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Certainty and Chance in the Physical Sciences

Wytse Van Dijk
Dordt College

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by Wytse Van Dijk
Associate Professor of Physics

Dr. Wytse van Dijk received his Ph.D. in Physics from McMaster University in 1968. He spent two years as a postdoctoral fellow at the University of Oxford, and taught one year at Mount Allison University before joining the Dordt faculty in 1971. His area of research is nuclear theory.

Introduction

Some profound changes have taken place in the description and understanding of the physical aspect of reality. These changes have been pervasive; not only do they affect the application of the scientific results, the technology, but they have also altered the foundational presupposition on which the whole of physical theory rests.

In the physical sciences we attempt to describe and explain physical reality. The science is an experimental or observational one; that is, we gain insight and knowledge about this aspect of reality by looking at and making measurements on the physical phenomena in creation. We do not stop at observations, however, but attempt to build a theoretic system which correlates and unifies the observations. The theoretic system, which is not perfect and which will never be complete, is nevertheless a reflection of the actual structure that we know exists in creation, and all our activity in this regard is geared to more and more accurately describing the laws, regularities, and orderliness that has been there since the beginning.

Bearing in mind then that all theories are constructs which are based on observations and correlations of them, we will look at two such systems in particular: classical physics, which was current around 1900, and modern physics, which has been developed since that time. In this short treatise we cannot be expected to present an exhaustive view, but rather try to emphasize some of the more important changes that have occurred. With these changes an attitude of certainty and optimism in the ability to know nature with infinite accuracy made way for indeterminism, a view that one cannot predict the course of physical events with an arbitrary degree of certainty.

Classical Physics

1. Description

Fundamental to classical physics are the laws of mechanics. These laws were stated at different times in various forms, but they all amount to the mathematical description of objects in motion. Newton's formulation in terms of his three laws of motion was the first, and probably still is the best known. More elegant mathematical formulations of mechanics were developed by Lagrange and Hamilton.

The laws of mechanics allow us to describe the motion of an object when the forces acting on it, its initial position, and its initial motion, are known. For example, given the position and speed of a baseball just after it has been struck by a bat, and knowing the force of gravity on the ball, we are able to predict exactly the trajectory of the ball and the speed of the ball at each point in its trajectory. Furthermore, we can determine at what instant the ball will be at a particular position in its path.

This is a rather simple example of a force acting on a single object, or particle as it is referred to in mechanics. But more complicated situations are analyzed equally well. The earth and moon interact by means of a gravitational force; this results in the moon travelling in a nearly circular orbit around the earth. The moon's orbit is wholly predicted by the laws of mechanics, as are the orbits of the earth and other planets around the sun. In fact, the theoretic determination of those orbits was one of the first triumphs of Newtonian mechanics.

One might consider even more complex situations involving many particles and forces acting between them all. In principle the evolution of such systems in time can be accurately predicted provided we know the positions and the velocities of all the particles at one instant.

It is quite clear that in classical mechanics one distinguishes between the object, or the particle, and its motion. The particle exists whether it moves or not, and the details of the motion are determined by the forces that act on it.

Another feature of mechanics is its closeness to everyday experience. We can touch or see a baseball. The motion of the moon is readily observed and may be measured with simple instrumental aids. The force on an object and its ensuing motion can be determined directly to verify Newton's second law of motion, that force equals mass times acceleration. This feature makes most physics students appreciate mechanics as a study in which common experience, if not common sense, applies.

In the nineteenth century the atomic theory of matter was also accepted as part of physical theory. According to Dalton's version of this theory, atoms are indivisible particles, the smallest entities into which any substance can be divided. These atoms are very small, approximately one nanometer (one billionth of a meter) in diameter. They are assumed to obey the laws of mechanics. It is, of course, impossible because of the atom's size to verify directly that this assumption is correct. Indirect evidence exists, however, through the branch of physics known as statistical mechanics.

In statistical mechanics one considers systems of atoms or molecules which are in a steady state; that is, the external or bulk properties of the systems are constant. The relationships between the bulk properties such as volume, temperature, pressure, etc. can be derived from the statistical distribution of velocities and positions of atoms making up the system. The atoms individually obey the laws of mechanics when they collide with one another and the walls of the system. The relationships of the bulk properties derived from this model correspond to the experimentally observed ones, and hence one has verified that atoms individually do indeed obey Newton's laws of motion.

Another important result of statistical mechanics is that the degree of motion of atoms is related to the absolute temperature of the substance of which they are part. The higher the temperature the faster the atoms are moving. At absolute zero all motion ceases and the result, it was believed, is a system of atoms all of which are at rest.

