

WIKIPEDIA

The Free Encyclopedia

Main page

Contents

Featured content

Current events

Random article

Donate to Wikipedia

Wikipedia store

Interaction

Help

About Wikipedia

Community portal

Recent changes

Contact page

Tools

What links here

Related changes

Upload file

Special pages

Permanent link

Page information

Wikidata item

Cite this page

Print/export

Create a book

Download as PDF

Printable version

In other projects

Wikimedia Commons

Wikibooks

Wikiquote

Languages

Afrikaans

Alemannisch

العربية

Aragonés

অসমীয়া

Asturianu

Azərbaycanca

বাংলা


Article

Talk

Read

Edit

View history



# Quantum mechanics

From Wikipedia, the free encyclopedia

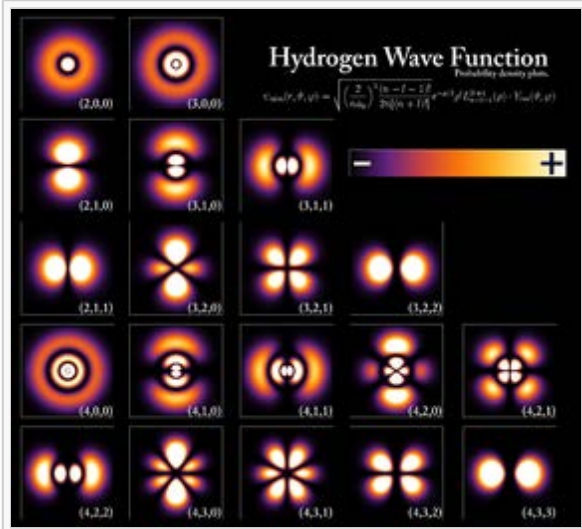
*For a more accessible and less technical introduction to this topic, see [Introduction to quantum mechanics](#).*

**Quantum mechanics** (**QM**; also known as **quantum physics** or **quantum theory**), including [quantum field theory](#), is a fundamental branch of [physics](#) concerned with processes involving, for example, [atoms](#) and [photons](#). Systems such as these which obey quantum mechanics can be in a [quantum superposition](#) of different states, unlike in [classical physics](#).

Quantum mechanics [gradually arose](#) from [Max Planck](#)'s solution in 1900 to the [black-body radiation](#) problem (reported 1859) and [Albert Einstein](#)'s 1905 paper which offered a quantum-based theory to explain the [photoelectric effect](#) (reported 1887). [Early quantum theory](#) was profoundly reconceived in the mid-1920s.


The reconceived theory is formulated in various [specially developed mathematical formalisms](#). In one of them, a mathematical function, the [wave function](#), provides information about the [probability amplitude](#) of position, momentum, and other physical properties of a particle.

Important applications of quantum theory<sup>[*1*]</sup> include [superconducting magnets](#), [light-emitting diodes](#) and the [laser](#), the [transistor](#) and [semiconductors](#) such as the [microprocessor](#), [medical and research imaging](#) such as [magnetic resonance imaging](#) and [electron microscopy](#), and explanations for many biological and physical phenomena.<sup>[*not verified in body*]</sup>



Solution to [Schrödinger's equation](#) for the hydrogen atom at different energy levels. The brighter areas represent a higher probability of finding an [electron](#).

## Quantum mechanics



*Schrödinger equation*

Introduction · Glossary · History

Background

Fundamentals

Experiments

Formulations

Equations

Interpretations

Advanced topics

Scientists

[show]

[show]

[show]

[show]

[show]

[show]

[show]

[show]

V • T • E

Contents [hide]

1

History

https://en.wikipedia.org/wiki/Quantum\_mechanics[8/15/2016 7:06:09 AM]

- Bân-lâm-gú
- Башҡортса
- Беларуская
- Беларуская (тарашкевіца)
- Български
- Boarisch
- Bosanski
- Català
- Чӕвашла
- Čeština
- Cymraeg
- Dansk
- Deutsch
- Eesti
- Ελληνικά
- Español
- Esperanto
- Estremeñu
- Euskara
- فارسی
- Fiji Hindi
- Français
- Gaeilge
- Galego
- 한국어
- Հայերեն
- हिन्दी
- Hrvatski
- Ido
- Bahasa Indonesia
- Interlingua
- Íslenska
- Italiano
- עברית
- ಕನ್ನಡ
- ქართული
- Қазақша
- Кыргызча
- Latina
- Latviešu
- Lietuvių
- Limburgs
- Lumbaart
- Magyar
- Македонски
- മലയാളം
- Malti
- मराठी
- مصرى
- مازرونی

- 2 Mathematical formulations
- 3 Mathematically equivalent formulations of quantum mechanics
- 4 Interactions with other scientific theories
  - 4.1 Quantum mechanics and classical physics
  - 4.2 Copenhagen interpretation of quantum versus classical kinematics
  - 4.3 General relativity and quantum mechanics
  - 4.4 Attempts at a unified field theory
- 5 Philosophical implications
- 6 Applications
  - 6.1 Electronics
  - 6.2 Cryptography
  - 6.3 Quantum computing
  - 6.4 Macroscale quantum effects
  - 6.5 Quantum theory
- 7 Examples
  - 7.1 Free particle
  - 7.2 Step potential
  - 7.3 Rectangular potential barrier
  - 7.4 Particle in a box
  - 7.5 Finite potential well
  - 7.6 Harmonic oscillator
- 8 See also
- 9 Notes
- 10 References
- 11 Further reading
- 12 External links

History [ edit ]

*Main article: History of quantum mechanics*

Scientific inquiry into the wave nature of light began in the 17th and 18th centuries, when scientists such as **Robert Hooke**, **Christiaan Huygens** and **Leonhard Euler** proposed a wave theory of light based on experimental observations.<sup>[2]</sup> In 1803, **Thomas Young**, an English **polymath**, performed the famous **double-slit experiment** that he later described in a paper titled *On the nature of light and colours*. This experiment played a major role in the general acceptance of the **wave theory of light**.

In 1838, **Michael Faraday** discovered **cathode rays**. These studies were followed by the 1859 statement of the **black-body radiation** problem by **Gustav Kirchhoff**, the 1877 suggestion by

Modern physics



*Manifold Dynamics: Schrödinger and Klein-Gordon equations*

- Founders** [show]
- Concepts** [show]
- Branches** [show]
- Scientists** [show]

V • T • E

Bahasa Melayu

Монгол

Nederlands

नेपाली

नेपाल भाषा

日本語

Norsk bokmål

Norsk nynorsk

Occitan

O‘zbekcha/Ўзбекча

ਪੰਜਾਬੀ

پنجابی

Patois

Piemontèis

Polski

Português

Română

Русиньскый

Русский

Scots

Shqip

Sicilianu

සිංහල

Simple English

Slovenčina

Slovenščina

Ślůnski

کوردیی ناوەندی

Српски / srpski

Srpskohrvatski / српскохрватски

Basa Sunda

Suomi

Svenska

Tagalog

தமிழ்

Татарча/tatarça

తెలుగు

ไทย

Türkçe

★ Українська

اردو

Tiếng Việt

Võro

Winaray

吴

עברית

語

Žemaitėška

★ 中文

**Ludwig Boltzmann** that the energy states of a physical system can be discrete, and the 1900 quantum hypothesis of **Max Planck**.<sup>[3]</sup> Planck's hypothesis that energy is radiated and absorbed in discrete "quanta" (or energy elements) precisely matched the observed patterns of black-body radiation.

In 1896, **Wilhelm Wien** empirically determined a distribution law of black-body radiation,<sup>[4]</sup> known as **Wien's law** in his honor. Ludwig Boltzmann independently arrived at this result by considerations of **Maxwell's equations**. However, it was valid only at high frequencies and underestimated the radiance at low frequencies. Later, Planck corrected this model using Boltzmann's statistical interpretation of thermodynamics and proposed what is now called **Planck's law**, which led to the development of quantum mechanics.

Following **Max Planck's** solution in 1900 to the black-body radiation problem (reported 1859), **Albert Einstein** offered a quantum-based theory to explain the **photoelectric effect** (1905, reported 1887). Around 1900-1910, the **atomic theory** and the **corpuscular theory of light**<sup>[5]</sup> first came to be widely accepted as scientific fact; these latter theories can be viewed as quantum theories of **matter** and **electromagnetic radiation**, respectively.

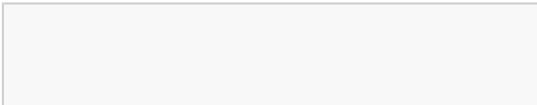
Among the first to study quantum phenomena in nature were **Arthur Compton**, **C. V. Raman**, and **Pieter Zeeman**, each of whom has a quantum effect named after him. **Robert Andrews Millikan** studied the **photoelectric effect** experimentally, and Albert Einstein developed a theory for it. At the same time, **Niels Bohr** developed his theory of the atomic structure, which was later confirmed by the experiments of **Henry Moseley**. In 1913, **Peter Debye** extended Niels Bohr's theory of atomic structure, introducing **elliptical orbits**, a concept also introduced by **Arnold Sommerfeld**.<sup>[6]</sup> This phase is known as **old quantum theory**.

According to Planck, each energy element (*E*) is proportional to its **frequency** (*ν*):

where *h* is **Planck's constant**.

Planck cautiously insisted that this was simply an aspect of the *processes* of absorption and emission of radiation and had nothing to do with the *physical reality* of the radiation itself.<sup>[7]</sup> In fact, he considered his **quantum hypothesis** a mathematical trick to get the right answer rather than a sizable discovery.<sup>[8]</sup> However, in 1905 **Albert Einstein** interpreted Planck's quantum hypothesis **realistically** and used it to explain the **photoelectric effect**, in which shining light on certain materials can eject electrons from the material. He won the 1921 Nobel Prize in Physics for this work.

