# PHYSICS: WHAT DOES ONE NEED TO KNOW?

*by John R. Albright*

*Abstract.* For the basic areas of physics—classical mechanics, classical field theories, and quantum mechanics—there are local dynamical theories that offer complete descriptions of systems when the proper subsidiary conditions also are provided. For all these cases there are global theories from which the local theories can be derived. Symmetries and their relation to conservation laws are reviewed. The standard model of elementary particles is mentioned, along with frontier questions about them. A case against reductionism in physics is presented.

*Keywords:* classical field theory; classical mechanics; collective phenomena; conservation laws; determinism, dynamical theory; Lagrangian mechanics; Maxwell's equations; Newton's laws; parity; phase transition; physics; quantum mechanics; quark; reductionism; Schrödinger equation; standard model; symmetry; teleology; uncertainty principle; wave function.

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Physics is the subject in which we consider the simplest systems and then attempt to analyze them completely. Such a description of physics may seem not entirely serious in view of the reputation for difficulty that the subject has earned. But the systems are really chosen by physicists for their inherent simplicity; the difficulty comes with the attempt at completeness of description, since it has been found that mathematics is the descriptive vehicle that most clearly summarizes what is happening.

In view of this definition, I will examine various fields of physics that have achieved a certain amount of success at the program of complete

John R. Albright is Professor of Physics and Head, Chemistry and Physics, at Purdue University Calument, Hammond, IN 46323. 

[*Zygon*, vol. 31, no. 3 (September 1996).]
 ISSN 0591-2385

analysis and understanding. For each special area of physics, certain questions are considered: (1) What is the historical background of the topic, and how has it been put to practical use? (2) What constitutes a *complete* description of a system? (3) What is the dynamical theory on which a complete description may be based? (4) What additional conditions are needed to augment the dynamical theory? (5) Is there an alternative to the dynamical theory, based on a global rather than a local view?

This set of questions emphasizes the importance of the theoretical structure of physics. It must be remembered that physics also is an experimental science, and that theories are not just ideas that have been made up by antisocial recluses who wear baggy sweaters and no socks. Theories are not valuable if they cannot make any connection with the real world. In this essay I shall limit the discussion to theories that have been tested often, with considerable sensitivity, and that have passed the tests: that is, they have been exposed to the risk of falsification and have survived. I shall not be able here to summarize the experimental basis of these theories. I shall also not attempt to survey all of physics, but instead I will concentrate mainly on those theories that Roger Penrose (1989, 152) called "superb" because of their wide-ranging applicability, their accuracy, and their beauty. Some attention will be paid to theories that are not yet complete in the same way that the superb theories are. Because of space limitations I shall not consider cosmology in any detail.

## CLASSICAL MECHANICS

The oldest superb theory in all of science is classical mechanics, the macroscopic theory of motion from the seventeenth century—the theory of Galileo Galilei, René Descartes, and Isaac Newton. It does a remarkable job of describing systems whose size corresponds to human scale; only for the very smallest and very largest systems do we need a better theory. Classical mechanics is useful as the basis for mechanical engineering. It enables the precise calculations of the orbits of everything in the solar system; it makes possible the prediction of the motions of the planets years in advance of when they actually happen. Its principles govern much of what we encounter in our daily lives.

A *system* in classical mechanics is construed as a set of points—each with its own mass—that are in motion; a *complete description* is achieved by getting a set of equations that tells us the space coordinates of each point as it evolves in time. These equations constitute the *trajectory* of the system. This description is complete in the sense that it enables calculation of the past and future motion of the parts of the system. Given enough mathematical prowess, this information can be used to calculate other quantities of interest, such as the velocity, the acceleration, the energy, the momentum, and the angular momentum. Since the time dependence is completely specified, the system is deterministic, with all the connections to religion and philosophy that are implied by that term.

The dynamical basis for obtaining the trajectory of a classical system is the set of equations obtained from Newton's laws, the *equations of motion.* They are differential equations of the second order, so that calculus is needed to set them up and to solve them for the trajectory. Here lies part of the reason why physics has a reputation for difficulty. The differential equations form a *local* theory, since they are applied to the system at a specific point in space and time. The opposite would be a *global* theory, in which all points in space and time are considered together.

