# AN INTRODUCTION TO AND OVERVIEW OF FUNDAMENTALS OF PHYSICS

**Jose Luis Moran–Lopez**
*Instituto Potosino de Investigación Científica, SLP, Mexico*

**Peter Otto Hess**
*Instituto de Ciencias Nucleares, UNAM, México D.F., Mexico*

**Keywords:**Atomic Physics, Chaos Theory, Classical Mechanics, Electrodynamics, Electromagnetic Interaction, Future direction in physics, General Relativity, Gravitational Interaction, Molecular Physics, Nuclear Physics, Non-Equilibrium Processes, Optics, Particle Physics, Phase Transitions, Quantum Mechanics, Radioactivity, Solid State Physics, Special Relativity, Strong Interaction, Thermodynamics, Weak Interaction, Nanoscience

## Contents

## Summary

An overview of the modern areas in physics, most of which had been crystallized in the 20th century, is given. First, some concepts of physics are mentioned, which are related to the definition of *force*, *velocity*, *acceleration*, etc.. The importance of *symmetry* is explained, which nowadays is one of the most powerful principles in physical theories. Afterwards, a more detailed description of the different areas in physics is provided, in an attempt to give an overview of the main fields of activity in physics today. Also, the contemporary, the future directions of physics and main problems to be resolved are discussed, without a claim of completeness. At the end, some important implications of physics to society and economy are mentioned.

## 1. Introduction

The term *physics* comes from Greek and means, in a broader sense, *science of the nature*. Galileo Galilei set the foundation for the modern understanding of physics and of the *scientific method*. One important ingredient is the requirement that all physical phenomena should be reproducible. The models of nature (theories) have to be confirmed by the experiment, if the theory has to be taken seriously.

The first step towards the development of a physical theory is the *experiment* or *observation* of a physical process. The second step consists in creating a *model* or *theory* which may explain the observations made in the experiment. A model has not only to reproduce the results of an experiment but also has to make *predictions*. Predictions are necessary for the understanding, provided by the model, of the physical process. Finally, the theory has to be verified by the experiments proposed by that model. If the predictions are correct, the model is accepted as a valid one. Of course, further experiments have to be conducted, with increasing accuracy, in order to test the theory again and again. In fact, a single experiment is enough to invalidate a model and there is no finite number of experiments which can prove a theory to be absolute correct. One experiment, which shows deviations from the theory hints at new physics. Such was the case in the transition from *Classical Mechanics* to *Quantum Mechanics*, when deviations of the former theory at small scales where observed, or the transition from *Classical Mechanics* to the theory of *Relativity* when at large scale and at large velocities deviations appeared.

There is also a difference between *fundamental theories* and *models in general*. Fundamental theories are bases on a few axioms from which *in principle* all physical phenomena can be described. Models in general may refer to simplified descriptions of nature. For example, when the rough structure of a complicated fundamental theory is described by a schematic model, or when a complex system is simplified by justifiable assumptions. Such models play a main role in nuclear physics where the interaction is too complex for allowing a treatment by first principles.

In all cases, the imagination and intuition of a physicist plays an important role, as Einstein once put it: *Imagination is more important than knowledge*. This refers to the understanding of the mechanics of *how* the universe works. However, in order to construct and verify a theory, rigorous methods like mathematical tools and logical reasoning have to be applied.

In this chapter we will outline the nature of physical theories, e.g. which are their *basic concepts* and *basic principles*. Starting from there, different areas of physics will be visited. The development of some areas experienced an explosive growth mainly in the 20th century. Before the 19th century, essentially Classical Mechanics and Optics dominated the field of activities of physicists. In the 19th century *Thermodynamics* and *Electrodynamics* were added. The 20th century brought the theory of *Special and General Relativity* and *Quantum Mechanics*. From there other areas evolved like: *Atomic Physics, Nuclear Physics, Particle Physics, Solid State Physics, Chaos Theory*, just to mention a few. One objective of this chapter is to review these different areas of physics and to give a brief introduction for the general reader.