Einstein further developed this idea to show that an electromagnetic wave such as light could also be described as a particle (later called the **photon**), with a discrete quantum of energy that was dependent on its frequency.<sup>[9]</sup>

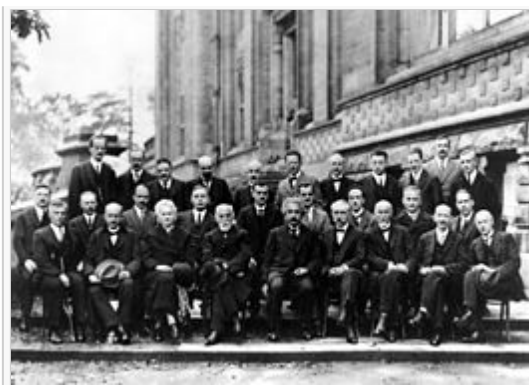


The foundations of quantum mechanics were established during the first half of the 20th



**Max Planck** is considered the father of the quantum theory.

 Edit links



The 1927 [Solvay Conference](#) in [Brussels](#). 

century by [Max Planck](#), [Niels Bohr](#), [Werner Heisenberg](#), [Louis de Broglie](#), [Arthur Compton](#), [Albert Einstein](#), [Erwin Schrödinger](#), [Max Born](#), [John von Neumann](#), [Paul Dirac](#), [Enrico Fermi](#), [Wolfgang Pauli](#), [Max von Laue](#), [Freeman Dyson](#), [David Hilbert](#), [Wilhelm Wien](#), [Satyendra Nath Bose](#), [Arnold Sommerfeld](#), and [others](#). The [Copenhagen interpretation](#) of [Niels Bohr](#) became widely accepted.

In the mid-1920s, developments in quantum mechanics led to its becoming the standard formulation for atomic physics. In the summer of 1925, Bohr and Heisenberg published results that closed the old quantum theory. Out of deference to their particle-like behavior in certain processes and measurements, light quanta came to be called [photons](#) (1926). From Einstein's simple postulation was born a flurry of debating, theorizing, and testing. Thus, the entire field of [quantum physics](#) emerged, leading to its wider acceptance at the Fifth [Solvay Conference](#) in 1927.<sup>[*[citation needed](#)*]</sup>

It was found that [subatomic particles](#) and electromagnetic waves are neither simply particle nor wave but have certain properties of each. This originated the concept of [wave–particle duality](#).<sup>[*[citation needed](#)*]</sup>

By 1930, quantum mechanics had been further unified and formalized by the work of [David Hilbert](#), [Paul Dirac](#) and [John von Neumann](#)<sup>[10]</sup> with greater emphasis on [measurement](#), the statistical nature of our knowledge of reality, and [philosophical speculation about the 'observer'](#). It has since permeated many disciplines including [quantum chemistry](#), [quantum electronics](#), [quantum optics](#), and [quantum information science](#). Its speculative modern developments include [string theory](#) and [quantum gravity](#) theories. It also provides a useful framework for many features of the modern [periodic table of elements](#), and describes the behaviors of [atoms](#) during [chemical bonding](#) and the flow of [electrons](#) in computer [semiconductors](#), and therefore plays a crucial role in many modern technologies.<sup>[*[citation needed](#)*]</sup>

While quantum mechanics was constructed to describe the world of the very small, it is also needed to explain some [macroscopic](#) phenomena such as [superconductors](#),<sup>[11]</sup> and [superfluids](#).<sup>[12]</sup>

The word *quantum* derives from the [Latin](#), meaning "how great" or "how much".<sup>[13]</sup> In quantum mechanics, it refers to a discrete unit assigned to certain [physical quantities](#) such as the [energy](#) of an [atom](#) at rest (see Figure 1). The discovery that particles are discrete packets of energy with wave-like properties led to the branch of physics dealing with atomic and subatomic systems which is today called quantum mechanics. It underlies the [mathematical](#) framework of many fields of [physics](#) and [chemistry](#), including [condensed matter physics](#), [solid-state physics](#), [atomic physics](#), [molecular physics](#), [computational physics](#), [computational chemistry](#), [quantum chemistry](#), [particle physics](#), [nuclear chemistry](#), and [nuclear physics](#).<sup>[14]</sup><sup>[*[better source needed](#)*]</sup> Some fundamental aspects of the theory are still actively studied.<sup>[15]</sup>

Quantum mechanics is essential to understanding the behavior of systems at [atomic](#) length



scales and smaller. If the physical nature of an atom were solely described by [classical mechanics](#), electrons would not *orbit* the nucleus, since orbiting electrons emit radiation (due to [circular motion](#)) and would eventually collide with the nucleus due to this loss of energy. This framework was unable to explain the stability of atoms. Instead, electrons remain in an uncertain, non-deterministic, *smeared*, [probabilistic](#) wave–particle [orbital](#) about the nucleus, defying the traditional assumptions of classical mechanics and [electromagnetism](#).<sup>[16]</sup>

Quantum mechanics was initially developed to provide a better explanation and description of the atom, especially the differences in the [spectra](#) of light emitted by different [isotopes](#) of the same [chemical element](#), as well as subatomic particles. In short, the quantum-mechanical atomic model has succeeded spectacularly in the realm where classical mechanics and electromagnetism falter.

Broadly speaking, quantum mechanics incorporates four classes of phenomena for which classical physics cannot account:

- [quantization](#) of [certain physical properties](#)
- [quantum entanglement](#)
- [principle of uncertainty](#)
- [wave–particle duality](#)

## Mathematical formulations  [ [edit](#) ]

*Main article:* [Mathematical formulation of quantum mechanics](#)

*See also:* [Quantum logic](#)

In the mathematically rigorous formulation of quantum mechanics developed by [Paul Dirac](#),<sup>[17]</sup> [David Hilbert](#),<sup>[18]</sup> [John von Neumann](#),<sup>[19]</sup> and [Hermann Weyl](#),<sup>[20]</sup> the possible states of a quantum mechanical system are symbolized<sup>[21]</sup> as [unit vectors](#) (called *state vectors*). Formally, these reside in a [complex separable Hilbert space](#)—variously called the *state space* or the *associated Hilbert space* of the system—that is well defined up to a complex number of norm 1 (the phase factor). In other words, the possible states are points in the [projective space](#) of a Hilbert space, usually called the [complex projective space](#). 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 proton is just the product of two complex planes. Each observable is represented by a maximally [Hermitian](#) (precisely: by a [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 attain only those discrete eigenvalues.

In the formalism of quantum mechanics, the state of a system at a given time is described by a [complex wave function](#), also referred to as state vector in a complex [vector space](#).<sup>[22]</sup> This abstract mathematical object allows for the calculation of [probabilities](#) of outcomes of concrete experiments. For example, it allows one to compute the probability of finding an electron in a particular region around the nucleus at a particular time. Contrary to classical mechanics, one can never make simultaneous predictions of [conjugate variables](#), such as position and momentum, with accuracy. For instance, electrons may be considered (to a certain probability)

to be located somewhere within a given region of space, but with their exact positions unknown. Contours of constant probability, often referred to as "clouds", may be drawn around the nucleus of an atom to conceptualize where the electron might be located with the most probability. Heisenberg's [uncertainty principle](#) quantifies the inability to precisely locate the particle given its conjugate momentum.<sup>[23]</sup>

According to one interpretation, as the result of a measurement the wave function containing the probability information for a system collapses from a given initial state to a particular eigenstate. The possible results of a measurement are the eigenvalues of the operator representing the observable—which explains the choice of *Hermitian* operators, for which all the eigenvalues are real. The probability distribution of an observable in a given state can be found 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 [probabilistic](#) nature of quantum mechanics thus stems from the act of measurement. This is one of the most difficult aspects of quantum systems to understand. It was the central topic in the famous [Bohr–Einstein debates](#), in which the two scientists attempted to clarify these fundamental principles by way of [thought experiments](#). In the decades after the formulation of quantum mechanics, the question of what constitutes a "measurement" has been extensively studied. Newer [interpretations of quantum mechanics](#) have been formulated that do away with the concept of "wave function collapse" (see, for example, the [relative state interpretation](#)). The basic idea is that when a quantum system interacts with a measuring apparatus, their respective wave functions become [entangled](#), so that the original quantum system ceases to exist as an independent entity. For details, see the article on [measurement in quantum mechanics](#).<sup>[24]</sup>

Generally, quantum mechanics does not assign definite values. Instead, it makes a prediction using a [probability distribution](#); that is, it describes the probability of obtaining the possible outcomes from measuring an observable. Often these results are skewed by many causes, such as dense probability clouds. Probability clouds are approximate (but better than [the Bohr model](#)) whereby electron location is given by a [probability function](#), the [wave function eigenvalue](#), such that the probability is the squared modulus of the [complex amplitude](#), or quantum state nuclear attraction.<sup>[25][26]</sup> Naturally, these probabilities will depend on the quantum state at the "instant" of the measurement. Hence, uncertainty is involved in the value. There are, however, certain states that are associated with a definite value of a particular observable. These are known as [eigenstates](#) of the observable ("eigen" can be translated from [German](#) as meaning "inherent" or "characteristic").<sup>[27]</sup>

In the everyday world, it is natural and intuitive to think of everything (every observable) as being in an eigenstate. Everything appears to have a definite position, a definite momentum, a definite energy, and a definite time of occurrence. However, quantum mechanics does not pinpoint the exact values of a particle's position and momentum (since they are [conjugate pairs](#)) or its energy and time (since they too are conjugate pairs); rather, it provides only a range of probabilities in which that particle might be given its momentum and momentum probability. Therefore, it is helpful to use different words to describe states having [uncertain](#) values and states having *definite* values (eigenstates). Usually, a system will not be in an [eigenstate](#) of the observable (particle) we are interested in. However, if one measures the observable, the wave function will

instantaneously be an eigenstate (or "generalized" eigenstate) of that observable. This process is known as [wave function collapse](#), a controversial and much-debated process<sup>[28]</sup> that involves expanding the system under study to include the measurement device. If one knows the corresponding wave function at the instant before the measurement, one will be able to compute the probability of the wave function collapsing into each of the possible eigenstates. For example, the free particle in the previous example will usually have a wave function that is a [wave packet](#) centered around some mean position  $x_0$  (neither an eigenstate of position nor of momentum). When one measures the position of the particle, it is impossible to predict with certainty the result.<sup>[24]</sup> It is probable, but not certain, that it will be near  $x_0$ , where the amplitude of the wave function is large. After the measurement is performed, having obtained some result  $x$ , the wave function collapses into a position eigenstate centered at  $x$ .<sup>[29]</sup>

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 the time evolution. The [time evolution](#) of wave functions is [deterministic](#) in the sense that - given a wave function at an *initial* time - it makes a definite prediction of what the wave function will be at any *later* time.<sup>[30]</sup>