To find the relevant solution to the equations of motion, we need to specify *initial conditions.* Like most differential equations, the equations of motion in classical mechanics have an infinite number of possible solutions, only one of which corresponds to the actual motion of the system. It is the initial conditions that render a solution unique and make determinism a possibility. The initial condition for a single point mass is usually a specification of the position and the velocity of the mass at a starting time. At this point it must be made clear that we do not need to know how to solve differential equations in order to teach the relation between science and religion. But it would help if—in a private setting—we made use of a computer to follow a simulation of a relatively simple system that evolves according to Newton's laws, starting from a given initial state. By changing the initial conditions, we would see a different time evolution pattern. Some systems are so stable that a slight change in the initial conditions leads to an almost imperceptible change in the development of the system. Others are so unstable (the technical term is *chaotic*) that their evolution is drastically different if the initial conditions are altered even a little.

Alternate formulations of Newton's laws were developed in the eighteenth and early nineteenth centuries by Moreau de Maupertuis, Leonhard Euler, Joseph Louis Lagrange, and William Rowan Hamilton. I will describe here the approach of Euler and Lagrange. We begin by writing the *Lagrangian* for a given system. For certain simple and important examples, the Lagrangian depends only on the positions and the velocities of the particles that make up the system; it is calculated by subtracting the potential energy from the kinetic energy. Next we construct the sum of all Lagrangians for all the points between (1) an initial point in space and time and (2) a final point. This summation is called the *action.*

There are many ways to calculate the action for a particular pair of points, depending on the path taken between the beginning and the end. The path that extremizes the action is the one actually used by the system for its motion. The *calculus of variations* is the branch of mathematics that we use to go from an extremized action to a set of equations, which turn out to be identical to those obtained directly from Newton's laws (Yourgrau and Mandelstam 1968). This Lagrangian procedure is a global approach to mechanics, since it requires (in principle only—we never really have to calculate all possible action quantities) calculating the action through all possible paths in space and time. As mentioned earlier, a local approach calculates quantities at a single point and uses them to figure out what will happen next. Nevertheless, the global approach leads to the same complete description that we get from the local approach. Global approaches are sometimes referred to as "modern teleology" (Barrow and Tipler 1986) because the system seems to act as though it knows it has to minimize (sometimes "maximize" should be used instead) the action, just as water acts as if it is supposed to minimize its potential energy by flowing toward the sea.

## CLASSICAL FIELD THEORIES

If instead of a collection of massive points we consider a physical quantity (e.g., pressure, electric field, magnetic field, height of water above or below the mean level) that can be defined for each point in space and time, then this *field quantity* can be treated in a way analogous to the displacement coordinate of classical mechanics. Theories of acoustics, electricity, magnetism, light, and fluid flow all can be considered in this way. To be specific, I will use James Clerk Maxwell's theory of electromagnetism as an exemplar for this section. The experiments of Benjamin Franklin, Charles Augustin de Coulomb, Alessandro Volta, Hans Christian Oersted, Michael Faraday, and Joseph Henry all helped guide the way to a synthesis in which electric and magnetic forces are described by field concepts. The electric field is defined at each point by a vector with three components corresponding to $x$, $y$, and $z$, the three space coordinates; the magnetic field has a similar set of three components. Experiments by Oersted, Faraday, and Henry showed conclusively that the electric field and magnetic field are not independent of each other whenever either one of them is changing in time. Maxwell synthesized a theory of both electric and magnetic fields and showed that these inseparable fields can propagate together as waves traveling at the speed of light. They *are* light. Maxwell's theory describes light considered as any electromagnetic wave, visible or not. Whether the human eye can see the wave depends entirely on the wavelength. X rays, ultraviolet, infrared, microwaves, and radio/television signals are just as much light as visible light. Practical application of Maxwell's electromagnetic theory includes much of electrical engineering—telephone, radio, television, radar, microwave ovens, and the lighting that allows us to see when it is dark.

