The methodology of physics Relation between physics and other disciplines and society

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ABSTRACT:
Physics is the most fundamental and all-inclusive of the sciences, and has had a profound effect on all scientific development. In fact, physics is the present-day equivalent of what used to be called natural philosophy, from which most of our modern sciences arose. Students of many fields find themselves studying physics because of the basic role it plays in all phenomena. In this chapter we shall try to explain what the fundamental problems in the other sciences are, but of course it is impossible in so small a space really to deal with the complex, subtle, beautiful matters in these other fields. Lack of space also prevents our discussing the relation of physics to engineering, industry, society, and war, or even the most remarkable relationship between mathematics and physics. (Mathematics is not a science from our point of view, in the sense that it is not a natural science. The test of its validity is not experiment.) We must, incidentally, make it clear from the beginning that if a thing is not a science, it is not necessarily bad. For example, love is not a science. So, if something is said not to be a science, it does not mean that there is something wrong with it; it just means that it is not a science.

I.   QUANTUM MECHANICS

[1]Although the various branches of physics differ in their experimental methods and theoretical approaches, certain general principles apply to all of them. The forefront of contemporary advances in physics lies in the submicroscopic regime, whether it be in atomic, nuclear, condensed-matter, plasma, or particle physics, or in quantum optics, or even in the study of stellar structure. All are based upon quantum theory (i.e., quantum mechanics and quantum field theory) and relativity, which together form the theoretical foundations of modern physics. Many physical quantities whose classical counterparts vary continuously over a range of possible values are in quantum theory constrained to have discontinuous, or discrete, values. Furthermore, the intrinsically deterministic character of values in classical physics is replaced in quantum theory by intrinsic uncertainty.

According to quantum theory, electromagnetic radiation does not always consist of continuous waves; instead it must be viewed under some circumstances as a collection of particle-like photons, the energy and momentum of each being directly proportional to its frequency (or inversely proportional to its wavelength, the photons still possessing some wavelike characteristics). Conversely, electrons and other objects that appear as particles in classical physics are endowed by quantum theory with wavelike properties as well, such a particle's quantum wavelength being inversely proportional to its momentum. In both instances, the proportionality constant is the characteristic quantum of action (action being defined as energy $\times$ time)—that is to say, Planck's constant divided by 2π, or $\hbar$.

In principle, all of atomic and molecular physics, including the structure of atoms and their dynamics, the periodic table of elements and their chemical behaviour, as well as the spectroscopic, electrical, and other physical properties of atoms, molecules, and condensed matter, can be accounted for by quantum mechanics. Roughly speaking, the electrons in the atom must fit around the nucleus as some sort of standing wave (as given by the Schrödinger

equation) analogous to the waves on a plucked violin or guitar string. As the fit determines the wavelength of the quantum wave, it necessarily determines its energy state. Consequently, atomic systems are restricted to certain discrete, or quantized, energies. When an atom undergoes a discontinuous transition, or quantum jump, its energy changes abruptly by a sharply defined amount, and a photon of that energy is emitted when the energy of the atom decreases, or is absorbed in the opposite case.