Towards the end, we will also mention some basic consequences of the developments of new areas in physics. Today, at the start of the 21st century, the impact of the physical theories are seen everywhere and are essential for modern societies, through the development of new technologies, better health systems, etc. Often, an inexperienced person takes the natural environment as God given and does not realize why it is as it is, and does not even understand the basic mechanisms, leading often to misunderstanding with the consequent damage. Science is not only the responsibility of scientists but also of the general public (it is recommended that it learns and gets accustomed to it), which provides the money and is exposed to the scientific results, for better and for worse.

## 2. Review of Different Areas of Physics

In Section 2.1 some basic concepts of physics are discussed, as Classical Mechanics, Optics, Electricity and Magnetism, Thermodynamics, Acoustics and others. In Section 2.2 several basic principles and laws are reviewed like the principle of symmetry, the laws of Classical Mechanics, Special and General Relativity, Quantum Mechanics, Complex Systems and Plasma Physics. In Section 2.3 the area of Particles and Fields is reviewed. Particular quantum mechanical systems are discussed in Section 2.4, order and disorder in Section 2.5 and nuclear processes in Section 2.6. In Sections 2.7 and 2.8 contemporary physics and some future developments in physics will be outlined.

This is only a broad review. For in-depth treatment we refer to the related chapters.

### 2.1. Basic Concepts in Physics

As already mentioned in the introduction, Galileo Galilei introduced the rigorous scientific procedure. He realized that under certain simplified assumptions, like neglecting friction in describing motions of objects on the earth, the physics of the celestial objects is the same as on one the Earth. This description represented the first grand unification in physics. On the other hand, Kepler used the experimental observations of Tycho Brahe to deduce his famous laws of planetary motion. The monumental work of both were used by Newton, creating the first fundamental theory in physics, known as *Classical Mechanics*, able to derive the laws of Kepler and to predict the motion of any planet around the sun and the objects on earth with a great precision.

Newton introduced concepts like *force*, *acceleration*, *velocity* and *potential energy* in order to formulate the equations of motion from which the trajectory of a body can be predicted, once the initial conditions (initial position and velocity) are known. The theory was written in terms of differential equations for which Newton had to develop first a mathematical tool, known as differential and integral calculus, created independently and simultaneously by Leibnitz.

Newton developed also the important concept of *inertial system*. Inertial systems are defined as frames of reference which move with respect to each other at arbitrary but constant velocity. When no force is applied to a body, it will remain in its state of rest or of uniform motion.

The concept of a particle was explicitly used by him, i.e. an object localized at a point in space and to which a trajectory can be associated. This concept of a particle was later part of a paradox when physics at microscopic scale was investigated in the 19th century and the beginning of the 20th century.

Newton also made important contributions to optics, an area that he helped to create. Due to him is the discovery that the sun's light is actually composed of a spectrum of colors. Newton tried to describe optical phenomena via a particle property of light, known as *geometrical optics or corposcular theory* . The particle description of light was abolished when interference phenomena were observed and the theory of Huygens, based on the wave description of light, predominated. The concept of wave is opposed to the one of a particle. A wave is described by a field distributed all over the space and it has an undulated behavior, like the waves in a pond of water. The definition of a position does not make sense but the description of amplitudes of the wave in different points of space. When two waves interact, the amplitudes are simply added and lead to interference phenomena. At that time one believed that a wave needs a medium in which it can propagates, like the water waves need the substance water, and sound waves the air.

A typical area in physics, in which waves play an important role, is the *Acoustics*; the science of propagation of sound waves in a medium. A typical medium is the air which surrounds us. We all know that the sound propagates by pressure waves within the air. But this field is not confined to that system alone.

When Maxwell formulated the electrodynamic theory, light was identified as an electromagnetic wave. This represented the second grand unification in physics, i.e. the electro- and magnetostatic phenomena with optics. Because light is a wave, it was thought that it needs a medium in which to propagate. This lead to the concept of ether, abolished later with the development of the theory of special relativity.

Up to this point, the theories of nature were deterministic, i.e. when all initial conditions are known exactly the outcome of an experiment can be predicted with any arbitrary precision.

