HISTORICAL REVIEW OF ELEMENTARY CONCEPTS IN PHYSICS

P.O. Hess
Instituto de Ciencias Nucleares, UNAM, Mexico

Keywords: Concepts in physics, classical mechanics, electrodynamics, history of physics, kinetic theory, magnetism, optics, quantum mechanics, relativity, statistical mechanics, thermodynamics

Contents

Summary

After a short discussion on the contributions the Greeks had on our thinking and defining concepts in physics, the basic ideas of classical mechanics are discussed combined with a historical overview. Afterwards, the same is done for Electrodynamics, Thermodynamics, Quantum Mechanics and Theory of Relativity. The presentation is kept on a basic level, apt for students at high school.

1. Introduction

Though, modern physics starts with Tycho Brahe, Kepler and Galileo Galiei, we cannot explain our understanding of the universe and our basic concepts in physics without the achievements of the Greek philosophers. They already set the basis of many aspects on how to look at the world around us. But, why they could not develop the astronomy and physics as we know it now? The Greeks never succeeded in constructing models and theories which connect the observations of the sky with those on earth *and* using mathematical formulations to predict, e.g., the position of the planets on the sky. One possible reason is the absence in their philosophy of physical laws, put in a mathematical language which enable us to calculate future events accordingly. This does not diminish their achievements, because they contributed an important part of our thinking.

The most dominant contribution is *geometry*, i.e. the Euclidian geometry which carries the name of its founder (Euclid, $\approx$360-300 B.C.). This geometry represents the most fundamental understanding about space in classical physics. Isaac Newton (1642-1727) based his axioms on the assumption that the space around us is Euclidian, an assumption only challenged at the beginning of the 20th century by Albert Einstein (1879-1955). Many contributions on geometry were provided by Pythagoras (560-480 B.C.). He was convinced that the motion of the planets can be understood in similar terms as the harmonics of musical notes. From there stems the notion of the *harmony of spheres* which influenced Kepler, who used this philosophy in his first attempts to understand the orbits of the planets.

Another important contribution of the Greeks is the atomic theory. According to Democritus ($\approx$460-370 B.C.) a piece of matter could be divided only by a finite number of steps, until reaching a fundamental, indivisible particle, which is called *atom.* There can be different sizes and colors of atoms, such that all properties of matter could eventually be explained. Note, that he could not provide the size of the atom, nor how possibly to measure it. His model remained at a mere philosophical level, though it had a great impact on our modern thinking.

Also electrical and magnetic phenomena were known by the Greeks, however without relating them and trying to understand their origins or the laws they obey.

One of the greatest Greek philosophers was Aristotle (382-322 BC.), who mostly influences the philosophy on nature for the next couple of thousand years. He is known for his contribution on observational astronomy and mainly for his classification scheme in biology. He also was the educator of Alexander the Great. A basic principle, though false, which stems from him is the assumption that a moving body can only be kept moving by applying constantly a force upon it, otherwise it would come to a standstill. This could be verified by everyday observations of a moving body on earth. He did, however, ignore friction. Also the laws of nature were considered to be different on earth and in the sky, because the planets kept moving without loosing speed. This also shows the main difficulty the Greeks had to develop a valid theory for the motion of celestial bodies. They did not recognize the common properties of motion in the sky and on earth and connecting them via a theory, supposing few basic principles and a mathematical tool to draw conclusions. Their understanding of the universe was basically geometrical. It took until Galileo Galilei (1564-1642), who showed through tedious measurements, which are the basic principles governing the motion of objects.

There are several important contributions in astronomy, made by the Greeks. For example, Pythagoras assumed an earth centered universe were the earth is a sphere and rotating around its own axis. The more common assumption was, however, that the earth is at the center and the moon, stars, sun and planets, are rotating around it.

Aristarchus of Samos (310-230 B.C.) was the first who proposed a heliocentric model of the universe. His conclusion came from the following observation: When the moon is half illuminated, as seen from the earth, the sun is at right angle to the moon. However, at this position the sun is also at a right angle to the observer, looking at the moon. This can only be explained assuming that the sun is very far away. Also noting that the apparent size of the sun is the same as the moon and that the sun is very far from the earth, the real size of the sun should be enormous compared to the moon and the earth, whose distance was also estimated. This fact provoked the question, why the earth should be at the center of the universe when the size of the sun is so dominant? (Again a pure philosophical question). This model of the universe did not attract many people, because it also lacked the ability on predicting positions of planets.

