Re: Epistemology 201: The Science of Science

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Lester Zick wrote:

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>
> *Quantum mechanics is necessary. Quantum postulates are not a*
> *mechanics.*

The mathematics along with its interpretations ARE the theory.

Modern quantum theory identifies quantum states as vectors in a seperable Hilbert space. Observables are Hermitean operators on the Hilbert Space. Possible values of the observable are eigenvalues of the Hermitean operator. In the early stages of the field quantum mechamics pertained to the wave mechanics derived from the Schroeding Equaton or the Matrix Mechanics derived from Heisneberg's formulaton. Now−a−days the terms quantum mechanics and quantum theory are used rather interchangably since it has been shown that Schroedinger's and Heisenberg's formulation are equivalent. The theory was generalized to subsume Special Theory of Relativity by Dirac and to resolve wave particle duality. The theory has been generalized to describe the interactions of all particles and fields (other than gravitational fields). The so−called Standard Model.

Here is some glossary information on how the terms −quantum theory−, −quantum mechanics− and −quantum field theory− are used:

quantum mechanics
Dictionary
quantum mechanics
n. (used with a sing. or pl. verb)

Quantum theory, especially the quantum theory of the structure and behavior of atoms and molecules.

logo

The American Heritage® Dictionary of the English Language, Fourth

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Technology
quantum mechanics

The branch of physics developed in the first part of the 20th century that was highly successful in explaining the behavior of atoms, molecules and nuclei. Developed between 1900 and 1930 and combined with the general and special theory of relativity, it revolutionized the field of physics. The new concepts, which were the particle properties of radiation, the wave properties of matter, quantization of physical properties and the idea that one can no longer know exactly where a single particle such as an electron is at any one time were necessary to explain all of the new experimental evidence that was available at the time. For example, quantum mechanics explains the behavior of semiconductors which are used to make the myriad of devices we use every day.

Following are the important contributors to the foundation of quantum mechanics and the principles they uncovered.

Year Researcher Quantum Mechanics Concept
1901 Planck Blackbody radiation
1905 Einstein Photoelectric effect
1913 Bohr Quantum theory of spectra
1922 Compton Scattering of photons
off electrons
1924 Pauli Exclusion principle
1925 de Broglie Matter waves
1926 Schroedinger Wave equation
1927 Heisenberg Uncertainty principle
1927 Davison and
Germer Wave properties of electrons
1927 Born Interpretation of the
wavefunction

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Encyclopedia

quantum field theory, study of the quantum mechanical interaction of elementary particles and fields. Quantum field theory applied to the understanding of electromagnetism is called quantum electrodynamics (QED), and it has proved spectacularly successful in describing the interaction of light with matter. The calculations, however, are often complex. They are usually carried out with the aid of Feynman diagrams (named after American physicist Richard P. Feynman), simple graphs that represent possible variations of interactions and provide an elegant shorthand for precise mathematical equations. Quantum field theory applied to the understanding of the strong interactions between quarks and between protons, neutrons, and other baryons and mesons is called quantum chromodynamics (QCD); QCD has a mathematical structure similar to that of QED.

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Science
quantum mechanics

The branch of physics that deals with the behavior of matter at the level of the atom, the nucleus, and the elementary particle. At this level, energy, mass, momentum, and other quantities do not vary continuously, as they do in the large−scale world, but come in discrete units, or quanta. (See Bohr atom and photon.)

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WordNet
Note: click on a word meaning below to see its connections and related words.

The noun quantum field theory has one meaning:

Meaning #1: the branch of quantum physics that is concerned with the theory of fields; it was motivated by the question of how an atom radiates light as its electrons jump from excited states

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Fig. 1: The wavefunctions of an electron in a hydrogen atom possessing definite energy (increasing downward: n=1,2,3,...) and angular momentum (increasing across: s, p, d,...). Brighter areas correspond to higher probability density for a position measurement. The angular momentum and energy are quantized, and only take on discrete values like those shown.

Enlarge

Fig. 1: The wavefunctions of an electron in a hydrogen atom possessing definite energy (increasing downward: n=1,2,3,...) and angular momentum (increasing across: s, p, d,...). Brighter areas correspond to higher probability density for a position measurement. The angular momentum and energy are quantized, and only take on discrete values like those shown.