Models of atomic structure
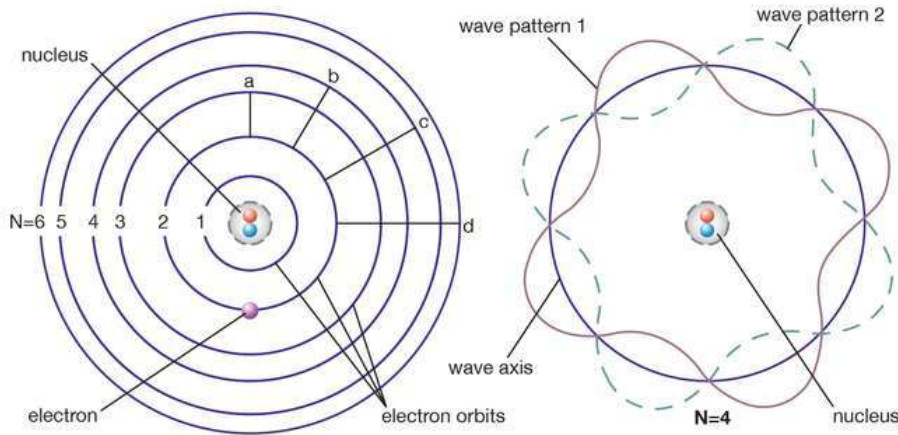
[2]Although atomic energies can be sharply defined, the positions of the electrons within the atom cannot be, quantum mechanics giving only the probability for the electrons to have certain locations. This is a consequence of the feature that distinguishes quantum theory from all other approaches to physics, the uncertainty principle of the German physicist Werner Heisenberg. This principle holds that measuring a particle's position with increasing precision necessarily increases the uncertainty as to the particle's momentum, and conversely. The ultimate degree of uncertainty is controlled by the magnitude of Planck's constant, which is so small as to have no apparent effects except in the world of microstructures. In the latter case, however, because both a particle's position and its velocity or momentum must be known precisely at some instant in order to predict its future history, quantum theory precludes such certain prediction and thus escapes determinism.

The complementary wave and particle aspects, or wave–particle duality, of electromagnetic radiation and of material particles furnish another illustration of the uncertainty principle. When an electron exhibits wavelike behavior, as in the phenomenon of electron diffraction, this excludes its exhibiting particle-like behavior in the same observation. Similarly, when electromagnetic radiation in the form of photons interacts with matter, as in the Compton effect in which X-ray photons collide with electrons, the result resembles a particle-like collision and the wave nature of electromagnetic radiation is precluded. The principle of complementarity, asserted by the Danish physicist Niels Bohr, who pioneered the theory of atomic structure, states that the physical world presents itself in the form of various complementary pictures, no one of which is by itself complete, all of these pictures being essential for our total understanding. Thus both wave and particle pictures are needed for understanding either the electron or the photon.
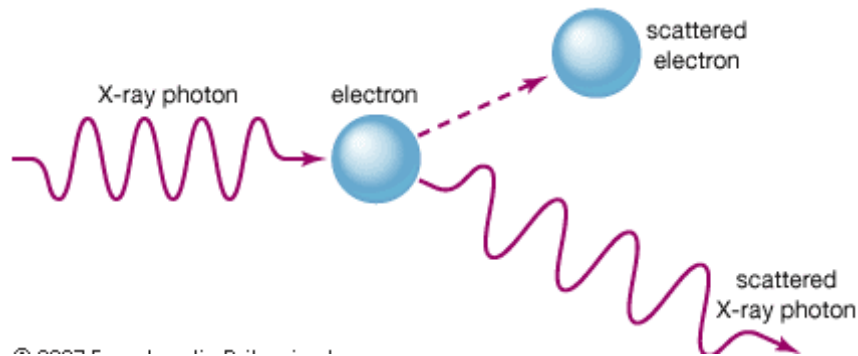
Although it deals with probabilities and uncertainties, the quantum theory has been spectacularly successful in explaining otherwise inaccessible atomic phenomena and in thus far meeting every experimental test. Its predictions, especially those of QED, are the most precise and the best checked of any in physics; some of them have been tested and found accurate to better than one part per billion.

II. RELATIVISTIC MECHANICS

In classical physics, space is conceived as having the absolute character of an empty stage in which events in nature unfold as time flows onward independently; events occurring simultaneously for one observer are presumed to be simultaneous for any other; mass is taken as impossible to create or destroy; and a particle given sufficient energy acquires a velocity that can increase without limit. The special theory of relativity, developed principally by Albert Einstein in 1905 and now so adequately confirmed by experiment as to have the status of physical law, shows that all these, as well as other apparently obvious assumptions, are false.