A distinction in classical physics which turned out to be very important is the difference between particles and waves. Substantial objects such as baseballs, planets, stars, atoms, etc. are particles, and as such obey the laws of mechanics.

On the other hand, a wave is an orderly disturbance of a medium. For example, a surface wave in water is an orderly disturbance of the water. More precisely, it is a disturbance of the water molecules in a collective and correlated fashion. Waves and particles are two quite different concepts, with particles being more fundamental since all substances consist of particles and waves are collective disturbances of the particles making up the medium. Starting with the particles in the medium and the laws of mechanics we are able to derive the properties of waves and the rules of propagation of waves in a medium. Thus in classical physics a variety of entities are referred to as particles, and another group of phenomena are called waves. Examples of the latter are light, sound, and electromagnetic radiation.

2. Assumptions and Implications

The first thing that strikes us is that classical physics is strictly causal; that is, a given physical situation can evolve in time in one, and only one, way. If the struck baseball mentioned earlier, is hit by the bat moving at a certain speed and angle, and at a certain position, there is only one trajectory that it can follow, and this path is completely determined by the way it was struck by the bat. Causality is also true in the more complex situations. Knowing the positions and velocities of all the atoms inside a closed box at some instant, we can predict the positions and velocities of the atoms at some later time.

Another prominent feature is the assumption of objectivity. It is taken for granted that one can study physical phenomena without altering the phenomena. Measurements can be made without affecting the behaviour of the thing measured. For example, the speed of an object can be measured by means of a pair of photocell gates. The measurement in this case depends on the object interrupting the two light beams, and this will hardly affect the motion. The movement of the planets and stars is not changed by our looking at them. In cases where measurement does affect the phenomenon, it was believed, the change can be theoretically accounted for, and one can deduce what the phenomenon would have been had no measurement been made.

When the causal and objective character of the physical sciences are extrapolated to have validity beyond the physical, a deterministic world view arises. Indicative of such a view is an oft-quoted statement of Laplace that an intelligence, who knows the forces on all atoms in the universe and the positions and velocities of these atoms at an instant, can describe the course of history and predict all future events.[1]

Because of the successes of the scientific endeavours of the nineteenth century a spirit of optimism arose. It was generally believed that virtually all of the physical laws, i.e. the laws of mechanics and electricity and magnetism, were known, and that most of the physical phenomena were explained in terms of them. There were still a few unsolved problems, but it was felt that in time with the application of the established principles these difficulties would also be removed. This attitude was exemplified by a statement of Michelson made as late as 1899:

> The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place of decimals.[2]

3. Some problems

With the perspective of recent developments we can point to certain problem areas in classical physics. One is related to the accuracy with which physical measurements can be made. Although many measurements lacked great precision in the past, it was believed that in time instruments and techniques would be improved to the extent that very accurate observations could be made. In principle, there would be no limit to the accuracy of the numbers that represent observations, and ultimately exact numbers would be obtained. This is, of course, contrary to experience with making measurements; whenever improvements are made there remain residual uncertainties.

This has implications for the deterministic view as stated by Laplace. It can easily be shown that a slight error in one datum of a complex system eventually leads to completely unpredictable results. Consider a box of atoms. The positions and velocities of all except one are known, and that one has only a small uncertainty in the velocity. It can be demonstrated that the uncertainty propagates as other atoms gain uncertainties in velocities and positions by colliding with it earlier. After some time all atoms have uncertainties in positions and velocities of such magnitudes that nothing can be said about any atom except that it is in the box. Complete predictability is achieved only when we have exact information to begin with, and that never seems to be the case. It may be that Laplace himself realized the limitation on human predictability of events by stating in this connection that "we must ever remain at an infinite distance from the goal of our aspirations."[3]

Another problem arose in connection with gravitational and electrical forces. With these forces it is found that objects of well-defined extent and location in space interact even when there is no apparent material medium connecting them. A good example is the gravitational pull of the sun on the earth across a long distance of near vacuum. This phenomenon is referred to as action-at-a-distance. The action of one object on another in this manner seemed even to Newton

> so great an absurdity that I believe no man who has in philosophic matters a competent faculty of thinking, can ever fall into it.[4]