During a [measurement](#), on the other hand, the change of the initial wave function into another, later wave function is not deterministic, it is unpredictable (i.e., [random](#)). A time-evolution simulation can be seen here.<sup>[31][32]</sup>

Wave functions change as time progresses. The [Schrödinger equation](#) describes how wave functions change in time, playing a role similar to [Newton's second law](#) in [classical mechanics](#). The Schrödinger equation, applied to the aforementioned example of the 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 with time. This also has the effect of turning a position eigenstate (which can be thought of as an infinitely sharp wave packet) into a broadened wave packet that no longer represents a (definite, certain) position eigenstate.<sup>[33]</sup>

Some wave functions produce probability distributions that are constant, or independent of time—such as when in a [stationary state](#) of constant energy, time vanishes in the absolute square of the wave function. Many systems that are treated dynamically in classical mechanics are described by such "static" wave functions. For example, a single [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](#) wave function surrounding the nucleus ([Fig. 1](#)) (note, however, that only the lowest angular

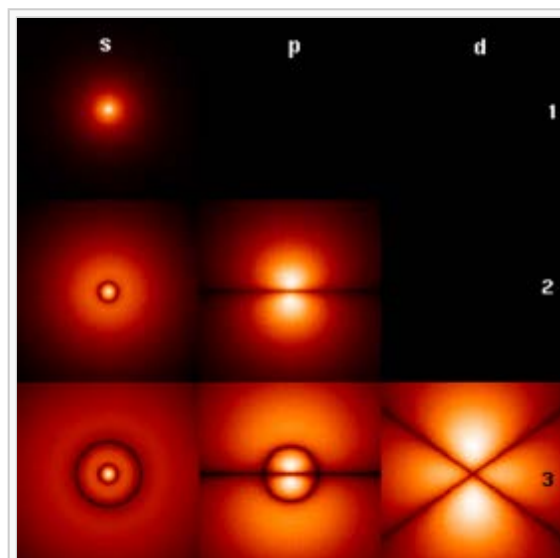


Fig. 1: [Probability densities](#) corresponding to the wave functions of an electron in a hydrogen

momentum states, labeled  $s$ , are spherically symmetric).<sup>[34]</sup>

The Schrödinger equation acts on the *entire* probability amplitude, not merely its absolute value. Whereas the absolute value of the probability amplitude encodes information about probabilities, its **phase** encodes information about the **interference** between quantum states. This gives rise to the "wave-like" behavior of quantum states. As it turns out, analytic solutions of the Schrödinger equation are available for only **a very small number of relatively simple model Hamiltonians**, of which the **quantum harmonic oscillator**, the **particle in a box**, the **dihydrogen cation**, and the **hydrogen atom** are the most important representatives. Even the **helium** atom—which contains just one more electron than does the hydrogen atom—has defied all attempts at a fully analytic treatment.

There exist several techniques for generating approximate solutions, however. In the important method known as **perturbation theory**, one uses the analytic result for a simple quantum mechanical model to generate a result for a more complicated model that is related to the simpler model by (for one 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 only weak (small) deviations from classical behavior. These deviations can then be computed based on the classical motion. This approach is particularly important in the field of **quantum chaos**.

atom possessing definite energy levels (increasing from the top of the image to the bottom:  $n = 1, 2, 3, \dots$ ) and angular momenta (increasing across from left to right:  $s, p, d, \dots$ ). Brighter areas correspond to higher probability density in a position measurement. Such wave functions are directly comparable to **Chladni's figures** of **acoustic** modes of vibration in **classical physics**, and are modes of oscillation as well, possessing a sharp **energy** and, thus, a definite **frequency**. The **angular momentum** and energy are **quantized**, and take **only** discrete values like those shown (as is the case for **resonant frequencies** in acoustics)

## Mathematically equivalent formulations of quantum mechanics

[ [edit](#) ]

There are numerous mathematically equivalent formulations of quantum mechanics. One of the oldest and most commonly used formulations is the "**transformation theory**" proposed by **Paul Dirac**, which unifies and generalizes the two earliest formulations of quantum mechanics - **matrix mechanics** (invented by **Werner Heisenberg**) and **wave mechanics** (invented by **Erwin Schrödinger**).<sup>[35]</sup>

Especially since **Werner Heisenberg** was awarded the **Nobel Prize in Physics** in 1932 for the creation of quantum mechanics, the role of **Max Born** in the development of QM was overlooked until the 1954 Nobel award. The role is noted in a 2005 biography of Born, which recounts his role in the matrix formulation of quantum mechanics, and the use of probability amplitudes. Heisenberg himself acknowledges having learned matrices from Born, as published in a 1940 *festschrift* honoring **Max Planck**.<sup>[36]</sup> In the matrix formulation, the **instantaneous state of a quantum system** encodes the probabilities of its measurable properties, or "**observables**". Examples of observables include **energy**, **position**, **momentum**, and **angular momentum**. Observables can be either **continuous** (e.g., the position of a particle) or **discrete** (e.g., the energy of an electron bound to a hydrogen atom).<sup>[37]</sup> An alternative formulation of quantum



mechanics is [Feynman's path integral formulation](#), in which a quantum-mechanical amplitude is considered as a sum over all possible classical and non-classical paths between the initial and final states. This is the quantum-mechanical counterpart of the [action principle](#) in classical mechanics.


## Interactions with other scientific theories [[edit](#)]

The rules of quantum mechanics are fundamental. They assert that the state space of a system is a [Hilbert space](#) and that observables of that system are [Hermitian operators](#) acting on that space—although they do not tell us which Hilbert space or which operators. These can 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 mechanics when a system moves to higher energies or, equivalently, larger quantum numbers, i.e. whereas a single particle exhibits a degree of randomness, in systems incorporating millions of particles averaging takes over and, at the high energy limit, the statistical probability of random behaviour approaches zero. In other words, classical mechanics is simply a quantum mechanics of large systems. This "high energy" limit is known as the *classical or correspondence limit*. One can even start from an established classical model of a particular system, then attempt to guess the underlying quantum model that would give 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 that has been employed since the inception of quantum mechanics, is to treat [charged](#) particles as quantum

### Unsolved problem in physics:

*In the [correspondence limit](#) of **quantum mechanics**: Is there a preferred interpretation of quantum mechanics? How  does the quantum description of reality, which includes elements such as the "[superposition of states](#)" and "[wave function collapse](#)", give rise to the reality we perceive? ([more unsolved problems in physics](#))*

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  [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 also been developed. The quantum field theory of the strong nuclear force is called [quantum chromodynamics](#), and describes the interactions of subnuclear particles such as [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](#)), by the physicists [Abdus Salam](#), [Sheldon Glashow](#) and [Steven Weinberg](#). These three men shared the Nobel Prize in Physics in 1979 for this work.<sup>[38]</sup>

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.

Classical mechanics has also been extended into the [complex domain](#), with complex classical mechanics exhibiting behaviors similar to quantum mechanics.<sup>[39]</sup>

## Quantum mechanics and classical physics  [ [edit](#) ]

Predictions of quantum mechanics have been verified experimentally to an extremely high degree of accuracy.<sup>[40]</sup> According to the [correspondence principle](#) between classical and quantum mechanics, all objects obey the laws of quantum mechanics, and classical mechanics is just an approximation for large systems of objects (or a statistical quantum mechanics of a large collection of particles).<sup>[41]</sup> The laws of classical mechanics thus follow from the laws of quantum mechanics as a statistical average at the limit of large systems or large [quantum numbers](#).<sup>[42]</sup> However, [chaotic systems](#) do not have good quantum numbers, and [quantum chaos](#) studies the relationship between classical and quantum descriptions in these systems.

[Quantum coherence](#) is an essential difference between classical and quantum theories as illustrated by the [Einstein–Podolsky–Rosen \(EPR\) paradox](#) — an attack on a certain philosophical interpretation of quantum mechanics by an appeal to [local realism](#).<sup>[43]</sup> [Quantum interference](#) involves adding together *probability amplitudes*, whereas classical "waves" infer that there is an adding together of *intensities*. For microscopic bodies, the extension of the system is much smaller than the [coherence length](#), which gives rise to long-range entanglement and other nonlocal phenomena characteristic of quantum systems.<sup>[44]</sup> Quantum coherence is not typically evident at macroscopic scales, though an exception to this rule may occur at extremely low temperatures (i.e. approaching [absolute zero](#)) at which quantum behavior may manifest itself macroscopically.<sup>[45]</sup> This is in accordance with the following observations:

- Many macroscopic properties of a classical system are a direct consequence of the quantum

behavior of its parts. For example, the stability of bulk matter (consisting of atoms and [molecules](#) which would quickly collapse under electric forces alone), the rigidity of solids, and the mechanical, thermal, chemical, optical and magnetic properties of matter are all results of the interaction of [electric charges](#) under the rules of quantum mechanics.<sup>[46]</sup>

- While the seemingly "exotic" behavior of matter posited by quantum mechanics and relativity theory become more apparent when dealing with particles of extremely small size or velocities approaching the [speed of light](#), the laws of classical, often considered "[Newtonian](#)", physics remain accurate in predicting the behavior of the vast majority of "large" objects (on the order of the size of large molecules or bigger) at velocities much smaller than the [velocity of light](#).<sup>[47]</sup>

## Copenhagen interpretation of quantum versus classical kinematics [\[ edit \]](#)

A big difference between classical and quantum mechanics is that they use very different kinematic descriptions.<sup>[48]</sup>

In [Niels Bohr](#)'s mature view, quantum mechanical phenomena are required to be experiments, with complete descriptions of all the devices for the system, preparative, intermediary, and finally measuring. The descriptions are in macroscopic terms, expressed in ordinary language, supplemented with the concepts of classical mechanics.<sup>[49][50][51][52]</sup> The initial condition and the final condition of the system are respectively described by values in a configuration space, for example a position space, or some equivalent space such as a momentum space. Quantum mechanics does not admit a completely precise description, in terms of both position and momentum, of an initial condition or "state" (in the classical sense of the word) that would support a precisely deterministic and causal prediction of a final condition.<sup>[53][54]</sup> In this sense, advocated by Bohr in his mature writings, a quantum phenomenon is a process, a passage from initial to final condition, not an instantaneous "state" in the classical sense of that word.<sup>[55][56]</sup>

Thus there are two kinds of processes in quantum mechanics: stationary and transitional. For a stationary process, the initial and final condition are the same. For a transition, they are different. Obviously by definition, if only the initial condition is given, the process is not determined.<sup>[53]</sup>

