psychophysics, quantum electrodynamics, and nanotechnonlogy;
- A brief, concrete summary of the topic and how the entry is organized;
- Principal terms that are fundamental to the discussion and to understanding the concepts presented;
- Illustrations that clarify difficult concepts via models, diagrams, and charts of such key topics as blackbody radiation, Bernouilli's principle, and Higgs boson;
- Equations that demonstrate how to determine mechanical advantage, understand the ideal gas law, the fundamentals of quantum mechanics, and Einstein's famous mass-energy equation—$E= mc^2$;
- Photographs of significant contributors to the study of physics;
- Sample problems that further demonstrate the concept, law, or constant presented;
- Bibliography lists that relate to the entry.

This reference work begins with a comprehensive introduction to the field, written by editor Donald R. Franceschetti, PhD. It starts with the ancient Greeks' quest to understand motion, both on earth and in the heavens, includes Einstein and the *annus mirabilis* and J. Robert Oppenheimer, the father of the atom bomb and a discussion of how vacuum tubes and digital processesors have fundamentally changed the way we live, and ends with a discussion of the challenge and the promise of physics education in today's high schools.

The book's backmatter is another valuable resource and includes:

- The Standard Model, a discussion of the key discoveries and concepts that led to a growing understanding of subatomic particles and the electromagnetic, strong, and weak interaction;
- Nobel Notes that explain the significance of the prizes in physics to the study of the science and their interdisciplinary nature;
- Nobel Prize Laureates in the area of physics from the first awards in 1901, given to William Conrad Röntgen to the prize awarded in 2015 to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass";
- Pre-Nobel Notables, recognizing some of the important figures in physics who did not receive a Nobel Prize;
- Physics Constants, showing their symbols, names, and values;
- Physics Laws;
- Glossary;
- General bibliography; and
- Subject index.

Grey House Publishing extends its appreciation to all involved in the development and production of this work. The entries have been written by experts in the field. Their names and affiliations follow the Editor's Introduction.

Principles of Physics, as well as all Salem Press titles, is available in print and as an e-book. Please visit www.salempress.com for more information.

Editor's Introduction

Natural philosophy, an antecedent to the field of study we now know as physics, was the term applied by the Ancient Greeks to the study of nature. Whenever they were asking questions or making direct observations about the nature of the world in which they lived–whether they were trying to understand why an arrow falls or why water rises when it is displaced by an object–they were engaged in a form of study we can readily identify as the direct precursor of all of the natural sciences. Natural philosophy itself gave direct rise to the study of physics; when one considers how long we have been studying and questioning our physical world, it is easy to see that the study of physics is actually far older than one might suppose. Physics is often referred to as the "foundation science," not merely because it is one of the oldest of the sciences but also because it has become essential to the study of so many of the natural sciences, from chemistry to geology to biology.

But what exactly is physics? Clearly physics is a science, so we might first attempt to answer the question, "What is a science?" Over 50 years ago, Nobel Laureate Richard P. Feynman, lecturing to Caltech students, attempted to answer that question by suggesting that science is like watching a complex game that is being played at high speed, chess perhaps, and trying to deduce the rules of the game from what you see. While you are permitted to rearrange the game board a little (i.e., do an experiment), there are stringent limits on the observations that can be made.

Physics—The Foundation Science

We can think of physics as a search for nature's rule book and an attempt to learn the principles that underly observable events and phenomona. While people have wondered about and tried to understand falling bodies and the paths taken by arrows on the way to their targets since earliest times, the ancient Greeks were among the first to think about "motion" in the abstract. Some historians of science see the origins of physical theory in the debate between two pre-Socratic Greeks philosophers: Heraclitus, who held that all was in flux, and Parmenides, who claimed that all change is illusory.

Many people would argue that the beginnings of physics as a science may be traced back to Plato's *Timaeus*, one of his famous dialogs, written in 360 C.E. This work speculates on the ultimate constituents of matter. But it was Aristotle, Plato's student, who introduced the term *physics* and stressed the importance of observation. While Aristotle deserves credit for careful analytical thought about motion, he also deserves some level of blame for misleading conclusions. Perhaps most far-reaching and long-lasting of these incorrect conclusions was the distinction between motion in the heavens and motion on earth. As Aristotle watched the stars parade across the night sky, he made a natural assumption that the stars were somehow attached (fixed) to a celestial sphere. As he watched the planets move against the background of these "fixed" stars, it seemed only natural to conceive a cosmology based on spheres within spheres. Even Copernicus, writing *On the Revolution of the Heavenly Orbs* two thousand years later, was still influenced, at least to some degree, by these same mental images.

We now know that the Greeks made several natural, but serious, errors in classifying motion. The Greeks, masters of mathematics, made a distinction between motions in the celestial and terrestrial realms. They assumed that motions in the celestial realm were perfect and therefore different from motions in the terrestrial realm, which they believed were necessarily imperfect. They also believed that mathematics, being perfect, could not be applied to terrestrial motions. While their mathematical prowess allowed Greek astronomy to flourish, the practical result of drawing a distinction between a "perfect" celestial realm and an "imperfect" terrestrial realm meant that Greek physics languished.

Yet another problem arose from the fact that the Greeks interpreted motions teleologically, i.e. as resulting from an object's desire to achieve a certain end. Thus, they assumed that the path taken by falling bodies represented the desires of the bodies. Heavy objects "wanted" to be as near as possible to the center of the earth. The weight of an object represented the strength of its desire to be on the earth's surface. This may seems reasonable enough but, as Galileo would point out centuries later, it fails to explain the constant acceleration of a falling body when air resistance can be removed from consideration.

The Scientific Revolution

It would be an error to assume no progress occurred in physics during the Middle Ages, but the birth of physics in the modern sense can rightly be assigned to the period of time referred to as the late Renaissance and is most especially associated with the work of a Florentine Italian, Galileo Galilei, and an Englishman, Sir Isaac Newton.

Galileo was born in 1564, twenty-one years after the death of Copernicus, whose deathbed publication of *De Revolutionibus Orbium Coelestim* proposed the heliocentric model of the solar system as a computational aid for the calendar. Galileo was professor of mathematics at Pisa, and later Padua, and one of the first to embrace the use of experiments to expand our knowledge of the physical world. Galileo differed from Copernicus in that he wrote in the dialog form made famous by Plato and in the vernacular Italian, making it easier to appeal to the broader (but still educated) public, rather than the more limited world of academics capable of reading Corpernicus in Latin. Like Copernicus, however, Galileo eventually incurred the displeasure of Church leaders of the time, who put him on trial in 1633. By the time Galileo died, he was under house arrest and his theories had been officially condemned by the Church.