Quantum mechanics is a physical theory which, for very small objects such as atoms, produces results that are very different and much more accurate than those of classical mechanics. It is the underlying framework of many fields of physics and chemistry, including condensed matter physics, quantum chemistry, and particle physics. It is derived from a small set of basic principles, and predicts at least three types of phenomena that classical mechanics and classical electrodynamics cannot account for: quantization, wave−particle duality, and quantum entanglement. It also explains the behavior of many physical systems that contradict classical mechanics, such as the existence of stable atoms and the fact that the total radiation emitted by a black body is finite.

The terms quantum physics and quantum theory are often used as synonyms of quantum mechanics. Some authors refer to "quantum mechanics" in the restricted sense of non−relativistic quantum mechanics. Quantum mechanics should however be taken to mean quantum theory in its most general sense when used in this article.

The foundations of quantum mechanics were established during the first half of the 20th century by Max Planck, Albert Einstein, Niels Bohr, Werner Heisenberg, Erwin Schrödinger, Max Born, Paul Dirac, Richard Feynman and others. Some fundamental aspects of the theory are still actively studied.

Description of the theory

Wave functions and measurement

There are a number of mathematically equivalent formulations of quantum mechanics. One of the earliest and easiest to understand is the "wave mechanics" formulation invented by Erwin Schrödinger, in which the instantaneous state of a system is described by a "wavefunction" that encodes the probability distribution of all measurable properties, or "observables". Examples of observables include energy, position, momentum, and angular momentum.

Generally, quantum mechanics does not assign definite values to observables. Instead, it makes predictions about their probability distributions; that is, the probability of obtaining each of the possible outcomes from measuring an observable. Naturally, these probabilities will depend on the wavefunction at the instant of the measurement. There are, however, certain wavefunctions that are associated with a definite value of a particular observable. These are known as "eigenstates" of the observable ("eigen" meaning "own" in German).

A concrete example will be useful here. Let us consider a free particle. Its wavefunction is a wave, of arbitrary shape, extending over all of space, and its position and momentum are observables. An eigenstate of position is a wavefunction that is very large at a particular position x, and zero everywhere else. If we perform a position measurement on such a wavefunction, we will obtain the result x with 100% probability. An eigenstate of momentum, on the other hand, has the form of a plane wave. It turns out that the wavelength is equal to h/p, where h is Planck's constant and p is the momentum of the eigenstate.

Usually, a system will not be in an eigenstate of whatever observable we are interested in. However, if we measure the observable, the wavefunction will immediately become an eigenstate of that observable. This process is known as wavefunction collapse. If we know the wavefunction at the instant before the measurement, we will be able to compute the probability of collapsing into each of the possible eigenstates. For example, the free particle in our previous example will usually have a wavefunction that is a wave packet centered around some mean position x0, neither an eigenstate of position nor of momentum. When we measure the position of the particle, it is impossible for us to predict with certainty the result that we will obtain. It is probable, but not certain, that it will be near x0, where the amplitude of the wavefunction is large. After we perform the measurement, obtaining some result x, the wavefunction collapses into a position eigenstate centered at x.

Wave functions can change as time progresses. An equation known as the Schrödinger equation describes how wave functions change in time, a role similar to Newton's second law in classical mechanics. The Schrödinger equation, applied to our free particle, predicts that the center of a wave packet will move through space at a constant velocity, like a classical particle with no forces acting on it. However, the wave packet will also spread out as time progresses, which means that the position becomes more uncertain. This also has the effect of turning position eigenstates into broadened wave packets that are not position eigenstates.

Some wave functions produce probability distributions that are constant in time. Many systems that are treated dynamically in classical mechanics are described by such "static" wave functions. For example, an electron in an unexcited atom is pictured classically as a particle moving in a circular trajectory around the atomic nucleus, whereas in quantum mechanics it is described by a static, spherically symmetric probability cloud surrounding the nucleus (Fig. 1).

The time evolution of wave functions is deterministic in the sense that, given a wavefunction at an initial time, it makes a definite prediction of what the wavefunction will be at any later time. During a measurement, the change of the wavefunction into another one is probabilistic, not deterministic. The probabilistic nature of quantum mechanics thus stems from the act of measurement. There are some interpretations of quantum mechanics that do away with the concept of "wavefunction collapse" by altering the concept of what constitutes a "measurement" in quantum mechanics. For further details, see for example the relative state interpretation.

Quantum mechanical effects

As mentioned in the introduction, there are several classes of phenomena that appear under quantum mechanics which have no analogue in classical physics. These are sometimes referred to as "quantum effects".