Given its initial condition, prediction of its final condition is possible, causally but only probabilistically, because the Schrödinger equation is deterministic for wave function evolution, but the wave function describes the system only probabilistically.<sup>[57][58]</sup>

For many experiments, it is possible to think of the initial and final conditions of the system as being a particle. In some cases it appears that there are potentially several spatially distinct pathways or trajectories by which a particle might pass from initial to final condition. It is an important feature of the quantum kinematic description that it does not permit a unique definite statement of which of those pathways is actually followed. Only the initial and final conditions are definite, and, as stated in the foregoing paragraph, they are defined only as precisely as allowed by the configuration space description or its equivalent. In every case for which a quantum kinematic description is needed, there is always a compelling reason for this restriction of kinematic precision. An example of such a reason is that for a particle to be experimentally found in a definite position, it must be held motionless; for it to be experimentally found to have a definite momentum, it must have free motion; these two are logically incompatible.<sup>[59][60]</sup>

Classical kinematics does not primarily demand experimental description of its phenomena. It

allows completely precise description of an instantaneous state by a value in phase space, the Cartesian product of configuration and momentum spaces. This description simply assumes or imagines a state as a physically existing entity without concern about its experimental measurability. Such a description of an initial condition, together with Newton's laws of motion, allows a precise deterministic and causal prediction of a final condition, with a definite trajectory of passage. [Hamiltonian](#) dynamics can be used for this. Classical kinematics also allows the description of a process analogous to the initial and final condition description used by quantum mechanics. [Lagrangian mechanics](#) applies to this.<sup>[61]</sup> For processes that need account to be taken of actions of a small number of [Planck constants](#), classical kinematics is not adequate; quantum mechanics is needed.

## General relativity and quantum mechanics   [\[ edit \]](#)

Even with the defining postulates of both Einstein's theory of general relativity and quantum theory being indisputably supported by rigorous and repeated [empirical evidence](#), and while they do not directly contradict each other theoretically (at least with regard to their primary claims), they have proven extremely difficult to incorporate into one consistent, cohesive model.<sup>[62]</sup>

Gravity is negligible in many areas of particle physics, so that unification between general relativity and quantum mechanics is not an urgent issue in those particular applications. However, the lack of a correct theory of [quantum gravity](#) is an important issue in [cosmology](#) and the search by physicists for an elegant "[Theory of Everything](#)" (TOE). Consequently, resolving the inconsistencies between both theories has been a major goal of 20th and 21st century physics. Many prominent physicists, including [Stephen Hawking](#), have labored for many years in the attempt to discover a theory underlying *everything*. This TOE would combine not only the different models of subatomic physics, but also derive the four [fundamental forces of nature](#) - the [strong force](#), [electromagnetism](#), the [weak force](#), and [gravity](#) - from a single force or phenomenon. While Stephen Hawking was initially a believer in the Theory of Everything, after considering [Gödel's Incompleteness Theorem](#), he has concluded that one is not obtainable, and has stated so publicly in his lecture "Gödel and the End of Physics" (2002).<sup>[63]</sup>

## Attempts at a unified field theory   [\[ edit \]](#)

*Main article: [Grand unified theory](#)*

The quest to unify the [fundamental forces](#) through quantum mechanics is still ongoing. [Quantum electrodynamics](#) (or "quantum electromagnetism"), which is currently (in the perturbative regime at least) the most accurately tested physical theory in competition with general relativity,<sup>[64][65]</sup> has been successfully merged with the weak nuclear force into the [electroweak force](#) and work is currently being done to merge the electroweak and strong force into the [electrostrong force](#). Current predictions state that at around  $10^{14}$  GeV the three aforementioned forces are fused into a single unified field.<sup>[66]</sup> Beyond this "grand unification", it is speculated that it may be possible to merge gravity with the other three gauge symmetries, expected to occur at roughly  $10^{19}$  GeV. However — and while special relativity is parsimoniously incorporated into quantum electrodynamics — the expanded [general relativity](#), currently the best theory describing the gravitation force, has not been fully incorporated into quantum theory. One of those searching for a coherent TOE is [Edward Witten](#), a theoretical physicist who formulated the [M-theory](#), which

is an attempt at describing the supersymmetrical based [string theory](#). M-theory posits that our apparent 4-dimensional [spacetime](#) is, in reality, actually an 11-dimensional spacetime containing 10 spatial dimensions and 1 time dimension, although 7 of the spatial dimensions are - at lower energies - completely "compactified" (or infinitely curved) and not readily amenable to measurement or probing.

Another popular theory is [Loop quantum gravity](#) (LQG), a theory first proposed by [Carlo Rovelli](#) that describes the quantum properties of gravity. It is also a theory of [quantum space](#) and [quantum time](#), because in general relativity the geometry of spacetime is a manifestation of [gravity](#). LQG is an attempt to merge and adapt standard quantum mechanics and standard [general relativity](#). The main output of the theory is a physical picture of space where space is granular. The granularity is a direct consequence of the quantization. It has the same nature of the granularity of the photons in the quantum theory of electromagnetism or the discrete levels of the energy of the atoms. But here it is space itself which is discrete. More precisely, space can be viewed as an extremely fine fabric or network "woven" of finite loops. These networks of loops are called [spin networks](#). The evolution of a spin network over time is called a spin foam. The predicted size of this structure is the [Planck length](#), which is approximately  $1.616 \times 10^{-35}$  m. According to theory, there is no meaning to length shorter than this (cf. [Planck scale](#) energy). Therefore, LQG predicts that not just matter, but also space itself, has an atomic structure.

## Philosophical implications [\[ edit \]](#)

*Main article: [Interpretations of quantum mechanics](#)*

Since its inception, the many [counter-intuitive](#) aspects and results of quantum mechanics have provoked strong [philosophical](#) debates and many [interpretations](#). Even fundamental issues, such as [Max Born](#)'s basic [rules](#) concerning [probability amplitudes](#) and [probability distributions](#), took decades to be appreciated by society and many leading scientists. [Richard Feynman](#) once said, "I think I can safely say that nobody understands quantum mechanics."<sup>[67]</sup> According to [Steven Weinberg](#), "There is now in my opinion no entirely satisfactory interpretation of quantum mechanics."<sup>[68]</sup>

The [Copenhagen interpretation](#) — due largely to Niels Bohr and Werner Heisenberg — remains most widely accepted amongst physicists, some 75 years after its enunciation. According to this interpretation, the probabilistic nature of quantum mechanics is not a *temporary* feature which will eventually be replaced by a deterministic theory, but instead must be considered a *final* renunciation of the classical idea of "causality." It is also believed therein that any well-defined application of the quantum mechanical formalism must always make reference to the experimental arrangement, due to the [conjugate](#) nature of evidence obtained under different experimental situations.

Albert Einstein, himself one of the founders of quantum theory, did not accept some of the more philosophical or metaphysical interpretations of quantum mechanics, such as rejection of determinism and of [causality](#). He is famously quoted as saying, in response to this aspect, "God does not play with dice".<sup>[69]</sup> He rejected the concept that the state of a physical system depends on the experimental arrangement for its measurement. He held that a state of nature occurs in its own right, regardless of whether or how it might be observed. In that view, he is supported by the currently accepted definition of a quantum state, which remains invariant under arbitrary



choice of configuration space for its representation, that is to say, manner of observation. He also held that underlying quantum mechanics there should be a theory that thoroughly and directly expresses the rule against [action at a distance](#); in other words, he insisted on the [principle of locality](#). He considered, but rejected on theoretical grounds, a particular proposal for hidden variables to obviate the indeterminism or acausality of quantum mechanical measurement. He considered that quantum mechanics was a currently valid but not a permanently definitive theory for quantum phenomena. He thought its future replacement would require profound conceptual advances, and would not come quickly or easily. The [Bohr-Einstein debates](#) provide a vibrant critique of the Copenhagen Interpretation from an [epistemological](#) point of view. In arguing for his views, he produced a series of objections, the most famous of which has become known as the [Einstein–Podolsky–Rosen paradox](#).

[John Bell](#) showed that this "EPR" paradox led to [experimentally testable differences](#) between quantum mechanics and theories that rely on added hidden variables. [Experiments](#) have been performed confirming the accuracy of quantum mechanics, thereby demonstrating that quantum mechanics cannot be improved upon by addition of hidden variables.<sup>[70]</sup> Alain Aspect's initial experiments in 1982, and many subsequent experiments since, have definitively verified quantum entanglement.

Entanglement, as demonstrated in Bell-type experiments, does not, however, violate [causality](#), since no transfer of information happens. Quantum entanglement forms the basis of [quantum cryptography](#), which is proposed for use in high-security commercial applications in banking and government.

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.<sup>[71]</sup> This is not accomplished by introducing some "new axiom" to quantum mechanics, but on the contrary, by *removing* the axiom of the collapse of the wave packet. *All* of the possible consistent states of the measured system and the measuring apparatus (including the observer) are present in a *real* physical - not just formally mathematical, as in other interpretations - [quantum superposition](#). Such a superposition of consistent state combinations of different systems is called an [entangled state](#). While the multiverse is deterministic, we perceive non-deterministic behavior governed by probabilities, because we can only observe the universe (i.e., the consistent state contribution to the aforementioned superposition) that we, as observers, inhabit. Everett's interpretation is perfectly consistent with [John Bell](#)'s experiments and makes them intuitively understandable. However, according to the theory of [quantum decoherence](#), these "parallel universes" will never be accessible to us. The inaccessibility can be understood as follows: once a measurement is done, the measured system becomes [entangled](#) with *both* the physicist who measured it *and* a huge number of other particles, some of which are [photons](#) flying away at the [speed of light](#) towards the other end of the universe. In order to prove that the wave function did not collapse, one would have to bring *all* these particles back and measure them again, together with the system that was originally measured. Not only is this completely impractical, but even if one *could* theoretically do this, it would have to destroy any evidence that the original measurement took place (including the physicist's memory). In light of these [Bell tests](#), Cramer (1986) formulated his [transactional interpretation](#).<sup>[72]</sup> [Relational quantum mechanics](#) appeared in the late 1990s as the modern

derivative of the [Copenhagen Interpretation](#).