[3]Specific and unusual relativistic effects flow directly from Einstein's two basic postulates, which are formulated in terms of so-called inertial reference frames. These are reference systems that move in such a way that in them Isaac Newton's first law, the law of inertia, is valid. The set of inertial frames consists of all those that move with constant velocity with respect to each other (accelerating frames therefore being excluded). Einstein's postulates are: (1) All observers, whatever their state of motion relative to a light source, measure the same speed for light; and (2) The laws of physics are the same in all inertial frames.

The first postulate, the constancy of the speed of light, is an experimental fact from which follow the distinctive relativistic phenomena of space contraction (or Lorentz-FitzGerald contraction), time dilation, and the relativity of simultaneity: as measured by an observer assumed to be at rest, an object in motion is contracted along the direction of its motion, and moving clocks run slow; two spatially separated events that are simultaneous for a stationary observer occur sequentially for a moving observer. As a consequence, space intervals in three-dimensional space are related to time intervals, thus forming so-called four-dimensional space-time.

$$T = \frac{T_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$L = L_0 \sqrt{1 - \frac{v^2}{c^2}}$$

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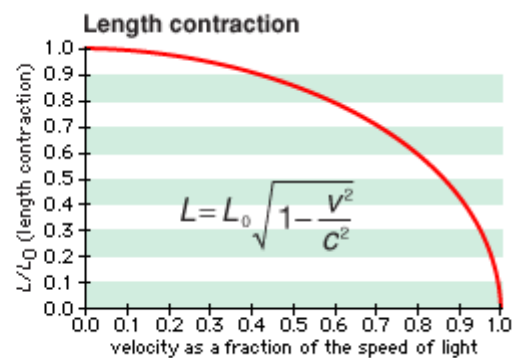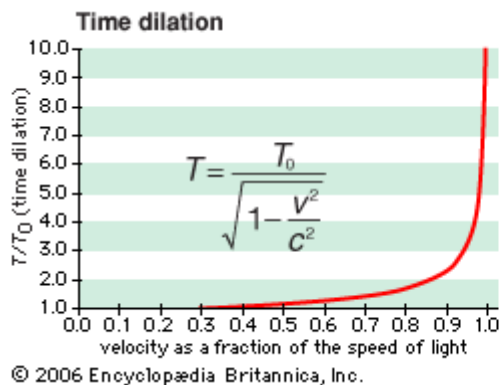
The second postulate is called the principle of relativity. It is equally valid in classical mechanics (but not in classical electrodynamics until Einstein reinterpreted it). This postulate

implies, for example, that table tennis played on a train moving with constant velocity is just like table tennis played with the train at rest, the states of rest and motion being physically indistinguishable. In relativity theory, mechanical quantities such as momentum and energy have forms that are different from their classical counterparts but give the same values for speeds that are small compared to the speed of light, the maximum permissible speed in nature (about 300,000 kilometres per second, or 186,000 miles per second). According to relativity, mass and energy are equivalent and interchangeable quantities, the equivalence being expressed by Einstein's famous mass-energy equation $E = mc^2$, where m is an object's mass and c is the speed of light.

The general theory of relativity is Einstein's theory of gravitation, which uses the principle of the equivalence of gravitation and locally accelerating frames of reference. Einstein's theory has special mathematical beauty; it generalizes the "flat" space-time concept of special relativity to one of curvature. It forms the background of all modern cosmological theories. In contrast to some vulgarized popular notions of it, which confuse it with moral and other forms of relativism, Einstein's theory does not argue that "all is relative." On the contrary, it is largely a theory based upon those physical attributes that do not change, or, in the language of the theory, that are invariant.

Conservation laws and symmetry

Since the early period of modern physics, there have been conservation laws, which state that certain physical quantities, such as the total electric charge of an isolated system of bodies, do not change in the course of time. In the 20th century it has been proved mathematically that such laws follow from the symmetry properties of nature, as expressed in the laws of physics. The conservation of mass-energy of an isolated system, for example, follows from the assumption that the laws of physics may depend upon time intervals but not upon the specific time at which the laws are applied. The symmetries and the conservation laws that follow from them are regarded by modern physicists as being even more fundamental than the laws themselves, since they are able to limit the possible forms of laws that may be proposed in the future.