A complete description of an electromagnetic system requires that we know the three components of the electric field and the three components of the magnetic field as functions of space and time for all points. The dynamical theory that governs such systems is the set of four equations (as written in their usual vector form) called Maxwell's equations. They constitute the local theory, since all four are valid at each point of space and time. As in the mechanical case, they have an infinite number of solutions, and so the physical description of the fields requires additional conditions, analogous to the initial conditions of classical mechanics. These are called *boundary conditions*, since they often involve knowing the properties of the fields on a surface that surrounds an interior region; the fields are known on this surface but are unknown in the interior volume. With the given conditions and with Maxwell's equations it is possible to arrive at the complete description.

The Lagrangian approach works for electromagnetism. The Lagrangian must be replaced by a Lagrangian density (i.e., the amount of Lagrangian per unit volume), which is then turned into an action by summing over both space and time. The calculus of variations is next used to extremize the action to a maximum or a minimum. It should be no surprise to learn that the result of all this is the reappearance of Maxwell's equations (Jackson 1975, 597). Once again, the global theory contains the local one.

The general features of electromagnetic theory presented here are typical of other classical field theories. A feature that often appears in such theories, including electromagnetism, is the propagation of waves governed by a wave equation that results from the theory. In all these cases there also is a global form of the theory.

## Quantum Mechanics

In 1925 and 1926, Werner Heisenberg, P. A. M. Dirac, and Erwin Schrödinger invented three different approaches to quantum mechanics, a new theory of matter in the small. It was quickly recognized that these formulations were consistent with one another. A fourth consistent approach was invented later by Richard Feynman. Quantum mechanics rapidly became the method of choice for describing systems the size of molecules or smaller. The theory is not outrageously difficult, but it is unfamiliar to those who are used to classical physics. It has proved to be extremely practical, since without it there would be little or no understanding of atomic physics: lasers would be a total mystery. Those working in physics of the solid state would have been unable to make the progress that has led to transistors, integrated circuits, chips, and the associated technology of computers and communication. Nuclear technology also depends on quantum mechanics to provide the basis of understanding.

When we use the methods of Schrödinger, the complete description of a quantum mechanical system resides in the wave function, *psi*, which is a field quantity very similar to those described in the preceding section. If we know psi as a function of time and the space coordinates, we know all that is knowable about the system. It happens that quantum mechanics does not permit us to know some of the things that classical mechanics allows. The celebrated example is that of Heisenberg's uncertainty principle, which states that we cannot know simultaneously both the position and the momentum of a particle to arbitrary accuracy. The best we can do is to calculate probabilities of finding the position within a certain range or the momentum in its range. It follows that Newtonian determinism is impossible in quantum mechanics, since the initial conditions required in classical mechanics to compute the trajectory are made unavailable as a result of the uncertainty principle. It must be emphasized that the uncertainty principle is not a starting point for quantum mechanics. It is a consequence of the basic assumptions of the theory. Heisenberg began by seeking a theory that would emphasize those aspects of atoms that could be directly observable; he was then led to a set of assumptions that constitute the theory. Not until two years later did he find that these assumptions implied the uncertainty principle, and the logic is inexorable. If the uncertainty principle is wrong, then quantum mechanics must be abandoned.

According to quantum mechanics, a system wherein the energy does not depend on time will get into a stationary state and stay there until it emits a photon (a small package of electromagnetic energy) and makes a sudden transition into a state of lower energy. There may in fact be several such states of lower energy into which the transition may occur. Quantum mechanics says that for any single example of a transition, it is not possible to predict into which state the system will jump; what *is* possible is to calculate the probabilities for jumping into the various states. If the experiment is repeated often enough, the frequencies of jumping agree statistically with those predicted by quantum mechanics. Again, the explicit denial of determinism is unavoidable.

The dynamical equation that we use to find the wave function is either the Schrödinger equation or its relativistic generalization, the Dirac equation. These equations have both been remarkably successful at enabling the calculation of the properties of atoms and molecules. They have been somewhat successful but less impressive in the analogous task for nuclei and elementary particles. In any event, we need to have boundary conditions in order to find the relevant solution (and discard the irrelevant ones) of the Schrödinger equation or the Dirac equation.