## Applications [[edit](#)]

Quantum mechanics has had enormous<sup>[73]</sup> success in explaining many of the features of our universe. Quantum mechanics is often the only tool available that can reveal the individual behaviors of the [subatomic particles](#) that make up all forms of matter ([electrons](#), [protons](#), [neutrons](#), [photons](#), and others). Quantum mechanics has strongly influenced [string theories](#), candidates for a [Theory of Everything](#) (see [reductionism](#)).

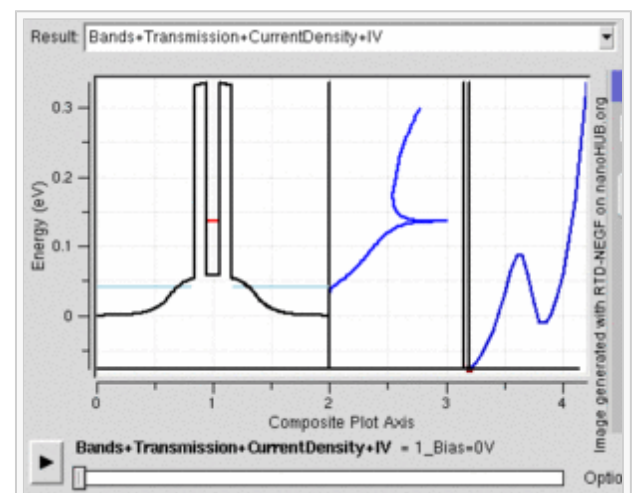
Quantum mechanics is also critically important for understanding how individual atoms combine covalently to form [molecules](#). The application of quantum mechanics to [chemistry](#) is known as [quantum chemistry](#). Relativistic quantum mechanics can, in principle, mathematically describe most of chemistry. Quantum mechanics can also provide quantitative insight into [ionic](#) and [covalent bonding](#) processes by explicitly showing which molecules are energetically favorable to which others and the magnitudes of the energies involved.<sup>[74]</sup> Furthermore, most of the calculations performed in modern [computational chemistry](#) rely on quantum mechanics.

In many aspects modern technology operates at a scale where quantum effects are significant.

## Electronics [[edit](#)]

Many modern electronic devices are designed using quantum mechanics. Examples include the [laser](#), the [transistor](#) (and thus the [microchip](#)), the [electron microscope](#), and [magnetic resonance imaging](#) (MRI). The study of [semiconductors](#) led to the invention of the [diode](#) and the [transistor](#), which are indispensable parts of modern [electronics](#) systems, [computer](#) and [telecommunication](#) devices. Another application is the [light emitting diode](#) which is a high-efficiency source of light.

Many electronic devices operate under effect of [Quantum tunneling](#). It even exists in the simple [light switch](#). The switch would not work if electrons could not quantum tunnel through the layer of oxidation on the metal contact surfaces. [Flash memory](#) chips found in [USB drives](#) use quantum tunneling to erase their memory cells. Some negative differential resistance devices also utilizes quantum tunneling effect, such as [resonant tunneling diode](#). Unlike classical diodes, its current is carried by [resonant tunneling](#) through two [potential barriers](#) (see right figure). Its negative resistance behavior can only be understood with quantum mechanics: As the confined state moves close to [Fermi level](#), tunnel current increases. As it moves away, current decreases. Quantum mechanics is vital to understanding and designing such electronic devices.



A working mechanism of a [resonant tunneling diode](#) device, based on the phenomenon of [quantum tunneling](#) through [potential barriers](#). (Left: [band diagram](#); Center: [transmission coefficient](#); Right: current-voltage characteristics) As shown in the band diagram (left), although there are two barriers, electrons still tunnel through via the confined states between two barriers (center), conducting current.

## Cryptography [ [edit](#) ]

Researchers are currently seeking robust methods of directly manipulating quantum states. Efforts are being made to more fully develop [quantum cryptography](#), which will theoretically allow guaranteed secure transmission of [information](#).

## Quantum computing [ [edit](#) ]

A more distant goal is the development of [quantum computers](#), which are expected to perform certain computational tasks exponentially faster than classical [computers](#). Instead of using classical bits, quantum computers use [qubits](#), which can be in [superpositions](#) of states. Another active research topic is [quantum teleportation](#), which deals with techniques to transmit quantum information over arbitrary distances.

## Macroscale quantum effects [ [edit](#) ]

While quantum mechanics primarily applies to the smaller atomic regimes of matter and energy, some systems exhibit [quantum mechanical effects](#) on a large scale. [Superfluidity](#), the frictionless flow of a liquid at temperatures near [absolute zero](#), is one well-known example. So is the closely related phenomenon of [superconductivity](#), the frictionless flow of an electron gas in a conducting material (an [electric current](#)) at sufficiently low temperatures.

## Quantum theory [ [edit](#) ]

Quantum theory also provides accurate descriptions for many previously unexplained phenomena, such as [black-body radiation](#) and the stability of the [orbitals](#) of electrons in atoms. It has also given insight into the workings of many different [biological systems](#), including [smell receptors](#) and [protein structures](#).<sup>[75]</sup> Recent work on [photosynthesis](#) has provided evidence that quantum correlations play an essential role in this fundamental process of plants and many other organisms.<sup>[76]</sup> Even so, [classical physics](#) can often provide good approximations to results otherwise obtained by quantum physics, typically in circumstances with large numbers of particles or large [quantum numbers](#). Since classical formulas are much simpler and easier to compute than quantum formulas, classical approximations are used and preferred when the system is large enough to render the effects of quantum mechanics insignificant.

## Examples [ [edit](#) ]

### Free particle [ [edit](#) ]

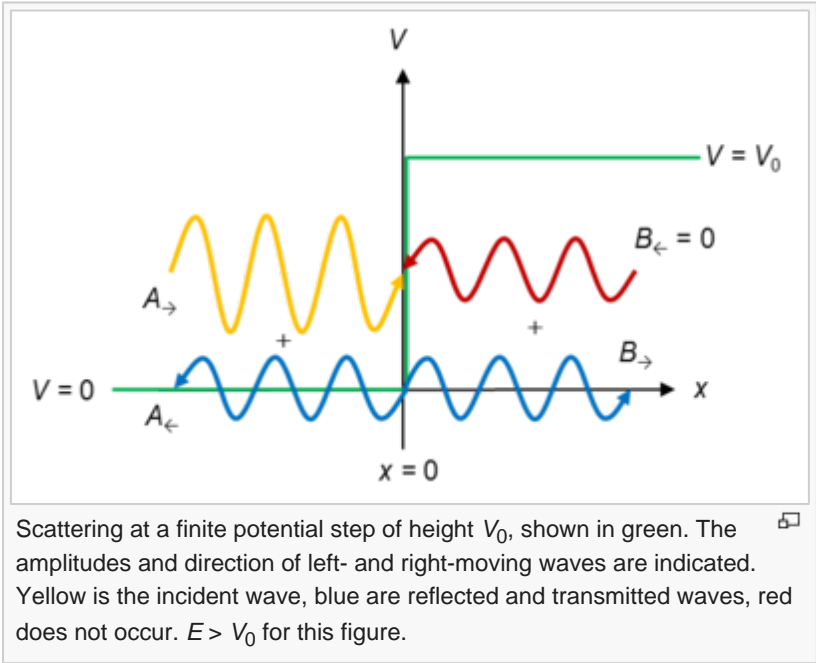
For example, consider a [free particle](#). In quantum mechanics, there is [wave–particle duality](#), so the properties of the particle can be described as the properties of a wave. Therefore, its [quantum state](#) can be represented as a [wave](#) of arbitrary shape and extending over space as a [wave function](#). The position and momentum of the particle are [observables](#). The [Uncertainty Principle](#) states that both the position and the momentum cannot simultaneously be measured with complete precision. However, one *can* measure the position (alone) of a moving free particle, creating an eigenstate of position with a wave function that is very large (a [Dirac delta](#)) at a particular position *x*, and zero everywhere else. If one performs a position measurement on

such a wave function, the resultant  $x$  will be obtained with 100% probability (i.e., with full certainty, or complete precision). This is called an eigenstate of position—or, stated in mathematical terms, a *generalized position eigenstate* (*eigendistribution*). If the particle is in an eigenstate of position, then its momentum is completely unknown. On the other hand, if the particle is in an eigenstate of momentum, then its position is completely unknown.<sup>[77]</sup> In an eigenstate of momentum having a *plane wave* form, it can be shown that the *wavelength* is equal to  $h/p$ , where  $h$  is *Planck's constant* and  $p$  is the momentum of the *eigenstate*.<sup>[78]</sup>

**Step potential** [ edit ]

*Main article: [Solution of Schrödinger equation for a step potential](#)*

The potential in this case is given by:



?

The solutions are superpositions of left- and right-moving waves:

?
?

where the *wave vectors* are related to the energy via

?	, and
?	

with coefficients  $A$  and  $B$  determined from the *boundary conditions* and by imposing a continuous *derivative* on the solution.

Each term of the solution can be interpreted as an incident, reflected, or transmitted component of the wave, allowing the calculation of transmission and reflection coefficients. Notably, in contrast to classical mechanics, incident particles with energies greater than the potential step

are partially reflected.

Rectangular potential barrier [edit]

Main article: Rectangular potential barrier

This is a model for the quantum tunneling effect which plays an important role in the performance of modern technologies such as flash memory and scanning tunneling microscopy. Quantum tunneling is central to physical phenomena involved in superlattices.

Particle in a box [edit]

Main article: Particle in a box

The particle in a one-dimensional potential energy box is the most mathematically simple example where restraints lead to the quantization of energy levels. The box is defined as having zero potential energy everywhere *inside* a certain region, and infinite potential energy everywhere *outside* that region. For the one-dimensional case in the  $x$  direction, the time-independent Schrödinger equation may be written<sup>[79]</sup>

With the differential operator defined by

the previous equation is evocative of the classic kinetic energy analogue,

with state  $n$  in this case having energy  $E_n$  coincident with the kinetic energy of the particle.