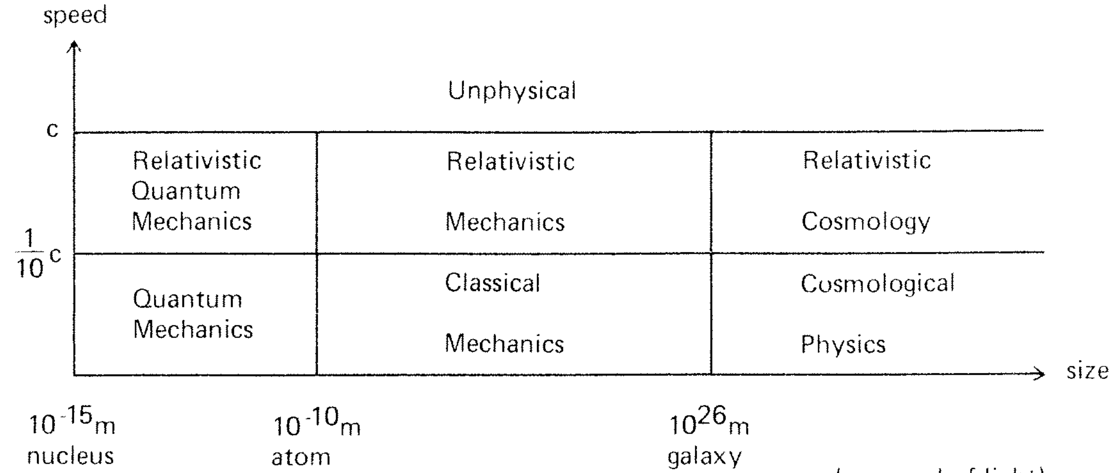
This from Newton who formulated the law of universal gravitation indeed emphasizes the conceptual and logical difficulties inherent in forces acting on objects placed apart in vacuum. Although our everyday experience has conditioned us to accept such phenomena, it is still not easy to explain.

With this sketchy outline of some prominent features of classical physics and possible ramifications, we now turn to more recent developments, and show how the latter have affected our understanding of the physical world.

Modern Physics

1. Description

The developments in the twentieth century have completely changed the complexion of physical science. We can categorize the advances as being of two different types. On the one hand, advances have been made in studying systems involving much smaller and much larger distances than ever before. Scientists are now capable of investigating and theorizing about stellar objects millions of light years away; they have also gained some understanding of atomic nuclei which are a million-billionth of a meter across. On the other hand, objects have been studied with speeds greater than ever before. Particles travelling close to the speed of light have been investigated. Indeed we know that the speed of light is the ultimate speed, which may be approached but which can never be exceeded. Both types of advances have moved into realms in which direct observation is no longer possible, but in which we have to rely on indirect measurements by means of sophisticated instrumentation. We illustrate in the diagram the different areas of study in terms of distances and speeds involved. Classical physics had been developed prior to 1900, the other areas since.



(c - speed of light)

We will be concerned with the developments in the area labelled quantum mechanics, that area in which sizes are submicroscopic and speeds are relatively small. It is impossible to explain quantum mechanics in a few pages. What follows will be a description of some of the salient characteristics and results. People associated with the early development of quantum mechanics are Planck, Heisenberg, Schrödinger and Bohr.

Planck, rather reluctantly, came to the conclusion that the energy of radiation in a black body is quantized. By this is meant that there is not a continuum of energies of radiation but rather only certain discrete energies. A similar situation obtains for atoms. Atoms are observed to have sharply defined energies which are characteristic of the element. No energies besides the characteristic ones are observed. The quantization of atomic energies gives rise to the atomic line spectra, in which light emitted by atoms has only certain discrete frequencies (colors). The fact that on the atomic level energy states are discrete was disconcerting to the classical physicist, since this was not explainable in terms of his theory. It was found that not only energy, but also momentum (mass times velocity) and the corresponding angular quantity, angular momentum, are quantized. The quantization of physical properties is peculiar to systems of submicroscopic dimensions.

The mathematical theory to explain the quantization of observed properties was worked out by Heisenberg, in his matrix mechanics, and by Schrödinger, in his wave mechanics. At first it seemed as if two distinctly different theories were explaining the same physical phenomena, but it was not long before the mathematical equivalence of the two theories was shown. These theories explain in principle atomic and molecular structure, and therefore form the basis for atomic and molecular physics and theoretical chemistry.

The strict causal and deterministic character of classical physics is no longer present. Quantum mechanics is statistical, even when a single particle is considered. If we were to know the state of motion of a particle at a given instant, we would be able to predict the probability of its state of motion at a later instant. Even for a single particle we cannot say with certainty where it is going to go. If we started the same particle with the same initial motion many times, we would be able to give an accurate statistical prediction of how often it would go in a particular direction, but we would not be able to predict the behaviour of it when we consider it only once. It is like flipping a coin. For a single toss we cannot state whether it will land heads or tails, but if we flip it many times we can predict with only a small error that of the total number of tosses half of the time the coin will land heads, and half of the time tails.