Isaac Newton was born in 1642, less than a year after Galileo's death. As Protestant, Newton did not have to worry about his reception in Catholic countries. Newton was a unique and most complex personality. He never married, but wrote voluminously on religion, the Bible, history, alchemy and physics. He did not write in vernacular English but rather, for the most part, in scholarly Latin. There is a story that Newton, who had been appointed a Professor of Mathematics at Cambridge University, was not a very good teacher. He would often lecture (in Latin) to an empty room, since the condition of his employment was that he lecture three times a week, whether or not anyone attended his classes. His *magnum opus*, the *Principia Mathematica Philosophiae Naturalis,* was not fully published in English until after his death. Newton began with Galileo's principle of inertia, and then he added a second and third law of motion and a law of universal gravitation. These additional laws allowed him to deal with both celestial and terrestrial motions.

Over the succeeding years, mathematicians developed methods to apply Newton's laws in numerous cases: The anomalies they saw in the orbit of Uranus allowed them to calculate the position of a new planet, Neptune. In 1930, careful measurements of Neptune's orbit made it possible for them to locate Pluto. In more recent days, some 2000 extra-solar planets have been found using those same mathematical techniques, coupled with the more highly accurate data provided by the Hubble telescope.

It is difficult to fully appreciate the impact of Newton's laws on the evolution of human culture. Consider the Church's arguments for the existence of God: Writing in the thirteenth century, St. Thomas Aquinas included a proof from motion among his five proofs for the existence of God. Aquinas claimed that every object that moved was either moved by itself or moved by another agent. In Aquinas's thinking, God was—among a great many other things—the unmoved mover who was ultimately responsible for motion in the universe. But according to Galileo's principle of inertia and Newton's second law, an explanation was required only for *changes* in motion. Further, the law of universal gravitation said that there was nothing special about the center of the earth and that all masses should be attracted to it since every mass in the universe attracts every other mass with a force that is proportional to the product of the masses divided by the square of the distance between them.

Newton was one of the first individuals elected to membership in the Royal Society, so named because it functioned under the patronage of the King. Its charter eschewed "meddling in metaphysics, rhetoric, etc." and instead adhered to testable propositions. Thus, the physics of Newton became one of the pillars of the Industrial Revolution.

Impact of the Steam Engine & Thermodynamics

In addition to the theory of testable propositions, the steam engine was also responsible for driving the Industrial Revolution. This new power source, first devised by Thomas Savery in 1689 and then much improved by a number of individuals, most notably James Watt, was the first source of motive force that was independent from human or animal muscle power or a force of nature like the wind or falling water. Steam engines were, therefore, relatively location independent. This advance came with some significant environmental costs, including widespread deforestation of the countryside as well as coal-mining that removed coal from the ground at an alarming rate. Eventually, mineshafts that had been stripped of their coal began to fill with rainwater and a major technological challenge became finding an answer to the pressing question of how to pump the water out. It rapidly became apparent that a column of water more than thirty feet in length cannot be drawn up a vertical pipe. This challenge spurred research into the behavior of gases, ultimately leading to the serious scientific study of the gas laws and thermodynamics.

At the time, scientists were still arguing about whether there was any value in a theory dealing with entities too small to be seen, so the atomic theory was not an initial part of thermodynamics. At first, then, heat was seen as an imponderable fluid that flowed from hot to cold, filling objects according to their "heat capacity." Today, we understand heat to be random atomic motion, but it was not until the twentieth century that this understanding would become fully established.

Voltaic Cells & the Study of Optics

The voltaic cell, developed just before the year 1800 C.E., offered scientists yet another source of power. Although electric and magnetic phenomena had been known since 600 B.C.E., and a magnetic compass had been used by Chinese sailors since around the year 1100 C.E., electric and magnetic forces continued to be a mystery until the early nineteenth century. Once the voltaic cell was invented, however, discovery in the area of electromagnetism proceeded at a breathtaking pace. New elements could be isolated due to electrolysis. Discoveries were made about the behavior of electromagnets and the induction of an electric current when the magnetic flux through a coil was changed.

James Clerk Maxwell, a professor of physics at a Cambridge University in England, summarized what was known about electromagnetism in four differential equations, known today as Maxwell's equations. Maxwell then found that if he restricted the equations to empty space, electromagnetic disturbances could travel nonetheless, provided that they moved at the speed of light traveling in a vacuum. Thus the study of optics became a matter of electromagnetic theory. Equally important, there was no limitation to the frequency that light exhibited. Vast regions of the electromagnetic spectrum still had yet to be explored.

Nuclear Physics

The study of nuclear physics dates back little more than a century. The first three decades of the twentieth century, however, have been termed "the thirty years that shook physics." The year 1905 was particularly significant and has been termed the *annus mirabilis* (the year of miracles). It was in that year that Albert Einstein noted that it was not necessary that observers in relative motion with respect to each other agree on their length and time interval measurements. Indeed it would be impossible for them to do so, if the speed of light is to be independent of the velocity of the light source, as Maxwell's equations required. Further there were some incompatibilities involved in the idea that atoms, located at some point in space, could emit electromagnetic waves.

Analysis of the process used to locate a particle using light waves revealed that one could not precisely specify both the position and velocity of the particle at the same time. This led to the Heisenberg uncertainty principle and the emergence of quantum mechanics as the proper description of the interaction of atomic systems with the electromagnetic field.

By 1930, the three elementary particles—protons, neutrons, and electrons—had been discovered, as well as the first particle of antimatter, the positron. By that time, Ernest Rutherford had already scattered alpha particles from a sheet of gold leaf and found that, contrary to expectations, the positive charge in the atom was concentrated in a very tiny region known as the nucleus.