The Greek astronomer, who dominated the picture of the universe until Nicolaus Copernicus (1473-1543), was Ptolemaeus (100-170 B.C.). He favored the earth centered universe where all other celestial objects are moving around it, being attached to spheres. In order to describe irregularities, like retrograde orbits of the planets, he assumed smaller spheres attached to the bigger ones. His vision of the universe made it possible to describe the motion of planets sufficiently accurate for that time. His model was adopted later on also by the Christian church which considered it as a dogma.

Finally we mention two more important Greek astronomers. One is Eratosthenes of Alexandria (276-194 B.C.)who made the first measurements on the circumference of the earth. It was already known before that the earth must be a sphere. This conclusion was a consequence of the observation of sailors who noted that when one sails further north or further south, the celestial ceiling is changing, or noting the round shadow which earth casts on the moon during a lunar eclipse. Going towards the south, stars and new constellations not seen before came into sight. Eratosthense of Alexandria (276-194 B.C) based his measurement on the observation that at the longest day in the year the sun is its zenith in Syene but below the zenith by 7.25^0 at Alexandria. Measuring the distance from Syene to Alexandria he could deduce the circumference of the earth within 10%.

The other important astronomer was Hipparchus (190-120 B.C.) who is famous for his star catalog, used until the 19^{th} century.

From the explanation above, it becomes clear that the round shape of earth was also known to the scholars in the 15^{th} century. Portuguese sailors made the same observation of changing positions of constellations in the sky when sailing further south. The circumference of the earth was well known and when Christopher Columbus applied for financial support for his trips to the west it was perfectly known that his calculations of the distance to Asia were false. To refuse him the money had not its origin, as commonly teached, in the assumption that earth is flat but on his miscalculation.

2. Newtonian Physics

The next great step forward was achieved by Nicolaus Copernicus (1473-1543) who lived most of his life as a monk in Cracow (today Poland). He retook the ideas of the Greek philosopher Aristarchus of Samos and proposed the heliocentric picture of the universe in *De Revolutionibus* (1543), which was published just after his death. The advantage to the heliocentric model is that only a few concepts are needed, sufficient to explain several observations like the phases of the moon, day and night on earth and the retrograde motions of the planets, observed when the planet in consideration in near to earth. No complicated mechanical model is needed as the one given by Ptolemaeus. However, Copernicus assumed a circular orbit for the planets because of its geometrical beauty. This introduced several problems is describing the exact position of the planets and the need of additional constructions, as in the Ptolemaeian model, was needed.

Surely, this did not convince many scientists to adapt the heliocentric picture immediately.

The next on the scene was Tycho Brahe (1546-1601), a Danish astronomer and mainly active in Copenhagen and for some time in Prague. He realized that in order to understand the planetary motion, the exact measurements of the position of the celestial objects has to be obtained. He designed several astronomical instruments, which enabled him to the most detailed measurements possible by the naked eye. Tycho Brahe invited Kepler to Prague and gave him access to all his measurements, which Kepler inherited after the death of Tycho-Brahe.

Kepler (1577-1630) made several attempts to describe the planetary motion. His main concept of the universe consisted in the belief that everything must be of geometrical nature. He insisted in the *mathematical harmonies of the planetary motion*, that they could be fit into the five regular geometric solids known. Therefore only five planets (known up to this time) should exist and confirm the theory. He did not succeed. It took him quite long until he tried *unperfect* geometrical orbits, like the ellipse. The ellipse turned out to be fitting into the observations and from there he obtained the, now called, first Kepler law, namely that the *planets move in ellipses*. Through this success he looked for further regularities, a very tedious job. This resulted in the other two Kepler laws, the second that *the line which connects the planet with the sun covers in equal times equal areas* and the third one, that *the ratio of the square of the time needed in order to revolve once around the sun and the cubic power of the large axis of the ellipse is a constant for all planets*. The first is a consequence of the conservation of angular momentum, as was shown later by Newton, and the first and the third one are a consequence of the inverse square power law of the gravitational force. The last law is only approximately true, because in the exact treatment the ratio of the planetary masses to the sun's mass appear. This ratio is normally very small and the effect was out of the reach of the measurements of these times.