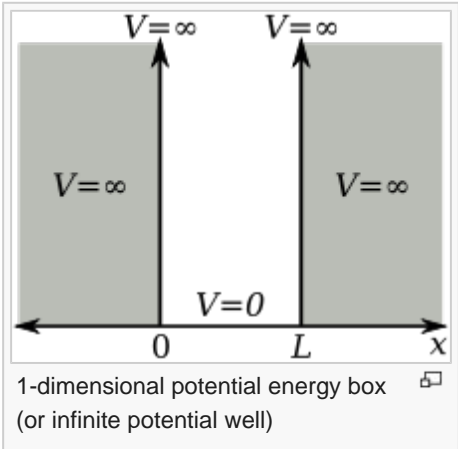
The general solutions of the Schrödinger equation for the particle in a box are

or, from Euler's formula,

The infinite potential walls of the box determine the values of  $C$ ,  $D$ , and  $k$  at  $x = 0$  and  $x = L$  where  $\psi$  must be zero. Thus, at  $x = 0$ ,

and  $D = 0$ . At  $x = L$ ,

in which  $C$  cannot be zero as this would conflict with the Born interpretation. Therefore, since  $\sin(kL) = 0$ ,  $kL$  must be an integer multiple of  $\pi$ ,





The quantization of energy levels follows from this constraint on  $k$ , since

?

**Finite potential well** [\[ edit \]](#)

*Main article: [Finite potential well](#)*

A finite potential well is the generalization of the infinite potential well problem to potential wells having finite depth.

The finite potential well problem is mathematically more complicated than the infinite particle-in-a-box problem as the wave function is not pinned to zero at the walls of the well. Instead, the wave function must satisfy more complicated mathematical boundary conditions as it is nonzero in regions outside the well.

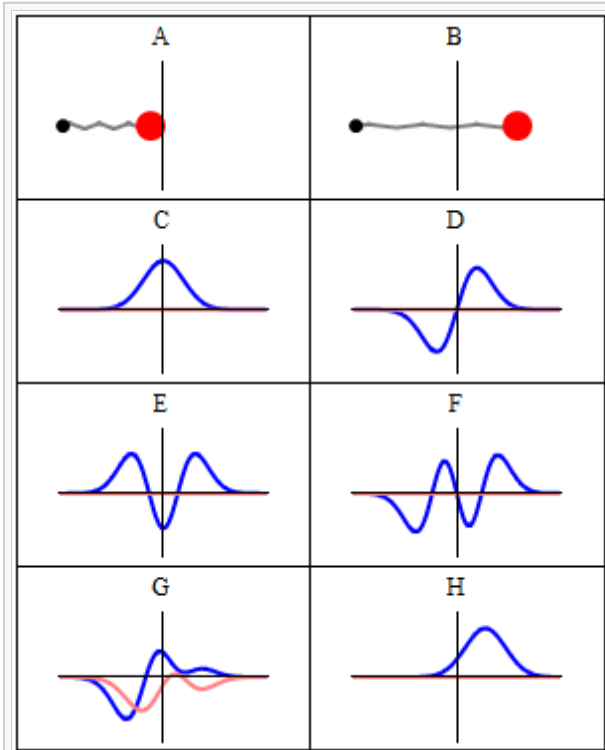
**Harmonic oscillator** [\[ edit \]](#)


*Main article: [Quantum harmonic oscillator](#)*

As in the classical case, the potential for the quantum harmonic oscillator is given by

?

This problem can either be treated by directly solving the Schrödinger equation, which is not trivial, or by using the more elegant "ladder method" first proposed by Paul Dirac. The [eigenstates](#) are given by



Some trajectories of a [harmonic oscillator](#) (i.e. a ball  attached to a [spring](#)) in [classical mechanics](#) (A-B) and quantum mechanics (C-H). In quantum mechanics, the position of the ball is represented by a [wave](#) (called the [wave function](#)), with the [real part](#) shown in blue and the [imaginary part](#) shown in red. Some of the trajectories (such as C,D,E,and F) are [standing waves](#) (or "[stationary states](#)"). Each standing-wave frequency is proportional to a possible [energy level](#) of the oscillator. This "energy quantization" does not occur in classical physics, where the oscillator can have *any* energy.



where  $H_n$  are the [Hermite polynomials](#),



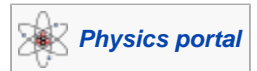
and the corresponding energy levels are



This is another example illustrating the quantization of energy for bound states.

## See also [\[ edit \]](#)


























- [Angular momentum diagrams \(quantum mechanics\)](#)
- [EPR paradox](#)
- [Fractional quantum mechanics](#)
- [List of quantum-mechanical systems with analytical solutions](#)
- [Macroscopic quantum phenomena](#)
- [Phase space formulation](#)
- [Regularization \(physics\)](#)
- [Spherical basis](#)



## Notes [\[ edit \]](#)

- ↑ Matson, John. "What Is Quantum Mechanics Good for?" . Scientific American. Retrieved 18 May 2016.
- ↑ [Max Born](#) & Emil Wolf, Principles of Optics, 1999, Cambridge University Press
- ↑ Mehra, J.; Rechenberg, H. (1982). *The historical development of quantum theory*. New York: Springer-Verlag. ISBN 0387906428.
- ↑ Kragh, Helge (2002). *Quantum Generations: A History of Physics in the Twentieth Century* . Princeton University Press. p. 58. ISBN 0-691-09552-3. Extract of page 58
- ↑ Ben-Menahem, Ari (2009). *Historical Encyclopedia of Natural and Mathematical Sciences, Volume 1* . Springer. p. 3678. ISBN 3540688315. Extract of page 3678
- ↑ E Arunan (2010). "Peter Debye" (PDF). *Resonance (journal)*. Indian Academy of Sciences. **15** (12).
- ↑ [Kuhn, T. S.](#) (1978). *Black-body theory and the quantum discontinuity 1894-1912*. Oxford: Clarendon Press. ISBN 0195023838.
- ↑ Kragh, Helge (1 December 2000), *Max Planck: the reluctant revolutionary* , PhysicsWorld.com
- ↑ Einstein, A. (1905). "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" [On a heuristic point of view concerning the production and transformation of light]. *Annalen der Physik*. **17** (6): 132–148. Bibcode:1905AnP...322..132E . doi:10.1002/andp.19053220607 . Reprinted in *The collected papers of Albert Einstein*, John Stachel, editor, Princeton University Press, 1989, Vol. 2, pp. 149-166, in German; see also




*Einstein's early work on the quantum hypothesis*, *ibid.* pp. 134-148.

10. <sup>^</sup> van Hove, Leon (1958). "Von Neumann's contributions to quantum mechanics"  (PDF). *Bulletin of the American Mathematical Society*. **64** (3): Part2:95–99. doi:10.1090/s0002-9904-1958-10206-2 .
11. <sup>^</sup> Feynman, Richard. "The Feynman Lectures on Physics III 21-4" . California Institute of Technology. Retrieved 2015-11-24. ""...it was long believed that the wave function of the Schrödinger equation would never have a macroscopic representation analogous to the macroscopic representation of the amplitude for photons. On the other hand, it is now realized that the phenomena of superconductivity presents us with just this situation."
12. <sup>^</sup> Richard Packard (2006) "Berkeley Experiments on Superfluid Macroscopic Quantum Effects"  Archived  November 25, 2015, at the [Wayback Machine](#). accessdate=2015-11-24
13. <sup>^</sup> "Quantum - Definition and More from the Free Merriam-Webster Dictionary" . Merriam-webster.com. Retrieved 2012-08-18.
14. <sup>^</sup> Thall, Edwin. "Thall's History of Quantum Mechanics" . Florida Community College at Jacksonville. Archived from the original  on October 7, 2009. Retrieved May 23, 2009.
15. <sup>^</sup> "ysfine.com" . *ysfine.com*. Retrieved 11 September 2015.
16. <sup>^</sup> "QUANTUM MECHANICS" . *geocities.com*. 2009-10-26. Archived from the original  on 2009-10-26. Retrieved 2016-06-13.
17. <sup>^</sup> P.A.M. Dirac, *The Principles of Quantum Mechanics*, Clarendon Press, Oxford, 1930.
18. <sup>^</sup> D. Hilbert *Lectures on Quantum Theory*, 1915–1927
19. <sup>^</sup> J. von Neumann, *Mathematische Grundlagen der Quantenmechanik*, Springer, Berlin, 1932 (English translation: *Mathematical Foundations of Quantum Mechanics*, Princeton University Press, 1955).
20. <sup>^</sup> H.Weyl "The Theory of Groups and Quantum Mechanics", 1931 (original title: "Gruppentheorie und Quantenmechanik").
21. <sup>^</sup> Dirac, P.A.M. (1958). *The Principles of Quantum Mechanics*, 4th edition, Oxford University Press, Oxford UK, p. ix: "For this reason I have chosen the symbolic method, introducing the representatives later merely as an aid to practical calculation."
22. <sup>^</sup> Greiner, Walter; Müller, Berndt (1994). *Quantum Mechanics Symmetries, Second edition* . Springer-Verlag. p. 52. ISBN 3-540-58080-8., Chapter 1, p. 52 
23. <sup>^</sup> "Heisenberg - Quantum Mechanics, 1925–1927: The Uncertainty Relations" . Aip.org. Retrieved 2012-08-18.
24. <sup>^</sup> <sup>a</sup> <sup>b</sup> Greenstein, George; Zajonc, Arthur (2006). *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics, Second edition* . Jones and Bartlett Publishers, Inc. p. 215. ISBN 0-7637-2470-X., Chapter 8, p. 215 
25. <sup>^</sup> "[Abstract] Visualization of Uncertain Particle Movement" . Actapress.com. Retrieved 2012-08-18.
26. <sup>^</sup> Hirshleifer, Jack (2001). *The Dark Side of the Force: Economic Foundations of Conflict Theory* . Cambridge University Press. p. 265. ISBN 0-521-80412-4., Chapter , p. 
27. <sup>^</sup> "dict.cc dictionary :: eigen :: German-English translation" . dict.cc. Retrieved 11 September 2015.
28. <sup>^</sup> "Topics: Wave-Function Collapse" . Phy.olemiss.edu. 2012-07-27. Retrieved 2012-08-18.
29. <sup>^</sup> "Collapse of the wave-function" . Farside.ph.utexas.edu. Retrieved 2012-08-18.
30. <sup>^</sup> "Determinism and Naive Realism : philosophy" . Reddit.com. 2009-06-01. Retrieved 2012-08-18.
31. <sup>^</sup> Michael Trott. "Time-Evolution of a Wavepacket in a Square Well — Wolfram Demonstrations Project" . Demonstrations.wolfram.com. Retrieved 2010-10-15.
32. <sup>^</sup> Michael Trott. "Time Evolution of a Wavepacket In a Square Well" .

Demonstrations.wolfram.com. Retrieved 2010-10-15.