The community of physics researchers was quite small in 1930, but by 1939, Albert Einstein's discoveries had brought physics and physicists to the attention of President Franklin D. Roosevelt, which dramatically changed the situation. The natural radioactivity of the element uranium had been discovered by Henri Becquerel in 1896. The discovery first made by Lisa Meitner and Otto Hahn in 1934, that nuclei of 235-uranium could spontaneously break apart into smaller nuclei, and that particles emitted by a fissioning uranium nucleus could collide with other nuclei and stimulate their decay, led physicists to contemplate a chain reaction that could release immense power. In fact, it was that precise discovery that eventually triggered a massive program of military spending by the American government and ultimately resulted in the destruction of two Japanese cities and the loss of hundreds of thousands of lives in 1945.

The development of the atomic bomb had clearly changed the nature of warfare and state of international politics dramatically. Following World War II, many of the physics and chemistry professors who had been working for the government returned to their campuses to find things quite changed. The ability of the community of physicists to respond to a national crisis by producing a weapon unique in its destructive potential was a lesson not lost on the physics community, the military, or the politicians. The bombs dropped on Japanese cities with their incredible destructive power did not escape the notice of other nations around the world. Although the United States had a monopoly on atomic bombs for about four years following the bombing of Hiroshima and Nagasaki, the Soviet Union exploded its first atomic bomb in 1949, thus beginning its arms race against western countries.

The power of the first atomic bombs could be described in terms of tons of TNT equivalent. The first atomic explosion in New Mexico was described as having an explosive yield of more than 20 thousand tons of TNT. Scientists already knew that more energy was available from the fusion of smaller nuclei than the fission of large ones and eventually, the United States exploded its first thermonuclear, or hydrogen, bomb in 1952. The Soviet Union followed with their first hydrogen bomb the following year, in 1953. Now, instead of bombs with an explosive yield measured in the tens of thousands of tons of TNT, the explosive yields would be measured in tens of millions of tons of TNT.

Many Americans were suspicious of the speed with which the Soviets moved forward in the arms race. Those suspicions had significant ramifications that exposed the uneasy relationship between science, politics, and the government and which came to a head during the so-called McCarthy era, a time when people thought to have Communist sympathies were often persecuted without much evidence of wrongdoing. J. Robert Oppenheimer was one such person.

J. Robert Oppenheimer & the McCarthy Era

Today, we know Oppenheimer as the "father of the atomic bomb" because of the work he did as the director of the Los Alamos Laboratory during World War II. Born to a wealthy New York family in 1904, Opje (as he was called by all who knew him) was an extremely intelligent person. He completed his education in Europe and then took faculty positions at Caltech and Berkley upon his return to the United States. When he was not working, he busied himself with liberal political causes.

When the decision was made to pursue the development of an atomic bomb during World War II, the project was given the code name Manhattan Project. It was assigned to the U. S. Army under the supervision of Brigadier General Leslie Groves, who sought out Oppenheimer to be part of the effort. Oppenheimer's standing in the community of physicists was such that General Groves considered him indispensible. His propensity to get involved with liberal political causes made some of the lower-ranking officers involved in the project doubt his loyalty to the United States. Groves overruled them, however, and Oppenheimer was granted a security clearance.

The Manhattan Project demanded the utmost secrecy. It was so closely guarded that most people working on it were unaware of the project's ultimate goal. It was only at the Los Alamos Laboratory, a facility under the direction of Oppenheimer, that staff were aware that they were building a new weapon based on nuclear fission.

After the war, most of the project structure was dismantled and many of the leading physicists either returned to academia or took up lucrative appointments as government consultants for the Defense Department or Atomic Energy Commission (AEC), an agency established after the World War II by presidential order. Among the AEC's responsibilities was oversight of the system of national laboratories, seventeen in all. Staff members at those laboratories were charged with conducting scientific research, particularly in areas where research was too expensive and complex and had too many national security implications to be conducted on college campuses. The AEC instituted its own security clearance program and began to systematically screen almost all applicants for federal employment in the atomic energy area.

Oppenheimer himself assumed the directorship of the Institute for Advanced Study at Princeton, New Jersey, in 1947. At the same time, he took up the position of Chairman of General Advisory Committee of the AEC. Then, in December of 1953, at the height of the McCarthy Era, his security clearance was revoked by order of President Eisenhower. Oppenheimer requested an administrative hearing but, even though he was exonerated of any wrongdoing, the suspension of his clearance was upheld. Ultimately, President Lyndon Johnson presented him with the Enrico Fermi Award of the Atomic Energy Commission in 1963, a gesture that was widely interpreted as symbolically reinstating him to the good graces of the government.

By 1974, the AEC itself had come under attack, and it was dissolved by Congress. The Nuclear Regulatory Commission (NRC) was established by the Energy Reorganization Act of 1974 and began its operations on January 19, 1975. Today, the focus of the NRC is nuclear reactor safety as well as oversight and reviewing applications for new licenses.

Many comparisons have been made between the Oppenheimer case and that of Galileo four centuries earlier. While Oppenheimer was not tortured, he was branded a traitor in the minds of many. Other physicists saw the potential risks to their own careers and turned to nongovernmental employment. There were more than a few scientists who felt that the loss of life at Hiroshima and Nagasaki could not be justified, despite the fact that it won the war for the Allies. As Oppenheimer put it, physicists had "known sin" and the world would never be quite the same.

Vacuum Tube Electronics, the Computer, Solid State Devices, & Photolithography

Vacuum tube electronics and the digital computer have had a major effect on the development of physics as a science. Thomas Edison noticed that, if one heats a metal filament in vacuum, the filament tended to be surrounded by electrons that have boiled off the filament's surface. He recorded this in his laboratory notebook in 1883 and but did not pursue it further.

In 1904 Sir John Ambrose Fleming, who had visited Edison, was awarded a patent for a vacuum tube diode, which could rectify current. When an American scientist, Lee De Forrest, added a third element—a grid between the heated cathode and the anode—he was able to obtain a device in which a small voltage on the grid could control the current.

Meanwhile at Cambridge University, a young mathematical logician, Alan M. Turing, had developed the notion of a programmable digital computer while trying to solve a problem in pure mathematics. A few computers had been built using vacuum tubes in the years preceding World War II. These machines showed some promise but there were practical problems in using them for large-scale computation; the tubes burned out with some regularity. If each tube had a probability of burning out at the rate of only 0.01 per hour and if a machine had 1000 tubes, then the probability that the entire machine would have at least one tube fail in the first hour was greater than 50 percent.