We saw that in classical physics the behaviour of a particle can be accurately predicted from its velocity and position at an instant. In quantum mechanics it is impossible to state accurately the momentum and position of a particle at an instant. This effect is the celebrated Heisenberg uncertainty principle; the product of the uncertainty of position and the uncertainty of momentum is always larger than a small but finite number. Often the principle is stated as an inequality,

$$\Delta p \cdot \Delta x \geq \tfrac{1}{2}\hbar,$$

where Δp is the amount by which the momentum is uncertain, and Δx the amount by which the position is not known. $\hbar$ is known as Planck's constant and is a very small number. Δp and Δx can never both be zero or the principle would be violated. There are a number of pairs of observable quantities like momentum and position for which the uncertainty relation holds, such as energy and time, angular momentum and angular displacement, and others. These are pairs of quantities which theoretically could be known with infinite accuracy in classical physics, but according to quantum theory they have an inherent uncertainty associated with them, which cannot be removed regardless how much we refine our techniques of measurement.

As a consequence of the uncertainty principle we find that the motion of atoms never ceases, not even at zero temperature on the absolute temperature scale. If atoms did come to rest at absolute zero (as classical physics states they do), then we would know the position and momentum at that temperature. Atoms in their lowest energy state have motion, or kinetic energy. This kinetic energy at absolute zero is referred to as zero-point energy.

Another feature of classical physics that was changed with the development of quantum theory was the classification of physical phenomena in terms of waves or particles. There are definite prescriptions to determine whether something behaves like a wave or like a particle. In the absence of forces, a particle will travel in a straight line. All the energy that a particle possesses can be thought of as being localized at the position of the particle. Waves on the other hand are disturbances of a medium, and according to Huygen's principle they tend to emanate in all directions from the source. The energy is distributed over the complete disturbance. One oft-used method for determining whether we are dealing with a wave is to test for interference or diffraction, as these phenomena are characteristic of waves. The distinction between wave and particle properties is very clear.

The results of recent experiments and the predictions of quantum mechanics, however, negate the notion that something is either a wave or a particle. Particles sometimes behave like waves, and waves like particles. They never display particle and wave characteristics at the same time, but depending on the experiment they indicate one or other of the two properties. Light, long considered a wave phenomenon because of its ability to form interference patterns, now under certain conditions, as in the photoelectric effect, behaves like particles. Electrons, known to be particles from their behaviour in cathode ray tubes, show typical wave diffraction and interference phenomena in slit experiments and when they pass through crystals. These results prompted Bohr to formulate the principle of complementarity that atomic phenomena in certain experiments yield wave-like properties and in other experiments particle-like properties; they never display both qualities at the same time; nevertheless, it is essential to have both types of properties in order to have a complete description of the physical phenomena.

Another difficulty arises with making measurements at the atomic level. In order to make measurements we have to cause the thing to be measured to interact with something else. For example, to detect an electron, we might shine light on it. The light however would impart energy and momentum to the electron, altering the state which we set out to observe. In a sense we become frustrated since we can no longer observe the way things behave when we are not looking at them. The measuring instrument becomes part of the system. This is very unlike the situation in classical physics where one believed that complete objectivity existed.

At this point one might wonder why we make such an ado about the strange behaviour of the submicroscopic world. The goings-on there do not appear to alter the classical view that we have of everyday ordinary-sized slow-moving objects and which we accept as having an ordered and strictly causal or deterministic character. We cannot dismiss the results of quantum theory, however irrelevant or far removed from reality they appear to be, since they do give us a deeper understanding of the physical aspect of creation.

Furthermore, even though classical theory describes events in a limited domain, but that domain with which we are most familiar, quantum theory has replaced classical physics. According to the correspondence principle, also formulated by Bohr, any new scientific theory ought to be a generalization or an extension of older established theories and ought to reduce to the older theories in the domain in which the older theories are known to be valid. In other words, quantum mechanics, besides correctly describing the submicroscopic world, must also describe correctly the classical physical world, and this it does. Features such as the uncertainty relation and the particle-wave duality are not immediately evident in our experience because of the small magnitude of Planck's constant. In fact, our measuring apparatus are not sufficiently accurate to verify the uncertainty for a baseball, as it has been verified for an electron or an atom. On the other hand, quantum theory will allow us to calculate the trajectory of a baseball just as well as it is calculated using classical mechanics.