33.  Mathews, Piravonu Mathews; Venkatesan, K. (1976). *A Textbook of Quantum Mechanics*. Tata McGraw-Hill. p. 36. ISBN 0-07-096510-2., Chapter 2, p. 36
34.  "Wave Functions and the Schrödinger Equation"  (PDF). Retrieved 2010-10-15.
35.  Rechenberg, Helmut (1987). "Erwin Schrödinger and the creation of wave mechanics" (pdf). *Acta Physica Polonica B*. **19** (8): 683–695. Retrieved 13 June 2016.
36.  Nancy Thorndike Greenspan, "The End of the Certain World: The Life and Science of Max Born" (Basic Books, 2005), pp. 124-8 and 285-6.
37.  [http://ocw.usu.edu/physics/classical-mechanics/pdf\\_lectures/06.pdf](http://ocw.usu.edu/physics/classical-mechanics/pdf_lectures/06.pdf)
38.  "The Nobel Prize in Physics 1979". Nobel Foundation. Retrieved 2010-02-16.
39.  Carl M. Bender; Daniel W. Hook; Karta Kooner (2009-12-31). "Complex Elliptic Pendulum". [arXiv:1001.0131](https://arxiv.org/abs/1001.0131)  [\[hep-th\]](#).
40.  See, for example, [Precision tests of QED](#). The relativistic refinement of quantum mechanics known as [quantum electrodynamics](#) (QED) has been shown to agree with experiment to within 1 part in 10<sup>8</sup> for some atomic properties.
41.  Tipler, Paul; Llewellyn, Ralph (2008). *Modern Physics* (5 ed.). W. H. Freeman and Company. pp. 160–161. ISBN 978-0-7167-7550-8.
42.  "Quantum mechanics course iwhatisquantummechanics". Scribd.com. 2008-09-14. Retrieved 2012-08-18.
43.  A. Einstein, B. Podolsky, and N. Rosen, *Can quantum-mechanical description of physical reality be considered complete?*  Phys. Rev. **47** 777 (1935). [\[1\]](#)
44.  N. P. Landsman (June 13, 2005). "Between classical and quantum"  (PDF). Retrieved 2012-08-19. *Handbook of the Philosophy of Science* Vol. 2: Philosophy of Physics (eds. John Earman & Jeremy Butterfield).
45.  (see [macroscopic quantum phenomena](#), [Bose–Einstein condensate](#), and [Quantum machine](#))
46.  "Atomic Properties". Academic.brooklyn.cuny.edu. Retrieved 2012-08-18.
47.  [http://assets.cambridge.org/97805218/29526/excerpt/9780521829526\\_excerpt.pdf](http://assets.cambridge.org/97805218/29526/excerpt/9780521829526_excerpt.pdf)
48.  Born, M., Heisenberg, W., Jordan, P. (1926). *Z. Phys.* **35**: 557–615. Translated as 'On quantum mechanics II', pp. 321–385 in [Van der Waerden, B.L.](#) (1967), *Sources of Quantum Mechanics*, North-Holland, Amsterdam, "The basic difference between the theory proposed here and that used hitherto ... lies in the characteristic kinematics ...", p. 385.
49.  Dirac, P.A.M. (1930/1958). *The Principles of Quantum Mechanics*, fourth edition, Oxford University Press, Oxford UK, p. 5: "A question about what will happen to a particular photon under certain conditions is not really very precise. To make it precise one must imagine some experiment performed having a bearing on the question, and enquire what will be the result of the experiment. Only questions about the results of experiments have a real significance and it is only such questions that theoretical physics has to consider."
50.  Bohr, N. (1939). The Causality Problem in Atomic Physics, in *New Theories in Physics, Conference organized in collaboration with the International Union of Physics and the Polish Intellectual Co-operation Committee, Warsaw, May 30th – June 3rd 1938*, International Institute of Intellectual Co-operation, Paris, 1939, pp. 11–30, reprinted in *Niels Bohr, Collected Works*, volume 7 (1933 – 1958) edited by J. Kalckar, Elsevier, Amsterdam, ISBN 0-444-89892-1, pp. 303–322. "The essential lesson of the analysis of measurements in quantum theory is thus the emphasis on the necessity, in the account of the phenomena, of taking the whole experimental arrangement into consideration, in complete conformity with the fact that all unambiguous interpretation of the quantum mechanical formalism involves the fixation of the external conditions, defining the initial state of the atomic system and the character of the possible predictions as regards subsequent observable properties of that system. Any measurement in

quantum theory can in fact only refer either to a fixation of the initial state or to the test of such predictions, and it is first the combination of both kinds which constitutes a well-defined phenomenon."

51. <sup>^</sup> [Bohr, N.](#) (1948). On the notions of complementarity and causality, *Dialectica* **2**: 312–319. "As a more appropriate way of expression, one may advocate limitation of the use of the word *phenomenon* to refer to observations obtained under specified circumstances, including an account of the whole experiment."
52. <sup>^</sup> [Ludwig, G.](#) (1987). *An Axiomatic Basis for Quantum Mechanics*, volume 2, *Quantum Mechanics and Macrosystems*, translated by K. Just, Springer, Berlin, [ISBN 978-3-642-71899-1](#), Chapter XIII, Special Structures in Preparation and Registration Devices, §1, Measurement chains, p. 132.
53. <sup>^</sup> <sup>[a](#)</sup> <sup>[b](#)</sup> [Heisenberg, W.](#) (1927). Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik, *Z. Phys.* **43**: 172–198. Translation as 'The actual content of quantum theoretical kinematics and mechanics' here [\[2\]](#) , "But in the rigorous formulation of the law of causality, — "If we know the present precisely, we can calculate the future" — it is not the conclusion that is faulty, but the premise."
54. <sup>^</sup> [Green, H.S.](#) (1965). *Matrix Mechanics*, with a foreword by [Max Born](#), P. Noordhoff Ltd, Groningen. "It is not possible, therefore, to provide 'initial conditions' for the prediction of the behaviour of atomic systems, in the way contemplated by classical physics. This is accepted by quantum theory, not merely as an experimental difficulty, but as a fundamental law of nature", p. 32.
55. <sup>^</sup> [Rosenfeld, L.](#) (1957). Misunderstandings about the foundations of quantum theory, pp. 41–45 in *Observation and Interpretation*, edited by S. Körner, Butterworths, London. "A phenomenon is therefore a process (endowed with the characteristic quantal wholeness) involving a definite type of interaction between the system and the apparatus."
56. <sup>^</sup> [Dirac, P.A.M.](#) (1973). Development of the physicist's conception of nature, pp. 1–55 in *The Physicist's Conception of Nature*, edited by J. Mehra, D. Reidel, Dordrecht, [ISBN 90-277-0345-0](#), p. 5: "That led Heisenberg to his really masterful step forward, resulting in the new quantum mechanics. His idea was to build up a theory entirely in terms of quantities referring to two states."
57. <sup>^</sup> [Born, M.](#) (1927). Physical aspects of quantum mechanics, *Nature* **119**: 354–357, "These probabilities are thus dynamically determined. But what the system actually does is not determined ..."
58. <sup>^</sup> [Messiah, A.](#) (1961). *Quantum Mechanics*, volume 1, translated by G.M. Temmer from the French *Mécanique Quantique*, North-Holland, Amsterdam, p. 157.
59. <sup>^</sup> [Bohr, N.](#) (1928). The Quantum postulate and the recent development of atomic theory, *Nature* **121**: 580–590.
60. <sup>^</sup> [Heisenberg, W.](#) (1930). *The Physical Principles of the Quantum Theory*, translated by C. Eckart and F.C. Hoyt, University of Chicago Press.
61. <sup>^</sup> [Goldstein, H.](#) (1950). *Classical Mechanics*, Addison-Wesley, [ISBN 0-201-02510-8](#).
62. <sup>^</sup> "There is as yet no logically consistent and complete relativistic quantum field theory.", p. 4. — V. B. Berestetskii, [E. M. Lifshitz](#), L P Pitaevskii (1971). J. B. Sykes, J. S. Bell (translators). *Relativistic Quantum Theory* **4**, **part I**. *Course of Theoretical Physics (Landau and Lifshitz)* [ISBN 0-08-016025-5](#)
63. <sup>^</sup> ["Stephen Hawking; Gödel and the end of physics"](#)  [cam.ac.uk](#). Retrieved 11 September 2015.
64. <sup>^</sup> ["The Nature of Space and Time"](#)  [google.com](#). Retrieved 11 September 2015.
65. <sup>^</sup> [Tatsumi Aoyama; Masashi Hayakawa; Toichiro Kinoshita; Makiko Nio](#) (2012). ["Tenth-Order](#)



QED Contribution to the Electron g-2 and an Improved Value of the Fine Structure Constant"[↗](#). *Physical Review Letters*. **109** (11): 111807. [arXiv:1205.5368v2](#)[↗](#).  
Bibcode:2012PhRvL.109k1807A[↗](#). doi:10.1103/PhysRevLett.109.111807[↗](#).

66. [↗](#) Parker, B. (1993). *Overcoming some of the problems*. pp. 259–279.

67. [↗](#) The Character of Physical Law (1965) Ch. 6; also quoted in *The New Quantum Universe* (2003), by Tony Hey and Patrick Walters

68. [↗](#) Weinberg, S. "Collapse of the State Vector"[↗](#), *Phys. Rev. A* 85, 062116 (2012).

69. [↗](#) Harrison, Edward (16 March 2000). *Cosmology: The Science of the Universe*[↗](#). Cambridge University Press. p. 239. ISBN 978-0-521-66148-5.

70. [↗](#) "Action at a Distance in Quantum Mechanics (Stanford Encyclopedia of Philosophy)"[↗](#). Plato.stanford.edu. 2007-01-26. Retrieved 2012-08-18.

71. [↗](#) "Everett's Relative-State Formulation of Quantum Mechanics (Stanford Encyclopedia of Philosophy)"[↗](#). Plato.stanford.edu. Retrieved 2012-08-18.

72. [↗](#) The Transactional Interpretation of Quantum Mechanics[↗](#) by John Cramer. *Reviews of Modern Physics* 58, 647-688, July (1986)

73. [↗](#) See, for example, the [Feynman Lectures on Physics](#) for some of the technological applications which use quantum mechanics, e.g., [transistors](#) (vol III, pp. 14–11 ff), [integrated circuits](#), which are follow-on technology in solid-state physics (vol II, pp. 8–6), and [lasers](#) (vol III, pp. 9–13).