For the computer to come into its own, it had to be more reliable and efficient than vacuum tube electronics allowed. An alternative to vacuum tube devices was provided by solid-state physics. Physicists had discovered that the electrical conductivity of a material like silicon was extremely sensitive to the presence of impurities. Adding an electron donor greatly enhanced the number of electrons that participated in current flow, while the presence of electron acceptors introduced mobile electron holes in the conduction band. In 1947 the transistor (short for *transfer resistor*) was invented. It was capable of acting like a vacuum tube triode because a small voltage applied to the middle section had a large effect on the current flowing between the outer regions.

Transistors can be reduced in size (miniaturized) in a way that vacuum tubes cannot. It is possible to grow nearly perfect silicon crystals with impurity atom concentrations of just one part per trillion. By means of masking and ion implantation, it is possible to create thousands of copies of the same circuit. The monolithic integrated circuit, first developed in 1958, made possible such marvels as the hand-held calculator and the desktop computer, as well as enormous computer memories that make it possible to simulate numerous processes.

The computational resources made possible by the integrated circuit along with establishment of the national laboratories in the United States and other countries, made further progress inevitable and physicists were able to explore the atomic nucleus at last. They learned that the short-range nature of the forces within the nucleus prevented the formulation of a simple force law like Coulomb's for the strong force. It became apparent, however, that the hadron family of particles were in fact composite. Each hadron consisted of three particles, which Murray Gell-Mann dubbed quarks (a nonsense word from James Joyce's *Finnegan's Wake*).

To explain why no free quarks had ever been detected, Gell-Mann assumed that the force between quarks got stronger as the distance between them increased, and that collisions with enough energy to break interquark bonds had enough energy, in fact, to create an additional quark-antiquark pair. That meant that the quarks were in effect confined to being either a tri-color combination that added up to white or a meson, a medium-mass particle that combined a quark and a complementary colored antiquark.

The Challenge of Physics Education

Because physics is so essential to so many fields of human endeavor, and because there are a diversity of physics curricula to draw from, there are conflicting opinions concerning which curricula is best. In the United States, the recommendations of the Committee of Ten, written over a hundred years ago, still holds sway. That curriculum assumed single-year courses in biology, chemistry, and physics, in that sequence, so that students could reach a certain level of mathematical skill before attempting to solve physics problems. That approach assumes that it is possible to have an understanding of biology without a working knowledge of physics and that the problem-solving skills demanded by chemistry can be developed without knowledge of physics. An alternative to this sequential ordering of science study is found in the "Physics First" movement, which encourages students to get the fundamentals of physics in the first year, before moving on to biology and chemistry, and then offers a more in-depth course in the junior or senior year to students who intend to pursue careers in science or engineering.

Yet another question deserving thought concerns how much modern physics education has to offer the non-specialist student. Although many students find the traditional physics course boring, they might find some of the recent developments in the field intriguing. It takes only a trip to the local bookshop or perusal of quality newspapers to come in contact with happenings at the forefront of research that are being presented to the general, non-specialized public as exciting, relevant information. This volume combines the latest topics with more traditional concepts to present a balanced view of this exciting and continuously evolving science.

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A

ABERRATIONS

FIELDS OF STUDY

Optics; Relativity; Quantum Physics

SUMMARY

Aberrations in the motion of light and other wave phenomena produce distortions in the perception of those phenomena. Waves moving at low velocities are described by Newton's laws of motion. Waves moving at relativistic velocities are described using relativity theory and the Lorentz transformation.

PRINCIPAL TERMS

- **chromatic aberration:** a distortion created by the separation of white light into its component wavelengths when passing from one medium into another, such as through a lens.
- **coma:** the extended geometric image formed along the optical axis of a lens by light entering the lens obliquely.
- **inertial reference frame:** a means of describing relative motions through space according to Newtonian mechanics.
- **Lorentz transformation:** a means of describing relative motions through space according to the mathematics of relativity.
- **refraction:** a change in the direction of light due to the different speeds of light when passing through various media.
- **relativistic beaming:** the effect in which a luminous beam appears brightest when pointing directly at an observer.
- **special relativity:** the theory that physical laws are constant for matter with a uniform motion.
- **spherical aberration:** the blurring or distortion of an image produced by a spherical lens or mirror due to differences in the refraction of light that enters the optical system along the optical axis and light that enters closer to the edge of the lens.

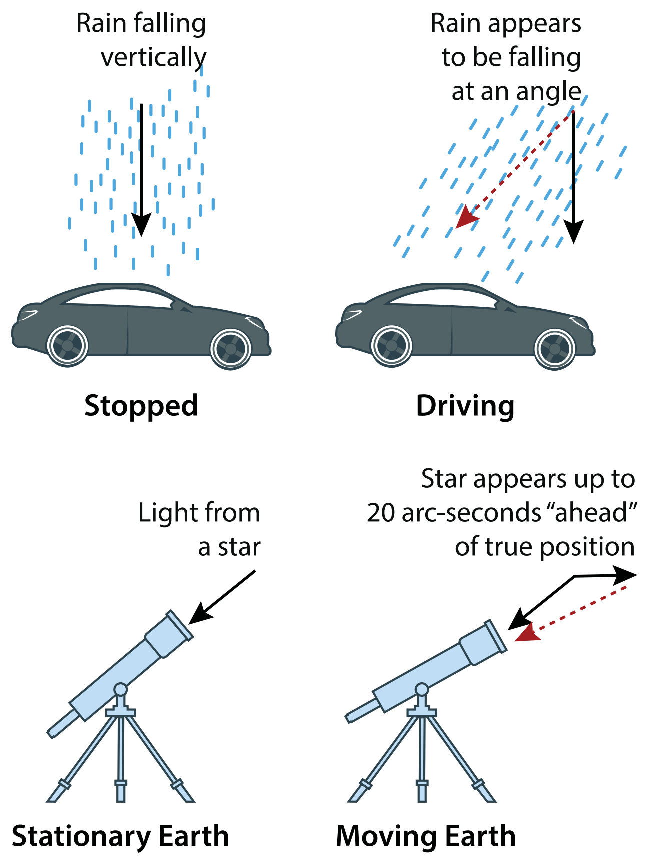
Aberrations

The image from a lens is produced by refraction of light rays passing from one medium, such as air, into another medium, such as glass. A convex lens refracts light rays in such a way that they converge at the focal length of the lens. The focal length is determined by the radius of curvature of the lens and the lens material's index of refraction. The focal length describes how strongly a lens converges or diverges light. Errors in images produced by lenses and other optical systems are called aberrations. Some common lens aberrations include coma, chromatic aberration, and spherical aberration.