Another reason that we cannot ignore the results of modern science is that they have become increasingly part of modern technology. Take the transistor for example; it is a device based purely on quantum mechanical principles. Without it modern computer and space technology would be virtually nonexistent.

2. Effect on Problems of Classical Physics

The advances in quantum theory have removed some of the problem areas of classical physics, and also created a few new difficulties. Let us consider the problems of classical physics discussed earlier.

Strict causality, in the sense that a given physical situation determines completely the sequel, no longer exists. The theory has become probabilistic; that is, probabilities of specific effects can be stated, but not certain results This becomes further complicated by the fact that initial conditions cannot be measured exactly. Even though the character of making predictions has changed, we do not live in a world of pure chance. For example, the baseball that was struck by a bat to obtain a certain speed with some error, at a certain position with some error, has a probability close to unity of going where we expect it to go according to the laws of classical physics. For electron trajectories the probabilities would usually be much less than one.

The uncertainty principle limits our measurements and our precise knowledge of physical systems, and consequently the objectivity that was so characteristic of classical physics is lost.

Finally the conceptual problem associated with action-at-a-distance has been resolved. In modern theory we no longer consider particles as being localized in space, nor do we object if several particles occupy the same region in space. The particles are mathematically described by a wave function, which is related to the probability of finding the particles at certain positions. Every particle has a probability of being anywhere in the universe. Usually however there is a small region in which a particle has a high probability of being located, and it has only a small probability of being anywhere else. Nevertheless the probability profiles of different particles overlap, and interaction at a distance is a real possibility. Even though some types of interactions are not fully understood yet, the conceptual problem of action-at-a-distance seems to have been eliminated.

3. Interpretation

There have been a number of interpretations of the probabilistic nature of events, most of which would fall in one of two categories. The Copenhagen school, with which Bohr, Heisenberg, and Schrödinger are associated, takes the view that the laws of nature are inherently statistical or probabilistic. Since this is characteristic of the laws of nature, we should not hold on nor expect to return to classical views of exact knowledge of trajectories and consequences of given causes, and so forth. Their point of view is that the probabilistic theory describes the observed phenomena and we ought not to put more into a theory than necessary to explain what we can observe, even if by limiting the input in this way we do not retain a deterministic theory.

The other interpretation of quantum theory seeks to retain a classical deterministic view. This approach is spearheaded by Bohm, and has among its sympathizers Einstein, DeBroglie, and Planck. Bohm's argument is that although the results of quantum mechanics are probabilistic (and true), there may be a substructure of the theory which is not probabilistic but deterministic. There is a close analogy then between statistical mechanics predicting the bulk properties of materials even though the atoms making up the systems obey classical laws. However in the latter case the bulk properties and substructure entities, the atoms, can be studied separately, and are both known to exist. With quantum theory however the substructure is not known, and no measurements have lead to the verification of its existence. The substructure is often said to consist of 'hidden variables,' which, if discovered, will restore the deterministic character of the laws of nature.

Conclusion

Certainty or chance, which is it? It is evident that the optimism, certainty, and determinism of the classical physicist was misplaced. He displayed too great a belief in the extrapolations of the results of his science. On the other hand, we would also argue with those who say that modern science reduces physical reality to pure chance. Although the theory gives statistical results, the results are governed by certain rules or laws. The theory corresponds to and describes that part of reality which we have observed.

The character of physical theory has undergone a complete change in the last century. This has been an humbling experience for the scientist, and urges him to continue his scientific quest by accepting valid presuppositions concerning the physical aspect of creation, by making valid deductions, and above all by realizing the limitations of the results that he has discovered. The theories so derived bring us closer to a full understanding of created reality.

References

1. P. S. Laplace, Essai Philosophique sur les Probabilités, V. Courcier, Paris, 1814. A translation of the statement is given by H. Margenua, The Nature of Physical Reality, McGraw-Hill, New York, 1950, page 397.

2. Michelson is quoted by F. K. Richtmyer, E. H. Kennard, and J. N. Cooper, Introduction to Modern Physics, McGraw-Hill, New York, 1969, page 43.

3. Laplace, op. cit. The quote is taken from L. W. Taylor, Physics, The Pioneer Science, Vol. I, Dover, New York, 1941, page 180.

4. Isaac Newton in Isaac Newton's Papers and Letters on Natural Philosophy, edited by I. B. Cohen, Harvard University Press, Cambridge, 1958, page 303.