In the 19th century a different kind of model emerged when treating complex systems like a gas. According to the mechanical understanding, the evolution of a gas can *in principle* be determined when the initial positions and velocities of all gas molecules are known. However, due to the large number of such molecules it is practically impossible to achieve this precision. One therefore had to recourse to the description of average properties, like the temperature, the volume and the pressure of a gas. Due to that the theory, called *Thermodynamics*, was not well received initially as a fundamental theory. Nevertheless, using concepts of a statistical description of molecular motion it is possible to deduce the observed properties of many particle systems like a gas, a liquid, or a solid. The concept of *Entropy* was introduced, which is related to the probability of a realization of a state with practically an infinite number of particles. Already in the theory of thermodynamics, problems related to the identity of particles appeared. In order to reproduce the observations, the particles have to be indistinguishable, i.e. physics should be invariant under the interchange of two particles. Gibbs had to introduce the definition of factorial of $N$ ($N!$), with $N$ being the number of particles involved. Also the stability of a solid was poorly understood, a problem only solved with the appearance of Quantum Mechanics.

Before Quantum Mechanics was developed, Einstein presented his *Special Theory of Relativity*. He showed that time can not be absolute and the reference to a particular scale in time depends on the observer. Therefore, the concept of time, considered to be absolute since Newton, suffered an important change. Time became part of a four dimensional space-time manifold. Later, in 1915, Einstein extended the concept of space-time to the curved space time, creating the *General Theory of Relativity*.

At the beginning of the 20th century, some experiments led to several paradoxes. For example, the radiation of a black body can only be understood, as shown by Planck in 1900, when the quantization of light is assumed. Rutherford in 1909 discovered that the atom consists of a positively charged center (the nucleus) and of electrons that are orbiting around this center. Under the electrodynamics framework this model created severe problems, since electrons should emit radiation; motion in a circular orbit implies acceleration and accelerated charges radiate. Another problem was related to the *photoelectric effect*: when light hits a metallic plate, submerged in a vacuum, electrons are released. The observation showed that the light must have a minimum frequency, below which no electrons are emitted. This minimum depends on the particular material used. Also, when the intensity of the light is increased, the energy of the electrons is not larger but simply more electrons with the same energy are emitted. The energy of the emitted electrons depends only on the frequency of the light. All this contradicted the classical picture. Einstein explained the photoelectric effect by assuming that the light is quantized, in accordance with Planck's theory. This represented the resurrection of the corpuscular theory of light proposed by Newton.

Newton demonstrated that the light coming from the sun is in reality a mixture of different colors. Passing that light through a prism generates a spectrum. The discovery made by Newton started a field known as *spectroscopy*. In 1814 Fraunhofer announced that the spectrum of the sun contains dark lines, whose origin remained a mystery for several decades. Later, in 1859, Kirchhoff published his results on the emission spectrum of different elements, which seemed to be very characteristic for each element. It was then noted that the position of the emission lines correspond to the position of the dark lines in the sun. Today we describe this as an absorption spectrum whose origin lies in the absorption of certain frequencies by a given element in the sun's atmosphere. Until the verge of the 20th century the origin of these lines remained a mystery. Later, systematic studies of the spectrum of hydrogen, by Balmer, led him to the discovery of helium.

After a *tour de force*, in the second half of the 1920's the final form of the theory of Quantum Mechanics started to crystallize. From then on, the evolution of physics accelerated in an unimaginable speed: the area of nuclear physics began to take shape. Particle physics developed, especially due to the construction of new powerful particle accelerators able to penetrate into the nucleus. Quantum Mechanics gave explanations of the structure of solid state, leading to solid state physics. The examples in which Quantum Mechanics boosted new developments, are many more. Practically all Nobel

Prize winners in physics made their historic discoveries and developments in areas where Quantum Mechanics is indispensable.