The first type of quantum effect is the quantization of certain physical quantities. In the example we have given, of a free particle in empty space, both the position and the momentum are continuous observables. However, if we restrict the particle to a region of space (the so−called "particle in a box" problem), the momentum observable will become discrete; it will only take on the values h/L, where L is the length of the box. Such observables are said to be quantized, and they play an important role in many physical systems. Examples of quantized observables include angular momentum, the total energy of a bound system, and the energy contained in an electromagnetic wave of a given frequency.

Another quantum effect is the uncertainty principle, which is the phenomenon that consecutive measurements of two or more observables may possess a fundamental limitation on accuracy. In our free particle example, it turns out that it is impossible to find a wavefunction that is an eigenstate of both position and momentum. This implies that position and momentum can never be simultaneously measured with arbitrary precision, even in principle: as the precision of the position measurement improves, the maximum precision of the momentum measurement decreases, and vice versa. Those variables for which it holds (e.g. momentum and position, or energy and time) are canonically conjugate variables in classical physics.

Another quantum effect is the wave−particle duality. It has been shown that, under certain experimental conditions, microscopic objects like atoms or electrons exhibit particle−like behavior, such as scattering. ("Particle−like" in the sense of an object that can be localized to a particular region of space.) Under other conditions, the same type of objects exhibit wave−like behavior, such as interference. We can observe only one type of property at a time.

Another quantum effect is quantum entanglement. In some cases, the wave function of a system composed of many particles cannot be separated into independent wave functions, one for each particle. In that case, the particles are said to be entangled. Entangled particles display remarkable and counter−intuitive properties. For example, a measurement made on a particle can produce, through the collapse of the total wavefunction, an instantaneous effect on the other particles with which it is entangled, even if they are far apart.

Mathematical formulation

In the mathematically rigorous formulation of quantum mechanics, developed by Paul Dirac and John von Neumann, the possible states of a quantum mechanical system are represented by unit vectors (called "state vectors") residing in a complex separable Hilbert space (variously called the "state space" or the "associated Hilbert space" of the system.) The exact nature of this Hilbert space is dependent on the system; for example, the state space for position and momentum states is the space of square−integrable functions, while the state space for the spin of a single electron is just the product of two complex planes. The time evolution of a quantum state is described by the Schrödinger equation, in which the Hamiltonian, the operator corresponding to the total energy of the system, generates time evolution.

Each observable is represented by a densely−defined Hermitian (or self−adjoint) linear operator acting on the state space. Each eigenstate of an observable corresponds to an eigenvector of the operator, and the associated eigenvalue corresponds to the value of the observable in that eigenstate. If the operator's spectrum is discrete, the observable can only attain those discrete eigenvalues. During a measurement, the probability that a system collapses to each eigenstate is given by the absolute square of the inner product between the eigenstate vector and the state vector just before the measurement. The possible results of a measurement are the eigenvalues of the operator − which explains the choice of Hermitian operators, for which all the eigenvalues are real. We can find the probability distribution of an observable in a given state by computing the spectral decomposition of the corresponding operator. Heisenberg's uncertainty principle is represented by the statement that the operators corresponding to certain observables do not commute.

The details of the mathematical formulation are contained in the article Mathematical formulation of quantum mechanics. See also the discussion in the article on Quantum logic.

It turns out that analytic solutions of Schrödinger's equation are only available for a small number of model Hamiltonians, of which the quantum harmonic oscillator and the hydrogen atom are the most important representatives. Even the helium atom, which contains just one more electron than hydrogen, defies all attempts at a fully analytic treatment. There exist several techniques for generating approximate solutions. For instance, in the method known as perturbation theory one uses the analytic results for a simple quantum mechanical model to generate results for a more complicated model related to the simple model by, for example, the addition of a weak potential energy. Another method is the "semi−classical equation of motion" approach, which applies to systems for which quantum mechanics produces weak deviations from classical behavior. The deviations can be calculated based on the classical motion. This approach is important for the field of quantum chaos.

An alternative formulation of quantum mechanics is Feynman's path integral formulation, in which a quantum−mechanical amplitude is considered as a sum over histories between initial and final states; this is the quantum−mechanical counterpart of action principles in classical mechanics.