Coma results when light rays enter a lens at an oblique angle. Coma creates an elongated image rather than a clear image at the focal length of the lens. A simple example of coma can be seen using an ordinary magnifying glass and holding it at an angle to a point light source such as the sun or a light bulb. A coma produces several images of various sizes. Rather than a clear image of the light source, the image will appear to resemble a comet, with a distinct head and a blurred tail spreading out behind it. This aberration occurs because the magnification of a lens is different for light that enters the lens near its center and light that enters near the edge.

Chromatic aberration results when light rays pass through two different media, such as air and the lens. Each medium has a specific index of refraction. The index of refraction is the ratio of the speed of light in a vacuum to its speed in a material. Light is diffracted by the medium in relation to its wavelength. As light passes through a lens, each wavelength of light changes direction by a slightly different amount. For example, sunlight that passes through a prism and becomes separated into bands of colored light. Chromatic aberration occurs when light entering a lens is diffracted, producing colored outlines, halos, and rings around the image. This is often seen in low-cost optical devices of poor quality, but it is also a major concern for even advanced optical telescopes and microscopes.

Spherical aberration is a problem that occurs in optical systems with spherical lenses or mirrors. For a curved surface, the reflected or refracted rays from each radial location on the surface converge along a central axis. However, the spherical geometry requires them to converge at different foci along that axis. The clearest image from a spherical lens is found at a point that is effectively the average value along the central axis. This point is termed the circle of least confusion.



The earth's rotation causes a change in the apparent position of the stars, called stellar aberration. Because our position is constantly moving, we interpret the light from stars to be coming at a different angle. This same phenomenon occurs when a person drives in the rain. Rain will fall vertically when a car is stopped, but when a car is in motion the rain appears to be coming toward us at a different angle due to an aberration.

DISTORTIONS

Light and sound depend on the movement of waves. Sound waves require a physical medium such as air to propagate. On the other hand, light propagates as electromagnetic waves that do not require a physical medium. They can thus travel easily through a vacuum. Each light wave has a specific wavelength and corresponding frequency that defines its essential properties. Any aberration, or change in the motion of the light waves, causes a distortion of the light as perceived by an observer. Aberrations and distortions are most commonly associated with lenses and mirrors, such as those used in powerful telescopes and similar optical devices.

Light coming through space from distant stars undergoes aberration due to the relative motion of Earth as it moves through its orbit around the sun. The sun itself is also moving through space relative to the other stars and galaxies in the universe. This relative motion can cause observers to see the stars as though they are ahead of their actual positions. The effect is similar to how a person sees raindrops through the window of a car. When the car is stationary, the raindrops are seen to fall straight down, but when the car is moving, the raindrops appear to be falling on an angle. The faster the car moves in relation to the raindrops, the steeper is the angle at which the raindrops appear to be falling.

FRAMES OF REFERENCE

The stationary car in the example above provides the view from an inertial reference frame. An inertial reference frame must be moving at a constant speed relative to the observed phenomena. The direction of the raindrops seen when the car is stationary can be described by the laws of motion English physicist Isaac Newton (1642–1727) formulated. However, when the car is moving, any mathematical description of the raindrops must account for the effect of the relative motion of the car and the raindrops. Similarly, the motion of light through space relative to Earth must be accounted for mathematically. This is something that Newton's laws of motion are not capable of describing. Instead, this is a job for the mathematics of relativity.

RELATIVITY

Newtonian mechanics, which describes motion and energy relationships, can account for the motion of objects with nonrelativistic velocities. The simple equations describe force as the product of mass and acceleration, and momentum as the product of mass and velocity. These equations are quite sufficient for objects that are moving very slowly relative to the speed of light. However, as velocity increases, the ability of Newtonian mechanics to accurately describe motion decreases. Therefore, one must use the Lorentz transformation to accurately describe its properties. The Lorentz transformation accounts for the differences in observations of the same phenomenon from two inertial reference frames that are moving at constant velocities with respect to one another. Any phenomenon that two observers want to describe can be converted from one reference frame to the other using the Lorentz transformation. In the theory of special relativity, formulated by German-born scientist Albert Einstein (1879–1955) in 1905, two assumptions are made. For one, it is held that the laws of physics are constant in all inertial reference frames. The second and most important assumption is that the velocity of light in a vacuum is constant regardless of the velocity of the light source. Because of this, an observer always sees light traveling at the same speed regardless of their reference frame.

This is a difficult concept to understand, because it is counterintuitive to the perception of human-scale motion governed by Newtonian mechanics. In everyday life, the motions of wave phenomena such as sound and water are seen to be affected by the motion of the source of the waves. Sound increases in pitch when the sound source is moving toward the observer and decreases when it is moving away. This is called the Doppler effect. What is observed for light sources in motion, such as stars, is the redshift and blueshift of the wavelength that they emit. A light source that is red-shifted appears to have a longer wavelength because it is moving away from the observer. A blue-shifted light source appears to have a shorter wavelength because it is moving toward the observer.

This perception masks the fact that the velocity of sound through some conductive medium is not affected by the motion of the medium. Similarly, the velocity of light through space or some other transparent medium is not affected by the relative motion of the medium and is thus constant. If the velocity of light is not affected by the motion of the medium that it travels through, then the velocity of light from a source moving through space is not affected by the motion of the source. For luminous beams traveling at relativistic velocities, such as those emitted by certain stars, an effect called relativistic beaming can be observed. The beam and its apparent source will appear brightest when the beam is oriented directly toward the observer. This is sometimes referred to as the headlight effect because the headlights of a vehicle moving toward an observer appear brightest when pointed directly at the observer but are barely visible from other angles.

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ABSORPTION

FIELDS OF STUDY

Acoustics; Electromagnetism

SUMMARY

The mechanisms by which acoustic and electromagnetic waves carry energy are briefly described. Absorption is the transfer of energy from a wave to the medium through which it propagates. Absorption is one main component of wave attenuation, the other being scattering. Each material has a unique absorption coefficient that characterizes how much energy it can absorb from a sound or light wave.