## 2.2. Physical Systems and Laws

A theory describing a physical system is based on a few basic laws, as for example the three axioms of Classical Mechanics. In Classical Mechanics one easily identifies the *integrals of motion* related to particular symmetries of the physical system.
In general, a symmetry is characterized by a transformation which leaves an object invariant. The simplest example is the symmetric appearance of a building, when the central line from top to bottom divides the building into two parts which are identical under reflection. A physical system is also invariant under a certain transformation when the physics does not change. For example, when an experiment is invariant under translation, e.g. the outcome is the same, no matter if the experiment is done in a particular spot or in another one after a translation; the physics is invariant under translation. When we do astronomical observations, which look back in time, the observations confirm that the physics has not changed significantly since the creation of the universe. This implies a symmetry of physics under translation in time.

All these symmetries have an important consequence, namely they lead to the *integrals of motion*. The invariance under spatial translation implies the conservation of the linear momentum (linear impulse) and the invariance under translation in time, results in the conservation of energy, $E$. Noether proved this connection at the beginning of the 20th century. All modern theories and the construction of new ones use this connection in order to obtain vital information and simplify the structure of physical theories.

In Classical Mechanics Newton introduced the concept of *inertial system,* requiring that all physical laws should be the same in any system which moves with respect to another at constant velocity. This was also postulated by Einstein in his theory of special relativity. In his Theory of General Relativity the restriction to an inertial system was relaxed. In general relativity *any system,* accelerated or not, is considered as equivalent and laws should be the same. The effect of accelerated versus non-accelerated systems is taken care of via a gravitational field, described by the curvature of space.

The concept of time and mass acquired a new meaning through the *Theory of Special and General Relativity*. Time turned out not to be absolute, as was postulated in Classical Mechanics, but, it depends on the system in which the observer is situated. Also the concept of mass reached a refinement in the theory of General Relativity: It is postulated that the accelerated and the gravitational mass are identical.

After the development of Quantum Mechanics the postulate of determinism had to be abolished. Instead, the description of the world became non-deterministic, a consequence of the Heisenberg's *uncertainty principle*. This principle states that certain conjugate variables, as the position and the linear momentum of a particle, cannot be measured simultaneously to any arbitrary precision. The limits are expressed in terms of Planck's constant $h$. This holds also for the conjugate variables *energy* and *time,* which allows the creation of energy out of nothing for a short time. The vacuum fluctuation is a consequence of this property and its existence has been confirmed in many cases.

One important change of the understanding of the physical world is related to the concepts of particle and wave. In the former subsection we mentioned that to the particle a trajectory is associated, while the wave is a property of space, i.e. a distribution of a field in space. Quantum Mechanics showed that all particles (photons, electron, nucleons,...) share both properties, i.e. particle and wave. The particular experiment determines which property it is probing.

Microscopic systems moving at a speed small as compared to light propagation (non-relativistic) are described by the *Schrödinger equation*. Relativistic systems require more sophisticated equations. For example, particles with spin $\frac{1}{2}$ are described by the Dirac equation, which predicted the existence of *antiparticles*. This prediction led to the concept of charge conjugation, which together with parity and time reversal, makes some of the most important transformations in physics. Today one knows that all physical theories have to be invariant under the transformation $PCT$, where $P$ is the parity transformation, $C$ is the charge conjugation, and $T$ is the time reversal. This was not always so. Up to the 1950's one assumed that all physical laws have to be invariant under $P$ alone. In 1956, the parity violation of the $\beta$-decay was proposed by T. D. Lee and C. N. Yang and confirmed shortly afterwards in an experiment by Wu et al. in 1957.

Development did not stop there. Today, the physics of complex systems has become more and more important. However, the basic laws (integrals of motion, how to implement symmetries, continuous and discrete symmetries) are still the same. All new physical theories have to obey the basic laws and symmetries which were observed and investigated in the 20th century.

-
-
-

**Bibliography**

Bishop D. M. (1973). *Group Theory and Chemistry* (Dover Publications, Inc, New York) [An excellent introduction to symmetry in Chemistry].

Bunde A. and Havlin S. (1995). *Fractals in Science* (Springer, Heidelberg) [The first chapter of this book contains a nice introduction to the theory of fractals. Further chapters describe recent developments.].