Interactions with other scientific theories

The fundamental rules of quantum mechanics are very broad. They state that the state space of a system is a Hilbert space and the observables are Hermitian operators acting on that space, but do not tell us which Hilbert space or which operators. These must be chosen appropriately in order to obtain a quantitative description of a quantum system. An important guide for making these choices is the correspondence principle, which states that the predictions of quantum mechanics reduce to those of classical physics when a system becomes large. This "large system" limit is known as the classical or correspondence limit. One can therefore start from an established classical model of a particular system, and attempt to guess the underlying quantum model that gives rise to the classical model in the correspondence limit.

When quantum mechanics was originally formulated, it was applied to models whose correspondence limit was non−relativistic classical mechanics. For instance, the well−known model of the quantum harmonic oscillator uses an explicitly non−relativistic expression for the kinetic energy of the oscillator, and is thus a quantum version of the classical harmonic oscillator.

Early attempts to merge quantum mechanics with special relativity involved the replacement of the Schrödinger equation with a covariant equation such as the Klein−Gordon equation or the Dirac equation. While these theories were successful in explaining many experimental results, they had certain unsatisfactory qualities stemming from their neglect of the relativistic creation and annihilation of particles. A fully relativistic quantum theory required the development of quantum field theory, which applies quantization to a field rather than a fixed set of particles. The first complete quantum field theory, quantum electrodynamics, provides a fully quantum description of the electromagnetic interaction.

The full apparatus of quantum field theory is often unnecessary for describing electrodynamic systems. A simpler approach, one employed since the inception of quantum mechanics, is to treat charged particles as quantum mechanical objects being acted on by a classical electromagnetic field. For example, the elementary quantum model of the hydrogen atom describes the electric field of the hydrogen atom using a classical 1/r Coulomb potential. This "semi−classical" approach fails if quantum fluctuations in the electromagnetic field play an important role, such as in the emission of photons by charged particles.

Quantum field theories for the strong nuclear force and the weak nuclear force have been developed. The quantum field theory of the strong nuclear force is called quantum chromodynamics, and describes the interactions of the subnuclear particles: quarks and gluons. The weak nuclear force and the electromagnetic force were unified, in their quantized forms, into a single quantum field theory known as electroweak theory.

It has proven difficult to construct quantum models of gravity, the remaining fundamental force. Semi−classical approximations are workable, and have led to predictions such as Hawking radiation. However, the formulation of a complete theory of quantum gravity is hindered by apparent incompatibilities between general relativity, the most accurate theory of gravity currently known, and some of the fundamental assumptions of quantum theory. The resolution of these incompatibilities is an area of active research, and theories such as string theory are among the possible candidates for a future theory of quantum gravity.

Applications of quantum theory

Quantum mechanics has had enormous success in explaining many of the features of our world. The individual behavior of the microscopic particles that make up all forms of matter − electrons, protons, neutrons, and so forth − can often only be satisfactorily described using quantum mechanics.

Quantum mechanics is important for understanding how individual atoms combine to form chemicals. The application of quantum mechanics to chemistry is known as quantum chemistry. Quantum mechanics can provide quantitative insight into chemical bonding processes by explicitly showing which molecules are energetically favorable to which others, and by approximately how much. Most of the calculations performed in computational chemistry rely on quantum mechanics.

Much of modern technology operates at a scale where quantum effects are significant. Examples include the laser, the transistor, the electron microscope, and magnetic resonance imaging. The study of semiconductors led to the invention of the diode and the transistor, which are indispensable for modern electronics.

Researchers are currently seeking robust methods of directly manipulating quantum states. Efforts are being made to develop quantum cryptography, which will allow guaranteed secure transmission of information. A more distant goal is the development of quantum computers, which are expected to perform certain computational tasks with much greater efficiency than classical computers. Another active research topic is quantum teleportation, which deals with techniques to transmit quantum states over arbitrary distances.

Philosophical consequences

Since its inception, the many counter−intuitive results of quantum mechanics have provoked strong philosophical debate and many interpretations. Even fundamental issues such as Max Born's basic rules concerning probability amplitudes and probability distributions took decades to be appreciated.

Another difficulty with quantum mechanics is that the nature of an object isn't known, in the sense that an object's position, or the shape of the spatial distribution of the probability of presence, is only known by the properties (charge for example) and the environment (presence of an electric potential).

The Copenhagen interpretation, due largely to Niels Bohr, was the standard interpretation of quantum mechanics when it was first formulated. According to it, the probabilistic nature of quantum mechanics predictions cannot be explained in terms of some other deterministic theory, and do not simply reflect our limited knowledge. Quantum mechanics provides probabilistic results because the physical universe is itself probabilistic rather than deterministic.