74. [↗](#) Pauling, Linus; Wilson, Edgar Bright (1985-03-01). *Introduction to Quantum Mechanics with Applications to Chemistry*[↗](#). ISBN 9780486648712. Retrieved 2012-08-18.

75. [↗](#) Anderson, Mark (2009-01-13). "Is Quantum Mechanics Controlling Your Thoughts? | Subatomic Particles"[↗](#). DISCOVER Magazine. Retrieved 2012-08-18.

76. [↗](#) "Quantum mechanics boosts photosynthesis"[↗](#). physicsworld.com. Retrieved 2010-10-23.

77. [↗](#) Davies, P. C. W.; Betts, David S. (1984). *Quantum Mechanics, Second edition*[↗](#). Chapman and Hall. p. 79. ISBN 0-7487-4446-0., Chapter 6, p. 79[↗](#)

78. [↗](#) Baofu, Peter (2007-12-31). *The Future of Complexity: Conceiving a Better Way to Understand Order and Chaos*[↗](#). ISBN 9789812708991. Retrieved 2012-08-18.

79. [↗](#) Derivation of particle in a box, [chemistry.tidalswan.com](#)[↗](#)

## References [\[ edit \]](#)

The following titles, all by working physicists, attempt to communicate quantum theory to lay people, using a minimum of technical apparatus.

- Chester, Marvin (1987) *Primer of Quantum Mechanics*. John Wiley. ISBN 0-486-42878-8
- Cox, Brian; Forshaw, Jeff (2011). *The Quantum Universe: Everything That Can Happen Does Happen*:. Allen Lane. ISBN 1-84614-432-9.
- Richard Feynman, 1985. *QED: The Strange Theory of Light and Matter*, Princeton University Press. ISBN 0-691-08388-6. Four elementary lectures on quantum electrodynamics and quantum field theory, yet containing many insights for the expert.
- Ghirardi, GianCarlo, 2004. *Sneaking a Look at God's Cards*, Gerald Malsbary, trans. Princeton Univ. Press. The most technical of the works cited here. Passages using algebra, trigonometry, and bra–ket notation can be passed over on a first reading.
- N. David Mermin, 1990, "Spooky actions at a distance: mysteries of the QT" in his *Boojums all the way through*. Cambridge University Press: 110-76.
- Victor Stenger, 2000. *Timeless Reality: Symmetry, Simplicity, and Multiple Universes*. Buffalo NY: Prometheus Books. Chpts. 5-8. Includes cosmological and philosophical considerations.

More technical:

- Bryce DeWitt**, R. Neill Graham, eds., 1973. *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, **Princeton University Press**. ISBN 0-691-08131-X
- Dirac, P. A. M.** (1930). *The Principles of Quantum Mechanics*. ISBN 0-19-852011-5. The beginning chapters make up a very clear and comprehensible introduction.
- Hugh Everett**, 1957, "Relative State Formulation of Quantum Mechanics", *Reviews of Modern Physics* 29: 454-62.
- Feynman, Richard P.**; **Leighton, Robert B.**; Sands, Matthew (1965). *The Feynman Lectures on Physics*. **1–3**. Addison-Wesley. ISBN 0-7382-0008-5.
- Griffiths, David J. (2004). *Introduction to Quantum Mechanics (2nd ed.)*. Prentice Hall. ISBN 0-13-111892-7. OCLC 40251748 . A standard undergraduate text.
- Max Jammer**, 1966. *The Conceptual Development of Quantum Mechanics*. McGraw Hill.
- Hagen Kleinert**, 2004. *Path Integrals in Quantum Mechanics, Statistics, Polymer Physics, and Financial Markets*, 3rd ed. Singapore: World Scientific. **Draft of 4th edition**.
- Gunther Ludwig, 1968. *Wave Mechanics*. London: Pergamon Press. ISBN 0-08-203204-1
- George Mackey** (2004). *The mathematical foundations of quantum mechanics*. Dover Publications. ISBN 0-486-43517-2.
- Albert Messiah**, 1966. *Quantum Mechanics* (Vol. I), English translation from French by G. M. Temmer. North Holland, John Wiley & Sons. Cf. chpt. IV, section III.
- Omnès, Roland** (1999). *Understanding Quantum Mechanics*. Princeton University Press. ISBN 0-691-00435-8. OCLC 39849482 .
- Scerri, Eric R., 2006. *The **Periodic Table**: Its Story and Its Significance*. Oxford University Press. Considers the extent to which chemistry and the periodic system have been reduced to quantum mechanics. ISBN 0-19-530573-6
- Transnational College of Lex** (1996). *What is Quantum Mechanics? A Physics Adventure*. Language Research Foundation, Boston. ISBN 0-9643504-1-6. OCLC 34661512 .
- von Neumann, John** (1955). *Mathematical Foundations of Quantum Mechanics*. Princeton University Press. ISBN 0-691-02893-1.
- Hermann Weyl**, 1950. *The Theory of Groups and Quantum Mechanics*, Dover Publications.
- D. Greenberger, K. Hentschel, F. Weinert, eds., 2009. *Compendium of quantum physics, Concepts, experiments, history and philosophy*, Springer-Verlag, Berlin, Heidelberg.










## Further reading [ edit ]

- Bernstein, Jeremy (2009). *Quantum Leaps* . Cambridge, Massachusetts: Belknap Press of Harvard University Press. ISBN 978-0-674-03541-6.
- Bohm, David** (1989). *Quantum Theory*. **Dover Publications**. ISBN 0-486-65969-0.
- Eisberg, Robert; **Resnick, Robert** (1985). *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles (2nd ed.)*. Wiley. ISBN 0-471-87373-X.
- Liboff, Richard L.** (2002). *Introductory Quantum Mechanics*. Addison-Wesley. ISBN 0-8053-8714-5.
- Merzbacher, Eugen (1998). *Quantum Mechanics*. Wiley, John & Sons, Inc. ISBN 0-471-88702-1.
- Sakurai, J. J.** (1994). *Modern Quantum Mechanics*. Addison Wesley. ISBN 0-201-53929-2.
- Shankar, R. (1994). *Principles of Quantum Mechanics*. Springer. ISBN 0-306-44790-8.
- Stone, A. Douglas (2013). *Einstein and the Quantum*. Princeton University Press. ISBN 978-0-691-13968-5.

















Martinus J. G. Veltman, 2003 *Facts and Mysteries in Elementary Particle Physics*.

- Shushi, Tomer (2014). *The Influence of Particle Interactions on the Existence of Quantum Particles Properties*  (PDF). Haifa, Israel: Journal of Physical Science and Application.



## External links [ [edit](#) ]

- 3D animations, applications and research for basic quantum effects  (animations also available in [commons.wikimedia.org](https://commons.wikimedia.org)  (Université paris Sud))
- Quantum Cook Book  by R. Shankar, Open Yale PHYS 201 material (4pp)
- The Modern Revolution in Physics  - an online textbook.
- J. O'Connor and E. F. Robertson: *A history of quantum mechanics*. 
- Introduction to Quantum Theory at Quantiki. 
- Quantum Physics Made Relatively Simple : three video lectures by Hans Bethe
- H is for h-bar. 
- Quantum Mechanics Books Collection : Collection of free books

### Course material

- Quantum Physics Database - Fundamentals and Historical Background of Quantum Theory. 
- Doron Cohen: Lecture notes in Quantum Mechanics (comprehensive, with advanced topics). 
- MIT OpenCourseWare: Chemistry 
- MIT OpenCourseWare: Physics . See 8.04 
- Stanford Continuing Education PHY 25: Quantum Mechanics  by Leonard Susskind, see course description  <sup>[*permanent dead link*]</sup> Fall 2007
- 5½ Examples in Quantum Mechanics 
- Imperial College Quantum Mechanics Course. 
- Spark Notes - Quantum Physics. 
- Quantum Physics Online : interactive introduction to quantum mechanics (RS applets). 
- Experiments to the foundations of quantum physics with single photons. 
- AQME  : Advancing Quantum Mechanics for Engineers — by T.Barzso, D.Vasileska and G.Klimeck online learning resource with simulation tools on [nanohub](#)
- Quantum Mechanics  by Martin Plenio
- Quantum Mechanics  by Richard Fitzpatrick
- Online course on *Quantum Transport* 

### FAQs

- Many-worlds or relative-state interpretation. 
- Measurement in Quantum mechanics. 

### Media

Find more about **Quantum mechanics** at Wikipedia's [sister projects](#)



[Definitions](#) from Wiktionary



[Media](#) from Commons



[News](#) from Wikinews



[Quotations](#) from Wikiquote



[Texts](#) from Wikisource



[Textbooks](#) from Wikibooks



[Learning resources](#) from Wikiversity

- [PHYS 201: Fundamentals of Physics II](#) by Ramamurti Shankar, Open Yale Course
- [Lectures on Quantum Mechanics](#) by Leonard Susskind
- [Everything you wanted to know about the quantum world](#) — archive of articles from *New Scientist*.
- [Quantum Physics Research](#) from *Science Daily*
- Overbye, Dennis (December 27, 2005). "Quantum Trickery: Testing Einstein's Strangest Theory". *The New York Times*. Retrieved April 12, 2010.
- [Audio: Astronomy Cast](#) Quantum Mechanics — June 2009. Fraser Cain interviews Pamela L. Gay.

Philosophy

- Ismael, Jenann. "Quantum Mechanics". *Stanford Encyclopedia of Philosophy*.
- Krips, Henry. "Measurement in Quantum Theory". *Stanford Encyclopedia of Philosophy*.

V • T • E

Quantum mechanics

[show]

V • T • E

Branches of physics

[show]

Authority control

GND: 4047989-4 • NDL: 00569870

Categories: [Concepts in physics](#) | [Quantum mechanics](#)

This page was last modified on 12 August 2016, at 15:48.

Text is available under the [Creative Commons Attribution-ShareAlike License](#); additional terms may apply. By using this site, you agree to the [Terms of Use](#) and [Privacy Policy](#). Wikipedia® is a registered trademark of the [Wikimedia Foundation, Inc.](#), a non-profit organization.

[Privacy policy](#) [About Wikipedia](#) [Disclaimers](#) [Contact Wikipedia](#) [Developers](#) [Cookie statement](#) [Mobile view](#)