Conservation laws are valid in classical, relativistic, and quantum theory for mass-energy, momentum, angular momentum, and electric charge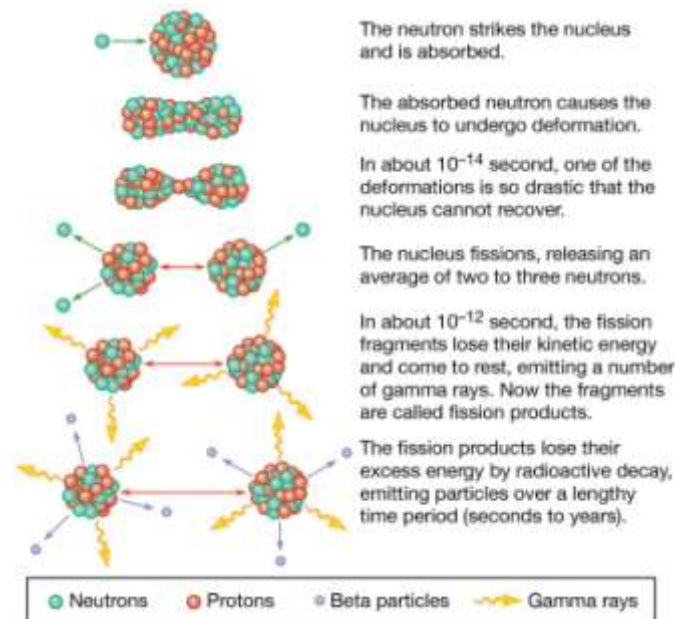. (In nonrelativistic physics, mass and energy are separately conserved.) Momentum, a directed quantity equal to the mass of a body multiplied by its velocity or to the total mass of two or more bodies multiplied by the velocity of their centre of mass, is conserved when, and only when, no external force acts. Similarly angular momentum, which is related to spinning motions, is conserved in a system upon which no net turning force, called torque, acts. External forces and torques break the symmetry conditions from which the respective conservation laws follow.

In quantum theory, and especially in the theory of elementary particles, there are additional symmetries and conservation laws, some exact and others only approximately valid, which play no significant role in classical physics. Among these are the conservation of so-called quantum numbers related to left-right reflection symmetry of space (called parity) and to the reversal symmetry of motion (called time reversal). These quantum numbers are conserved in all processes other than the weak force.

Other symmetry properties not obviously related to space and time (and referred to as internal symmetries) characterize the different families of elementary particles and, by extension, their composites. Quarks, for example, have a property called baryon number, as do protons, neutrons, nuclei, and unstable quark composites. All of these except the quarks are known as baryons. A failure of baryon-number conservation would exhibit itself, for instance, by a proton decaying into lighter non-baryonic particles. Indeed, intensive search for such proton decay has been conducted, but so far it has been fruitless. Similar symmetries and conservation laws hold for an analogously defined lepton number, and they also appear, as does the law of baryon conservation, to hold absolutely.

Fundamental forces and fields

The four basic forces of nature, in order of increasing strength, are thought to be: (1) the gravitational force between particles with mass; (2) the electromagnetic force between particles with charge or magnetism or both; (3) the colour force, or strong force, between quarks; and (4) the weak force by which, for example, quarks can change their type, so that a neutron decays into a proton, an electron, and an antineutrino. The strong force that binds protons and neutrons into nuclei and is responsible for fission, fusion, and other nuclear reactions is in principle derived from the colour force. Nuclear physics is thus related to QCD as chemistry is to atomic physics.

The neutron strikes the nucleus and is absorbed.

The absorbed neutron causes the nucleus to undergo deformation.

In about 10^{-14} second, one of the deformations is so drastic that the nucleus cannot recover.

The nucleus fissions, releasing an average of two to three neutrons.