PRINCIPAL TERMS

- **absorption coefficient:** a value characteristic of a particular medium that represents the amount of light or sound it absorbs from a wave passing through it.
- **acoustics:** the study of sound; also, the qualities of a space that affect how sound is heard within that space.
- **albedo:** the portion of electromagnetic energy that is reflected when its waves encounter a surface or boundary; often used to describe solar radiation reflecting off Earth or another body in space.
- **attenuation:** the loss of energy from a wave passing through a medium due to absorption or scattering.
- **Beer-Lambert law:** a formula that relates the attenuation of an electromagnetic wave in a given medium to the thickness of that medium and the concentration of attenuating materials within it.
- **light wave:** an oscillation in an electromagnetic field.
- **reflection:** the rebounding of a wave from a surface or boundary between two mediums, causing it to travel back through the original medium.

Wave Energies

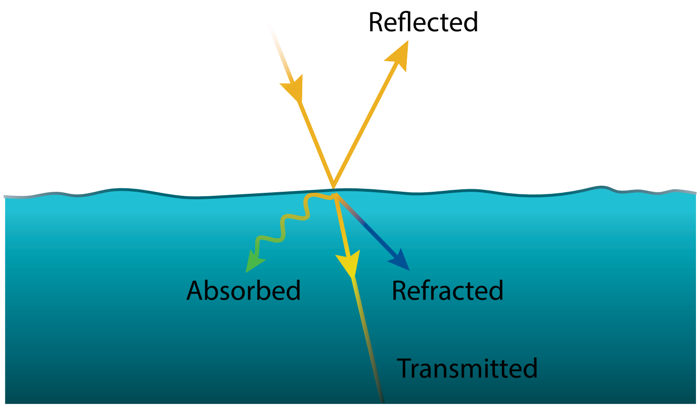
Energy comes in many different forms. Some types of energy, such as sound energy and radiant energy, travel in the form of waves. Sound energy is kinetic energy that is carried by sound waves, also called acoustic waves. Sound waves are a type of mechanical wave, meaning that they travel, or propagate, by oscillating the molecules of the surrounding medium. A mechanical wave must have a medium in order to propagate.

Radiant energy is the energy carried by electromagnetic radiation, which travels in the form of electromagnetic waves. These waves are sometimes called light waves because visible light is a kind of electromagnetic radiation. However, the electromagnetic spectrum extends far beyond the range of visible light. Electromagnetic waves do not require a medium, although the presence of one can influence how they propagate. Instead, they travel as oscillations in the electromagnetic field. This is why light can travel through the vacuum of space.

Different types of waves share a number of common physical properties. For example, all waves have a wavelength, frequency, and amplitude. Wavelength is the distance between identical points on two successive wave cycles. Frequency is the number of wave cycles per unit time. Amplitude is the distance between a wave's highest point (crest) and its lowest point (trough).

In addition, all waves experience reflection, refraction, diffraction, and interference. Reflection occurs when a wave bounces off a boundary between two mediums and changes direction. In the case of radiant energy, albedo refers to the amount of waves that are reflected. Refraction is a change in wave direction caused by the wave passing through the boundary rather than rebounding from it. Diffraction occurs when a wave bends around an obstacle or spreads out after passing through a small opening. Interference is the superposition of two or more waves to form a single wave with an amplitude equal to the sum of those of the contributing waves at the points where they meet.

Acoustic and electromagnetic waves are also subject to scattering and absorption. Scattering occurs when a portion of a wave's energy is reflected by irregularities in the medium. Absorption is the transfer of energy from a wave into the medium through which it is traveling. The medium takes up energy from the wave and transforms it into another kind of energy, such as heat.



Sound waves and light waves can move through a homogenous medium in a consistent manner, but when a wave interacts with a change in medium, it can either reflect, refract, transmit, or be absorbed. When a light wave is absorbed, the material absorbing it heats up. When a sound wave is absorbed, the sound seems to disappear.

ENERGY AND MATTER

Energy is observed and measured in terms of its effects on matter. When an acoustic wave passes through matter, the sound energy pushes its particles together, forming an area of compression, or increased particle density. Once the wave is no longer exerting pressure, this creates an area of rarefaction, or decreased particle density, just behind the area of compression. The rarefaction allows the compressed particles to return to their original position. These back-and-forth movements of particles are the oscillations that make up an acoustic wave. As they oscillate, the particles bump into each other, producing friction. The heat generated by this friction is sound energy that has been absorbed by the medium and transformed.

If light is directed in a beam through a medium, the energy of the beam can be measured on both sides of the medium and compared. The amount of energy transmitted per unit time is called "radiant power" or "radiant flux." It is measured in watts (W), the International System of Units (SI) derived unit of power. One watt is equal to one joule of energy transmitted per second (J/s). Transmitted radiant flux (φ_t) is the amount of radiant flux that exits a medium. The initial radiant flux (φ_i) is the amount that entered the medium. The ratio between the transmitted and initial radiant flux produces a value known as the transmittance (T):

$$T = \frac{\varphi_t}{\varphi_i}$$

Transmittance can be used to calculate both the attenuance (D) of a material and its optical depth (τ):

$$D = -\log_{10} T$$

$$\tau = -\ln T$$

Attenuance measures the radiant flux lost to attenuation. Optical depth is the opacity of a material to electromagnetic radiation. The function ln is the natural logarithm, or $\log_e$, where e is the mathematical constant known as Euler's number, roughly equal to 2.71828. The relationship between transmittance, absorbance, and optical depth can also be expressed using the inverse functions of the logarithms:

$$T = e^{-\tau} = 10^{-D}$$

There is some debate over the use of the term *attenuance* versus *absorbance*. The quantity defined here as attenuance is also commonly called absorbance (A), even though it measures energy lost by scattering as well as absorption. The International Union of Pure and Applied Chemistry (IUPAC) has recommended using absorbance only when attenuation due to scattering is negligible or otherwise not taken into account. Transmittance calculated using absorbance alone is known as internal transmittance, as opposed to total transmittance:

$$A = -\log_{10} T_{int}$$

$$T_{int} = 10^{-A}.$$

ATTENUATION AND ABSORPTION COEFFICIENTS

A wave may pass through a medium with little to no interaction. Or, it may lose some or all of its energy to that medium. This loss of energy is called attenuation. It results in a decrease in the wave's intensity, or its power per unit area.