A contemporary of Kepler was Galileo Galilei (1564-1642) an Italian philosopher and scientist. One can consider Galileo Galilei as the first real experimental physicist. His devotion consisted in measuring the motion of all kinds of objects and deduce regularities. In order to investigate the fall of the objects under the earth's attraction, he did let role down balls made of different materials on an inclined plane. He recognized the existence of air resistance and friction, thus using spheres of the same size. The inclination was necessary in order to slow down the motion such that it can be measured. As one of his conclusions he showed that all objects are accelerated in the same way, i.e., all objects fall equally rapid towards the bottom. He introduced for the first time the concept of *inertia*. He saw, that once the sphere has rolled down, it continued rolling on the plane surface of the table, until it had slowed down. The slowing down could be varied depending on the roughness of the table, thus recognizing friction as the main source for the stopping. Another important concepts, he introduced, is the *kinetic* and the *potential energy*. He noted in his experiments that the velocity obtained by the sphere is always the same, no matter how long the ramp is, with the only condition that the height from which the sphere starts is not varied. This let him to the introduction of the kinetic energy. When the sphere reached bottom and then is led to rise again on another ramp, the sphere reached bottom and then is led to rise again on another ramp, the sphere reaches the same height as before, as if it could remember its initial position. Galileo Galilei recognized that in the first step the sphere had a certain *potential energy* which was converted into *kinetic energy* and then back to potential energy again. In order to realize the measurements he had to invent the clock.

Galileo Galilei became most famous by the invention of the telescope, which started a tremendous revolution in observational astronomy. He discovered the first four moons of Jupiter and used this system as a model for the heliocentric picture. The moons now bear his name as *Galilean moons*. He also was active in describing the path of a cannon ball (important to know in those times) and recognized that the distance the cannon ball passes is maximal when the initial angle, at which the ball leaves the cannon, is 45^0.

The achievements by Kepler and Galileo Galilei formed the indispensable basis of the work of Isaac Newton. Isaac Newton (1642-1727), an English scientist, published in his *Principia* a complete theory for the motion of the planets and on earth. He recognized that the basic force, the *gravitational force* is common to the motion of the planets and objects on earth. This represents the first theory of unification in physics of before apparently unrelated objects. He realized that the gravitational attraction is in line with two objects attracting each other and that this force is inverse proportional to the square of the distance. He also noted that the force is a function of the product of the two masses.

But before he was able to formulate his theory, he had to make special assumptions on the structure of space and assume basic axioms. The only geometry known at that time was the Euclidian one. Thus, he adapted for the structure of space this geometry. Also with respect to time he used an absolute notion and that it flows only in one direction. Due to the observations of Galileo Galilei he proposed three axioms, known as the three basic laws of Newton: The first states that a *body keeps its motion in the same state as long as no force acts upon it,* i.e. a ball flying in a certain direction with a given velocity will continue to fly in the same direction with the same velocity (*law of inertia*). The second one is the famous *law of force,* i.e. that *the change of velocity is proportional to the force applied.* The third law states that *if a force is applied on one body by another one, the other body feels the same force but in opposite direction* .Using these basic axioms it is possible to deduce a whole series of consequences, explaining some observations and predicting others. The last is especially important for a theory, when it has to be accepted in the physics community. Also the fact that on one side there is a theory and on the other side there are experiments plays a tremendous role in physics.

The *force, velocity and acceleration* (three new concepts) have a vector character. In order to formulate his theory, Newton was forced to develop the infinitesimal calculus, at the same time as done by Gottfried Wilhelm Freiherr von Leibnitz (1646-1716). As one example, consider the notion of *instant velocity,* i.e., the velocity a body at a given time. Because an accelerated body changes its velocity continuously, the instant velocity has to be defined as the ratio of the interval of distance passed divided by the interval of time needed. The intervals have to be as small as possible. In practice, these intervals are always finite and the concept of infinitesimal intervals represents one the mayor achievements of human kind.

The second law of Newton defines how mass can be introduced. It is the proportionality factor between the force applied and the acceleration produced. Mass describes the *resistance* of a body to be accelerated by a certain amount of force. That this mass is the same as in the force of gravity, constitutes one of the greatest ideas accomplished by Newton. He also idealized the description of motion by assuming mass points for the planetary motion or bodies on earth. He showed for this motion it suffices to use the *center of mass* of a body and there is no need to know the extension of the object.