In about 10^{-12} second, the fission fragments lose their kinetic energy and come to rest, emitting a number of gamma rays. Now the fragments are called fission products.

The fission products lose their excess energy by radioactive decay, emitting particles over a lengthy time period (seconds to years).

● Neutrons   ● Protons   ⁘ Beta particles   〰 Gamma rays

According to quantum field theory, each of the four fundamental interactions is mediated by the exchange of quanta, called vector gauge bosons, which share certain common characteristics. All have an intrinsic spin of one unit, measured in terms of Planck's constant $\hbar$. (Leptons and quarks each have one-half unit of spin.) Gauge theory studies the group of transformations, or Lie group, that leaves the basic physics of a quantum field invariant. Lie groups, which are named for the 19th-century Norwegian mathematician Sophus Lie, possess a special type of symmetry and continuity that made them first useful in the study of differential equations on smooth manifolds (an abstract mathematical space for modeling physical processes). This symmetry was first seen in the equations for electromagnetic potentials, quantities from which electromagnetic fields can be derived. It is possessed in pure form by the eight massless gluons of QCD, but in the electroweak theory—the unified theory of electromagnetic and weak force interactions—gauge symmetry is partially broken, so that only the photon remains mass less, with the other gauge bosons (W^+, W^-, and Z) acquiring large masses. Theoretical physicists continue to seek a further unification of QCD with the electroweak theory and, more ambitiously still, to unify them with a quantum version of gravity in which the force would be transmitted by mass less quanta of two units of spin called gravitons.

III.   THE METHODOLOGY OF PHYSICS

[4]Physics has evolved and continues to evolve without any single strategy. Essentially an experimental science, refined measurements can reveal unexpected behaviour. On the other hand, mathematical extrapolation of existing theories into new theoretical areas, critical reexamination of apparently obvious but untested assumptions, argument

by symmetry or analogy, aesthetic judgment,   pure accident, and hunch—each of these plays a role (as in all of science). Thus, for example, the quantum hypothesis proposed by the German physicist Max Planck was based on observed departures of the character of blackbody radiation (radiation emitted by a heated body that absorbs all radiant energy incident upon it) from that predicted by classical electromagnetism. The English physicist P.A.M. Dirac predicted the existence of the positron in making a relativistic extension of the quantum theory of the electron. The elusive neutrino, without mass or charge, was hypothesized by the German physicist Wolfgang Pauli as   an alternative to   abandoning the conservation laws in the beta-decay process. Maxwell conjectured that if changing magnetic fields create electric fields (which was known to be so), then changing electric fields might create magnetic fields, leading him to the electromagnetic theory of light. Albert Einstein's special theory of relativity was based on a critical reexamination of the meaning of simultaneity, while his general theory of relativity rests on the equivalence of inertial and gravitational mass.

Although the tactics may vary from problem to problem, the physicist invariably tries to make unsolved problems more tractable by constructing a series of idealized models, with each successive model being a more realistic representation of the actual physical situation. Thus, in the theory of gases, the molecules are at first imagined to be particles that are as structure less as billiard balls with vanishingly small dimensions. This ideal picture is then improved on step by step.

The correspondence principle, a useful guiding principle for extending theoretical interpretations, was formulated by the Danish physicist Niles Bohr in the context of the quantum theory. It asserts that when a valid theory is generalized to a broader arena, the new theory's predictions must agree with the old one in the overlapping region in which both are applicable. For example, the more comprehensive theory of physical optics must yield the same result as the more restrictive theory of ray optics whenever wave effects proportional to the wavelength of light are negligible on account of the smallness of that wavelength. Similarly, quantum mechanics must yield the same results as classical mechanics in circumstances when Planck's constant can be considered as negligibly small. Likewise, for speeds small compared to the speed of light (as for baseballs in play), relativistic mechanics must coincide with Newtonian classical mechanics.

Some ways in which experimental and theoretical physicists attack their problems are illustrated by the following examples.