The two main components of attenuation are scattering and absorption, both of which depend on the characteristics of the medium. A given material is characterized by an attenuation coefficient (μ). This unique value represents how easily the material can be penetrated by a wave. Just as attenuation is the sum total of energy lost to scattering and to absorption, a material's attenuation coefficient is the sum of its scattering coefficient and its absorption coefficient.

For electromagnetic waves, one usually specifies either a molar absorption coefficient or a linear absorption coefficient. The molar absorption coefficient (ε) is typically used in chemical analysis of solutions. It relates absorbance (A) to path length (l)—that is, the distance the wave travels through the medium—and the concentration (c) of absorbing materials in the medium, as described by the Beer-Lambert law:

$$A = \varepsilon cl.$$

The linear absorption coefficient (a) is defined as the absorbance (A) per unit path length (l):

$$a = \frac{A}{l}$$

For acoustic waves, the absorption coefficient (α) of a material is the ratio of absorbed sound intensity (I_a), in watts per meter squared (W/m^2), to initial sound intensity (I_i):

$$\alpha = \frac{I_a}{I_i}$$

Its value ranges from 0 (no sound absorbed) to 1 (all sound absorbed). This value can be used to calculate the total sound absorption (A) of either a single surface or an enclosure of multiple surfaces, such as a room, according to the following equation:

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n.$$

Here, S is the surface area of a given material, and A is measured in sabins. The sabin, named after American physicist Wallace Clement Sabine (1868–1919), is a unit of sound absorption equal to the absorbing ability of a quantity of material with an absorption coefficient of 1. It can be either metric (one square meter of completely absorbing material) or imperial (one square foot), depending on whether S is measured in meters or feet squared.

Applications of Absorption

Electromagnetic absorption is an important factor in numerous fields. In medicine, x-ray imaging works because different tissues absorb different amounts of x-rays; in meteorology, temperature is affected by the absorption of solar radiation by Earth's atmosphere and surface. In chemistry and materials science, the Beer-Lambert law can be used to identify unknown solutions.

Acoustic absorption is an everyday concern for architects, engineers, and anyone else who designs buildings or other structures where sound propagation is an issue. An engineer may want to design a recording studio with soundproofed booths or an auditorium that can project sound to distant audience members. In either case, it is necessary to use materials with appropriate absorption coefficients. The studio material should have a higher coefficient, to prevent sound from entering from outside. The auditorium material should have a lower coefficient, to increase the reverberation time of sound from the stage. Engineers who deal with acoustics frequently consult tables showing the absorption coefficients of common building materials.

—Nathan Olsson, MEd, and Randa Tantawi, PhD

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THE STANDARD MODEL

The *Periodic Table of the Elements* was first proposed by Dmitri Mendeleev in 1869. It provided a systematic basis for understanding the chemical elements and their compounds. With the discovery of the electron and the development of quantum mechanics half a century later, the electron theory of matter provided a coherent explanation of how the electrical force was responsible for the properties of atoms and their combinations—molecules. The electron theory of matter seemed to explain everything outside the nucleus of the atom. In the words of Nobel Laureate Richard Feynman, "Outside the nucleus we seem to know everything." (As it turned out Feynman's observation was a bit premature; neutrinos are not massless as was thought in the 1960's. When we view them as they travel through space, we can see the effects of their rest mass and a new type of field is needed to explain the origins of that mass. Gravitational waves have only just been detected, but the gravitational force is the weakest by far, so new developments may yet be waiting.)

There were still more questions. What was going on inside the nucleus, that made protons and neutrons stick to each other? What about those strange antiparticles that matched normal matter in almost every respect but charge? Were the proton and neutron all that elementary or did they rattle when colliding with another particle, suggesting another layer of structure? What of the unusual particles created in those collisions? Within a few years of experimentation the number of new short-lived particles outnumbered the known chemical elements. Was there a set of underlying rules?

The answers to those questions constitute the standard model of particle physics. The standard model has reached a level of maturity culminating in the discovery of the Higgs boson on July 4, 2012, but still leaves some unanswered questions: Are gravity and electromagnetism related in some way? Einstein thought so. Why is there so much normal matter in the universe and so little antimatter? Exactly how does the nuclear weak force relate to the nuclear strong force?

The basic ingredients of the standard model are: (1) a common way of looking at the interactions among elementary particles, and (2) a system for classifying the particles based on symmetry and the quantum concept of spin.

Diagramming the Interaction of Particles

To begin a discussion of the standard model, it is helpful to create a mental picture or model of interacting particles. Consider two children on skateboards tossing a ball back and forth. The ball is one of the particles that carry the force that one nuclear particle exerts on another and the children are the nuclear particles that interact via the fundamental forces.

Historically the picture became clearest first for electrons and positrons interacting by the electromagnetic force. The positron, or anti-electron, was predicted by Paul Dirac in his search for a version of the Schrödinger equation that would be invariant under the Lorentz transformations of special relativity. Dirac found that the simplest equation that met the requirements of special relativity required that the wave function be a four component vector, two of the components describing the two allowed directions of spin for the electron and the other two describing the two allowed directions of spin for the antiparticle. The anti-electron or positron was found by 1932 in cosmic ray showers and soon thereafter in radioactive decays of certain isotopes.

A comprehensive theory of quantum electrodynamics (or QED) was worked out in the immediate postwar years by American physicists Richard P. Feynman and Julian Schwinger and the Japanese Sin-Itiro Tomonaga who shared the 1965 Nobel Prize in Physics for their work. While the theory can be cast in many mathematically equivalent forms Feynman pointed out a particularly appealing form that permitted an easy interpretation, as the sum of readily visualized scattering event, with each event representable by a diagram. One could in fact dispense with much of the mathematics and focus on the Feynman diagrams.

Experiments with the hadron family were next to yield to diagrammatic analysis. The lowest mass members of the hadron family were the proton and neutron. The remaining members have very short lifetimes and, generally, could only be made in the very powerful particle accelerators built in the 1950's and later. As the experimental data accumulated,

NOBEL NOTES: SUB-ATOMIC AND SUB-NUCLEAR PHYSICS

The committees charged with selecting the Nobel winners in physics and chemistry have given particular attention to atomic processes and to the radiation which we now associate with nuclear transitions. The very first Nobel Prize in Physics in 1901 went to Conrad Röntgen for the discovery of x-rays. X-rays result from electrons in the inner shells of atoms. In1903 Antoine Henri Becquerel, Marie Curie, and Pierre Curie were cited for the discovery of natural radioactivity in uranium salts. J. J. Thompson was honored in 1905 for the discovery of the electron. In 1908, Ernest Rutherford, who would shortly discover proof of the existence of the atomic nucleus, was awarded the Nobel Prize for Chemistry. In 1911, it was Marie Curie's work in the chemistry of radioisotopes that received the Nobel Prize for Chemistry.