The procedures bear a close resemblance to those of classical field theories; mathematical methods devised by Lord Rayleigh for analysis of classical light waves or sound waves have been taken over by quantum mechanics with little alteration. Furthermore, the Lagrangian formalism works in quantum mechanics in a way that resembles classical field theory. We might have expected such a property of the Schrödinger equation or the Dirac equation, since they are specific types of wave equation, mathematically akin to classical field theory.

## Symmetry and Conservation Principles

Physicists are very fond of *conservation laws*. If we can be sure that a certain physical quantity remains unchanged even though the rest of the system is changing drastically, then we say that the quantity is conserved. Such laws appear both in classical and in quantum physics. An important reason for stressing the Lagrangian in the preceding sections is that it is the best way to see the connection between symmetries and conservation laws. Noether's theorem states that if the Lagrangian has a specific type of symmetry, there will be a corresponding conservation law for the system described by that Lagrangian. Already in the case of classical mechanics we can see examples of this truth. If the Lagrangian does not depend explicitly on time, then the energy will be conserved. The symmetry is one of time translation: as time passes, the Lagrangian remains unchanged; therefore, it is symmetric in time. A similar principle arises for each space coordinate: if a change in the $x$ coordinate leaves the Lagrangian unchanged, then the $x$ component of the linear momentum will be conserved. In other words, invariance or symmetry under space translation leads to conservation of momentum. Invariance under rotation through an arbitrary angle implies the conservation of angular momentum.

A more subtle type of symmetry, called *gauge invariance*, arises in Maxwell's electromagnetism. The invariance already is present in the local form of the theory; if we perform a special type of transformation (a gauge transformation) on the electric and magnetic potentials, the electric and magnetic fields will remain unchanged, and there will be no observable physical consequences of the transformation, since the fields contain a complete description of the system. But if the transformation is done on the Lagrangian, it leads to conservation of electric charge, one of the most revered principles in all of science.

The great respect that physicists have developed for conservation laws might lead one to think that nearly every physical quantity obeys such a law. Such a belief would be mistaken, since there are many complicated combinations of physical quantities that are not conserved. They are unrelated to any symmetry of the Lagrangian.

There are three discrete (as opposed to continuous) symmetries that have been studied in great depth in the second half of the twentieth century: parity ($P$), charge conjugation ($C$), and time reversal ($T$) (Zee 1986). Parity refers to the transformation in which all three space coordinates ($x$, $y$, $z$) have their algebraic sign changed. This transformation incidentally changes the left hand into the right. Charge conjugation changes a particle into its antiparticle (electron into positron, proton into antiproton, and so on). Time reversal, as the name implies, causes the clock to run backward (Sachs 1987).

All of the theories considered above exhibit invariance under $C$, $P$, and $T$ separately or in any combination. It was once thought that all of physics had to be invariant under all three symmetries, but the carefully constructed suggestion of T. D. Lee and C. N. Yang in the 1950s led to several experiments that demonstrated conclusively that $P$ is not conserved in the weak nuclear interaction. It was and is still believed that physics is invariant under the product $CPT$; efforts to construct a theory without this invariance have failed. So it follows that if $P$ is violated, then at least one of the other two symmetries must also be violated. The correct answer is $C$; when $P$ is violated, $C$ is also. The combination of $CP$ (and therefore $T$) is conserved most of the time, but in the 1960s an experiment was performed that was the first in a sequence to show that a small violation of $T$ can exist.

These discrete symmetries and their violations may seem unimportant, but they point to large cosmological issues: why is it that we are made of protons, but antiprotons are so rare? Is there an imbalance of matter over antimatter in the universe? Or is the imbalance just a local effect that is averaged to equal amounts of matter and antimatter if we looked at more of outer space? If the imbalance is global, then how did the universe get this way?