Albert Einstein, himself one of the founders of quantum theory, disliked this loss of determinism in measurement. He held that there should be a local hidden variable theory underlying quantum mechanics and consequently the present theory was incomplete. He produced a series of objections to the theory, the most famous of which has become known as the EPR paradox. John Bell showed that the EPR paradox led to experimentally testable differences between quantum mechanics and local hidden variable theories. Experiments have been taken as confirming that quantum mechanics is correct and the real world cannot be described in terms of such hidden variables. "Loopholes" in the experiments, however, mean the question is still not quite settled.

See the Bohr−Einstein debates

The Everett many−worlds interpretation, formulated in 1956, holds that all the possibilities described by quantum theory simultaneously occur in a "multiverse" composed of mostly independent parallel universes. While the multiverse is deterministic, we perceive non−deterministic behavior governed by probabilities because we can observe only the universe we inhabit.

The Bohm interpretation, formulated by David Bohm, postulates the existence of a non−local, universal wavefunction (Schrödinger equation) which allows distant particles to interact instantaneously. Based on this interpretation, Bohm has speculated that the ultimate nature of physical reality is not a collection of separate objects (as it appears to us), but rather an undivided whole that is in perpetual dynamic flux. However, the Bohm interpretation is not popular among physicists, largely because it is considered very inelegant.

History

In 1900, Max Planck introduced the idea that energy is quantized, in order to derive a formula for the observed frequency dependence of the energy emitted by a black body. In 1905, Einstein explained the photoelectric effect by postulating that light energy comes in quanta called photons. In 1913, Bohr explained the spectral lines of the hydrogen atom, again by using quantization. In 1924, Louis de Broglie put forward his theory of matter waves.

These theories, though successful, were strictly phenomenological: there was no rigorous justification for quantization. They are collectively known as the old quantum theory.

The phrase "quantum physics" was first used in Johnston's Planck's Universe in Light of Modern Physics.

Modern quantum mechanics was born in 1925, when Heisenberg developed matrix mechanics and Schrödinger invented wave mechanics and the Schrödinger equation. Schrödinger subsequently showed that the two approaches were equivalent.

Heisenberg formulated his uncertainty principle in 1927, and the Copenhagen interpretation took shape at about the same time. In 1927, Paul Dirac unified quantum mechanics with special relativity. He also pioneered the use of operator theory, including the influential bra−ket notation. In 1932, John von Neumann formulated the rigorous mathematical basis for quantum mechanics as operator theory.

The field of quantum chemistry was pioneered by Walter Heitler and Fritz London, who published a study of the covalent bond of the hydrogen molecule in 1927. Quantum chemistry was subsequently developed by a large number of workers, including the American chemist Linus Pauling.

Beginning in 1927, attempts were made to apply quantum mechanics to fields rather than single particles, resulting in what are known as quantum field theories. Early workers in this area included Dirac, Pauli, Weisskopf, and Jordan. This area of research culminated in the formulation of quantum electrodynamics by Feynman, Dyson, Schwinger, and Tomonaga during the 1940s. Quantum electrodynamics is a quantum theory of electrons, positrons, and the electromagnetic field, and served as a role model for subsequent quantum field theories.

The many worlds interpretation was formulated by Everett in 1956.

The theory of quantum chromodynamics was formulated beginning in the early 1960s. The theory as we know it today was formulated by Polizter, Gross and Wilzcek in 1975. Building on pioneering work by Schwinger, Higgs, Goldstone and others, Glashow, Weinberg and Salam independently showed how the weak nuclear force and quantum electrodynamics could be merged into a single electroweak force.

Founding experiments

* Thomas Young's double−slit experiment proving the wave nature of light (c1805)
* Henri Becquerel discovers radioactivity (1896)
* Joseph John Thomson's cathode ray tube experiments (discovers the electron and its negative charge) (1897)
* The study of Black body radiation between 1850 and 1900.
* Robert Millikan's oil−drop experiment, which suggests that electric charge occurs as quanta (whole units), (1909)
* Ernest Rutherford's gold foil experiment disproved the plum pudding model of the atom which suggests that the positive charge and mass of the atom are almost uniformly distributed. (1911)
* Otto Stern and Walter Gerlach conduct the Stern−Gerlach experiment, which demonstrates particle spin (1920)
* Clyde L. Cowan and Frederick Reines confirm the existence of the neutrino in the neutrino experiment (1955)

Many more experiments have been done of course, but this is the short list given in the article.

Bob Kolker