The Thirty Years that Shook Physics

In 1921 Albert Einstein won the Nobel Prize for his explanation of the photoelectric effect; his work on the theory of relativity was still considered too controversial for an award. (Interestingly, although this award was not based on his remarkable theory of relativity, it was a foregone conclusion that Albert Einstein would win the Nobel Prize, and thus, the money from the award was included in his divorce settlement with Mileva Marić in 1919.) Einstein had by that time worked out his general theory of relativity, confirmed by a British expedition to South Africa in 1919 where they measured gravitational shifts in the apparent positions of the stars during a solar eclipse. Confirmation of the theory also came from its ability to explain the quite small precession of the perihelion of the planet Mercury. The most dramatic prediction of Einstein's general relativity, the existence of gravitational radiation, would have to wait until 2015 to achieve observational confirmation.

In the 1920s and 1930s, the emphasis for the awards was placed an improved theoretical understanding of the behavior of matter on the microscale and the growing number of elementary particles. The 1918 physics prize went to Max Planck, who had started the quantum revolution by assuming that the energy of electromagnetic radiation energy was quantized. The 1922 prize went to Niels Bohr, who found that he could predict the energy levels of the hydrogen atom (and 1-electron ions) but not of atoms with more than one electron. The 1923 prize went to an American, Robert Mulliken, for determining the size of the electron's charge. By 1929, a workable solution for many electron atoms was found, beginning with the work of Prince Louis-Victor Pierre Raymond de Broglie, which established that the wavelength for material particles was inversely proportional to their momentum. That de Broglie's work was sound was established eight years later by the Nobel Prize-winning work of Davisson and Thomson at Bell Labs (1937) when they diffracted electrons in a manner parallel to that of Sir William Henry Bragg and William Lawrence Bragg (Nobel Prize, 1915). This work fully established the wave–particle duality that had been predicted by Einstein nearly a decade earlier. Quantitative predictions of all atomic energy levels were made possible by the work of Heisenberg, for which he received the Nobel Prize in 1932. An alternative formulation was discovered by Schrödinger at about the same time. The existence of two such different mathematical approaches was puzzling for a time, but then Paul Adrian Maurice Dirac was able to show that the two approaches were in fact equivalent, despite apparent differences. Dirac and Schrödinger were both honored for their efforts by the Nobel Prize for Physics in 1933.

Physicist George Gamow has labeled the period from 1900-1930 as "the thirty years that shook physics." Physics research tended to concentrate at a few centers in Europe: at Cambridge University in England, at Gottingen in Germany and at Neil's Bohr's Institute in Denmark. Anyone serious about learning physics, and with the financial means to do so, went to one of these three locations. The international language of physics was referred to as "broken" German. By the end of the Second World War, however, things had changed dramatically. As Europe was slowly rebuilding, the United States came to play a significant role in physics research, and the international language of science had become a type of "broken" English. Dutch scientist C. C. G. Gorter went as far as to suggest formalizing the grammar of "broken" as an aid to scientific communication.

PHYSICS LAWS

Ampère's Law
The line integral of the magnetic flux around a closed curve is proportional to the algebraic sum of electric currents flowing through that closed curve; or, in differential form curl $B = J$. This was later modified to add a second term when it was incorporated into Maxwell's equations.

Archimedes' Principle
A body that is submerged in a fluid is buoyed up by a force equal in magnitude to the weight of the fluid that is displaced, and directed upward along a line through the center of gravity of the displaced fluid.

Avogadro's Hypothesis (1811)
Equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules. It is, in fact, only true for ideal gases.

Bernoulli's Equation
In an irrotational fluid, the sum of the static pressure, the weight of the fluid per unit mass times the height, and half the density times the velocity squared is constant throughout the fluid.

Boyle's Law (1662); Mariotte's law (1676)
The product of the pressure and the volume of an ideal gas at constant temperature is a constant.

Bragg's Law (1912)
When a beam of *X*-rays strikes a crystal surface in which the layers of atoms or ions are regularly separated, the maximum intensity of the reflected ray occurs when the complement of the angle of incidence, *theta*, the wavelength of the *X*-rays, *lambda*, and the distance between layers of atoms or ions, *d*, are related by the equation 2 *d* sin *theta* = *n lambda*,

Causality Principle
The principle that cause must always preceed effect. More formally, if an event *A* ("the cause") somehow influences an event *B* ("the effect") which occurs later in time, then event *B* cannot in turn have an influence on event *A*. That is, event *B* must occur at a later time *t* than event *A*, and further, all frames must agree upon this ordering.

Centrifugal Pseudoforce
A pseudoforce on an object when it is moving in uniform circular motion. The "force" is directed outward from the center of motion.

Charles' Law (1787)
The volume of an ideal gas at constant pressure is proportional to the thermodynamic temperature of that gas.

Complementarity Principle
The principle that a given system cannot exhibit both wave-like behavior and particle-like behavior at the same time. That is, certain experiments will reveal the wave-like nature of a system, and certain experiments will reveal the particle-like nature of a system, but no experiment will reveal both simultaneously.

Compton Effect (1923)
An effect that demonstrates that photons (the quantum of electromagnetic radiation) have momentum. A photon fired at a stationary particle, such as an electron, will impart momentum to the electron and, since its energy has been decreased, will experience a corresponding decrease in frequency.

Conservation Laws
Conservation of mass-energy
The total mass-energy of a closed system remains constant.
Conservation of electric charge
The total electric charge of a closed system remains constant.
Conservation of linear momentum
The total linear momentum of a closed system remains constant.
Conservation of angular momentum
The total angular momentum of a closed system remains constant.

Constancy Principle
One of the postulates of A. Einstein's special theory of relativity, which puts forth that the speed of light in vacuum is measured as the same speed to all observers, regardless of their relative motion.