Another example of the breaking of a discrete symmetry occurs in biological systems, where a specific preference for right-handed or left-handed molecules occurs in apparent violation of parity. Sugars, amino acids, and DNA all exhibit this effect. On a larger scale, handedness appears in the development of flounders and in the bicameral human brain.

## ELEMENTARY PARTICLES

The notion that all matter is made of many copies of a small number of building blocks can be traced to Democritus in ancient Greek culture. In the nineteenth century, the advances of chemistry led to the idea that atoms really exist and that *they* are the fundamental building blocks. The discovery of the electron and of the nucleus of the atom changed all that. The nucleus itself—after 1932 when James Chadwick discovered the neutron—is known to consist of a certain number of protons and neutrons. Nuclear physicists saw their task as the elucidation of the forces that hold the neutrons and protons together. To gain insight into the situation, they bombarded nuclei with projectiles, using ever-increasing energy in the mistaken hope that they would get the resolution to "see" the structure of the nucleus. Instead, they saw a great variety of species of particles—enough to threaten exhaustion of both the Latin and Greek alphabets to find symbols to designate the discoveries. Clearly, not all of these new particles could be fundamental in any meaningful sense.

A consensus has been achieved, called the *standard model*, in which the fundamental building blocks are called *quarks*. There are six types of quarks (up, down, charmed, strange, top, and bottom), and only the first two types are needed to explain conventional nuclear physics. A proton is not really an elementary particle; rather, it is made of three quarks (two up-quarks and one down-quark). A neutron is made of two down-quarks and one up-quark. Quarks are held together by *gluons* (there are eight species). Also fundamental are *leptons*, of which the six types are parallel to the six types of quarks. Both quarks and leptons obey the Dirac equation of quantum mechanics; therefore, each species has a corresponding antiparticle that has the opposite sign for its electric charge and various other properties as well. *Mesons* are particles once thought to be elementary but which are now understood to consist of a quark and an antiquark held together by gluons.

The standard model answers certain questions about fundamental particles but leaves others to be answered by future research. For example, why are there exactly six species of quarks? Why do the quarks and leptons have the masses that are observed? Are all these particles really fundamental, or is there a deeper layer for us to probe? Will we learn that there is a much smaller number of *really* fundamental particles, and that the ones we see are only composites?

## ANTIREDUCTIONISM

Physicists often are accused of being reductionist—believing that physics could in principle explain all the more complicated sciences, if only the time and the funds to figure out how were available. Dirac (1929) expressed such a vainglorious view: "The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble." Such an attitude is not likely to make a physicist popular with colleagues from other departments. But it is misguided for other reasons, since physics contains within itself strong weapons to use against reductionism. Three examples follow.

Exchange symmetry or antisymmetry is the first example of how reductionism is misleading. We can study the properties of a single isolated electron and feel that we have achieved the kind of complete understanding so desired in physics. Such study does not prepare us for what happens when two electrons are in the system. Their wave function is *antisymmetric:* it must change its algebraic sign every time we exchange the two electrons—a fact that does not follow from the one-electron theory but which has profound significance for the rest of science. Nuclear bonding, atomic structure, and molecular bonding are all possible because of the exchange antisymmetry of electrons.

A second example is the more general category of collective effects. When large numbers of atoms get together, we can observe phase transitions—solids melting to liquids, liquids boiling to gases, and so on. The sharp discontinuities from these phase transitions are not predictable from the one-atom theory. Condensed matter physics is replete with other examples of phase transitions involving order versus disorder: ferromagnetism, superconductivity, superfluid helium, and so on.

A third example is that of symmetry breaking. The parity violations seen in various organic molecules are not derivable from the single-atom theory. Inorganic molecules can show such effects at a simpler level: the water molecule has an electric dipole moment (i.e., one end of the molecule has a positive charge, the other a negative charge), a fact that appears to violate both parity and time-reversal invariance if we know only the properties of hydrogen and oxygen by themselves. Collective interaction yields qualitatively new phenomena. For all of its beauty, elegance, intricacy, practical worth, and closeness to the Mind of the Creator, physics does not necessarily hold the *only* key to the universe.

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