Chandler D. L. (2002). *Astronomy* **December 2002**, 42 [This article explains for the general public projects how to deviate an asteroid from its orbit avoiding its crash with the earth.].

Greiner W. (1985-2000). *Series of books on different topics in physics, ranging from classical mechanics to quantum field theory* (Springer, Heidelberg, Germany) [This is a series of books about the basic fields in physics, like Classical Mechanics, Electrodynamics, Quantum Mechanics, Thermodynamics and Statistics. It also includes several topics in Particle Physics and Field Theory. Strongly recommended for postgraduate students.].

Irion R. (2000). *LIGO's Mission of Gravity* (Science . April, 420) [A review on the experiment LIGO for the detection of gravitational waves.].

Kittel C. (1995). *Introduction to Solid State Physics* (John Wiley, New York) [The book is about solid state physics for beginners.].

Laloë F., *American Journal of Physics* (2001), 655-701 [An excellent article on the newest developments of Quantum Mechanics. It discusses the resolved and still open questions of Quantum Mechanics and its concepts.].

Lane A. M. and Thomas R. G. (1958). *Review of Modern Physics* , 257-353; Barrett R. F. , Robson B. A. and Tobocman W. (1983). *Review of Modern Physics* , 155-243. [Classical articles about reaction theory.].

*Los Alamos Science*, (1997), 1-191. [This volume consists of several articles exclusively dedicated to the neutrino physics and its history. It is a rich source of references from past to the present.].

Llewllyn Smith C. H. (1998). *What is the use of Science*, http://www.cern.ch [This article is published on-line in the CERN web page. It gives an excellent review on the importance of basic research, how it did lead to the industrial revolution in the 20'th century, its implications for the world economy and why the basic research has to be funded by the state and not by the industry.].

Nielssen M. and Chuang I. L. (2000). *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge) [ A basic introduction to quantum computing.].

Ratner, M. A. (2002). *Nanotechnology: A Gentle Introduction to the Next Big Idea* (Library of Congress Cataloging-inPublication Data, USA) [Reports on the recent advances in Nanotechnology and future directions.].

Sanders G. H. and Beckett D. (2000). *Sky and Telescope* **December 2000**, 40 [This article introduces for the general public the Project LIGO for the detection of gravitational waves.]

Taylor E. F. and Wheeler J. A. (1999). *Space Time Physics* (W.W. Freeman and Company, New York) [An excellent introduction to the concepts of relativity-for beginners *and* specialists.].

Waite S. R. (2004). *Quantum Investing* (Texere, ISBN-1587991403) [This book describes the impact the Quantum Mechanics had on the gross national product and of the economy].

*The New York Times* (August 15 2000) [Resumes the 10 most important questions related to particle physics and string theory].

Wilhelmsson H. (2001). *Fusion: A Voyage Through the Plasma Universe* (IOP-Publ., London) [An introduction to plasma physics in general and fusion.].

## Biographical Sketches

**José L. Mora-Lopez ,**was born in Charcas, San Luis Potosí, Mexico in 1950. His main scientific interests are the physicochemical properties of nanostructures materials. Other interests are phase transitions in low dimensional and confined systems, *Education:* M.Sc. Center for Research and Advanced Studies, Mexico City (1974)Doctor Rerum Naturalium, Freie Universitaet Berlin, Germany (1977)Posdoc at University of California, Berkeley, USAProfessor at the Institute for Scientific and Technological Research in San Luis Potosi, MexicoGeneral Director of the Institute for Scientific and Technological

Research in San Luis Potosi, MexicoJohn Simon Guggenheim Fellow (USA) 1984-1985Fellow, International Centre for Theoretical Physics, Trieste, Italy, 1985-1991*Senior Associate*, International Centre for Theoretical Physics, Trieste, Italy, 1992-1997.Alexander von Humboldt Fellow (Germany) 1992-1993.American Physical Society Fellow, 1993Member of the Third World Academy of Sciences (TWAS), 1991

**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 Invesitgadores, 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, algebraic nuclear collective models, structure of the ground state of Quantum Chromodynamics.