The theory of gravitation was not the only contribution of Newton. Later, in the discussion of electro magnetism and optics we will come back to this point. Newtonian physics was able to describe a huge spectrum of phenomena and it was considered as the perfect example how a theory should look like. Later on, the theory was perfected by the work of Joseph-Luis Lagrange (1736-1813), Henri Poincaré (1854-1912) and William Rowan Hamilton (1805-1865), who introduced and developed the variational principle, rendering much easier calculations in Classical Mechanics. The variational principle deal only with scalar quantities, like kinetic and potential energy combined into objects like the *Lagrange* or *Hamilton function*, which looks alike in any reference system. No vectorial properties enter, except in the final equations of motion. Also the introduction of the symmetry concept was very important i.e., if the system is invariant under certain continuous transformations (cyclic variables in the Lagrange or Hamilton function).

-
-
-

Bibliography

Herbert Goldstein (1980). *Classical Mechanics* (Addison Wesley, New York) [one of the best books on Classical Mechanics]

Walter Greiner, Ludwig Neisse and Horst Stöcker (1995). *Thermodynamics and Statistical Mechanics* (Springer, Heidelberg) [An excellent introductory book about Thermodynamics and Statistical Physics. Chapters on the application in Heavy Ion Physics are included.]

John David Jackson (1975). *Classical Electrodynamics* (John–Wiley, New York) [One of the classical books about Classical Electrodynamic]

Albert Messiah (1961). *Quantum Mechanics I and II* (North-Holland, Amsterdam) [These books give a detailed introduction into Quantum Mechanics and its heuristic justification. Furthermore, newer developments like Quantum Field Theory are discussed.]

Lloyd Motz and Jefferson Hane Weaver (1989). *The story of physics* (Plenum Press, New York) [An excellent book about history of modern physics. The emphasis of this book is on history and biographies.]

B. Mrowka, Zeitschrift für Physik **130** (1951), 164-173. *Zur Darstellung der Quantenmechanik I (Unrelativistische Wellengleichungen* (in german); D. Suhuch, K. -M. Chung and H. Hartmann, International Journal of Quantum Chemistry **25** (1984), 391-410 [The first is a classical article about the deduction of Schrödingers wave equation. The equation is *derived* from three basic axioms, which are a result of observation. The method is normally not shown in classes about Quantum Mechanics, though it should. In the second reference the same is repeated in english. Furthermore, it is shown how dissipation can be introduced in Quantum Mechanics, without violating Heisenberg's uncertainty relation, a nontrivial task.]

Sky and Telescope, October 2000 issue. (Sky Publishing Corporation, Cambridge, USA) [This is a popular journal on Astronomy. The issue is dedicated to the new gravitational wave observatories and contains several articles on this subject.]

Phillip R. Wallace (1991). *Physics, Imagination and Reality* (World Scientific, Singapore) [This book gives besides a historical overview, excellent discussions about basic concept in physics.]

www.biography.com [This is a website which contains about 10000 biographies of important persons in history.]

Biographical Sketch

Peter Otto Hess. Ph.D. in nuclear physics in 1980, University of Frankfurt (Germany), Habilitation, University of Frankfurt, 1985. 1981-1982 postdoc at the Instituto de Fisica, UNAM, Mexico. 1983 - February 1984, GSI, Darmstadt (Germany). March 1984 - June 1985, University of Cape Town, Cape Town (South Africa). Since July 1985, Instituto de Ciencias Nucleares, UNAM (Mexico). July 1986 - June 1991, Gastdozent of the Deutscher Akademischer Austauschdienst in Mexico, Distincion Universidad Nacional para Jovenes Academicos, 1993 (Prize given by the National Autonomous University of Mexico), Price of the Academy of Sciences of Mexico, 1993. Guestprofessor at the University of Giessen, June 1992 - June 1993 and August 1998 - July 1999. Sistema Nacional de nvesitgadores, level III. More than 120 published articles on the topics mentioned below. Area of interest: Theoretical Nuclear Physics, Mathematical Physics, Particle Physics.Main Contributions in: Geometrical nuclear collective models, nuclear molecules, alebraic nuclear collective models, structure of the ground state of Quantum Chromodynamics.