[5]The modern experimental study of elementary particles began with the detection of new types of unstable particles produced in the atmosphere by primary radiation, the latter consisting mainly of high-energy protons arriving from space. The new particles were detected in Geiger counters and identified by the tracks they left in instruments called cloud chambers and in photographic plates. After World War II, particle physics, then known as high-energy nuclear physics, became a major field of science. Today's high-energy particle accelerators can be several kilometers in length, cost hundreds (or even thousands) of millions of dollars, and accelerate particles to enormous energies (trillions of electron volts). Experimental teams, such as those that discovered the W^+, W^-, and Z quanta of the weak force at the European Laboratory for Particle Physics (CERN) in Geneva, which is funded by its 20 European member states, can have 100 or more physicists from many countries, along with a larger number of technical workers serving as support personnel. A variety of visual and electronic techniques are used to interpret and sort the huge amounts of data produced by their efforts, and particle-physics laboratories are major users of the most advanced technology, be it superconductive magnets or supercomputers.

Theoretical physicists use mathematics both as a logical tool for the development of theory and for calculating predictions of the theory to be compared with experiment. Newton, for one, invented integral calculus to solve the following problem, which was essential to his formulation of the law of universal gravitation: Assuming that the attractive force between any pair of point particles is inversely proportional to the square of the distance separating them, how does a spherical distribution of particles, such as Earth, attract another nearby object? Integral calculus, a procedure for summing many small contributions, yields the simple solution that Earth itself acts as a point particle with all its mass concentrated at the centre. In modern physics, Dirac predicted the existence of the then-unknown positive electron (or positron) by finding an equation for the electron that would combine quantum mechanics and the special theory of relativity.

Relations between physics and other disciplines and society Influence of physics on related disciplines

Because physics elucidates the simplest fundamental questions in nature on which there can be a consensus, it is hardly surprising that it has had a profound impact on other fields of science, on philosophy, on the worldview of the developed world, and, of course, on technology.

Indeed, whenever a branch of physics has reached such a degree of maturity that its basic elements are comprehended in general principles, it has moved from basic to applied physics and thence to technology. Thus almost all current activity in classical physics consists of applied physics, and its contents form the core of many branches of engineering. Discoveries in modern physics are converted with increasing rapidity into technical innovations and analytical tools for associated disciplines. There are, for example, such nascent fields as nuclear and biomedical engineering, quantum chemistry and quantum optics, and radio, X-ray, and gamma-ray astronomy, as well as such analytic tools as radioisotopes, spectroscopy, and lasers, which all stem directly from basic physics.

Apart from its specific applications, physics—especially Newtonian mechanics—has become the prototype of the scientific method, its experimental and analytic methods sometimes being imitated (and sometimes inappropriately so) in fields far from the related physical sciences. Some of the organizational aspects of physics, based partly on the successes of the radar and atomic-bomb projects of World War II, also have been imitated in large-scale scientific projects, as, for example, in astronomy and space research.

The great influence of physics on the branches of philosophy concerned with the conceptual basis of human perceptions and understanding of nature, such as epistemology, is evidenced by the earlier designation of physics itself as natural philosophy. Present-day philosophy of science deals largely, though not exclusively, with the foundations of physics. Determinism, the philosophical doctrine that the universe is a vast machine operating with strict causality whose future is determined in all detail by its present state, is rooted in Newtonian mechanics, which obeys that principle. Moreover, the schools of materialism, naturalism, and empiricism have in large degree considered physics to be a model for philosophical inquiry. An extreme position is taken by the logical positivists, whose radical distrust of the reality of anything not directly observable leads them to demand that all significant statements must be formulated in the language of physics.

The uncertainty principle of quantum theory has prompted a reexamination of the question of determinism, and its other philosophical implications remain in doubt. Particularly problematic is the matter of the meaning of measurement, for which recent theories and experiments confirm some apparently non causal predictions of standard quantum theory. It is fair to say that though physicists agree that quantum theory works, they still differ as to what it means.

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