

A short introduction to quantum mechanics I: observables and eigenvalues

This article is aimed at students with a solid knowledge of linear algebra and high school physics. It should be suitable for college sophomores studying science or engineering.

In quantum mechanics there is the concept of the observable. An observable is something that can be observed. There are many observables in quantum mechanics, including energy, momentum, angular momentum, position, etc. Each observable corresponds to a linear operator, in other words, a matrix. Thus there exist matrices for energy, momentum, angular momentum, position, etc. These are more commonly referred to as operators: energy operators, momentum operators, angular momentum operators, position operators, etc.

There should be eigenvalues and eigenvectors corresponding to each matrix. It is known that observed values are always eigenvalues.

Let's say you want to measure the energy of an object. The total energy is the sum of potential energy and kinetic energy, and there should be an energy operator (energy matrix) corresponding to this total energy. If you calculate the eigenvalues of this energy matrix you will get certain values. Only these values can be the energy of the object.

For example, let's say that the eigenvalues of the energy matrix are $2J$, $3J$, and $5J$. This implies that the energy of the object can be $2J$ or $3J$ or $5J$, but never $4J$.

For a real example, let's consider a hydrogen atom. If you know some chemistry, you may know that the energy level of a hydrogen atom can be represented by $E = -R/n^2$ where n is a natural number and R is the Rydberg constant. It is a well-known fact that the energy of a hydrogen atom admits only certain values. The reason is that the eigenvalues of a hydrogen atom's energy matrix are given by $-R/n^2$. As there are an infinite number of choices for the value of n , there are an infinite number of eigenvalues. Since the number of eigenvalues coincides with the order of a matrix, we see that the energy matrix of a hydrogen atom is an infinity by infinity square matrix (in fact, most linear operators, or matrices, considered in quantum mechanics are infinity by infinity matrices).

In quantum mechanics there is also a vector corresponding to each object. These are called "state vectors" or "wave functions." I will now explain how they play a role in quantum mechanics.

Let's come back to the example of an energy matrix with eigenvalues $2J$, $3J$, and $5J$ and corresponding eigenvectors $|2J\rangle$, $|3J\rangle$, and $|5J\rangle$ (in quantum mechanics, we usually denote vectors using this notation, called Dirac's bra-ket notation; please see my article entitled "Dirac's bra-ket notation: an exposition for science and engineering students" it for more information).

Let's say that an object's state vector (or wave function) is $|2J\rangle + |3J\rangle$. This object is in the state of half $|2J\rangle$ and half $|3J\rangle$. Upon observation, there is a 50% probability that the object's energy will be $2J$ and a 50 % probability that it will be $3J$ (notice that

the probability that the energy will be $2.5J$ is zero). Also upon observation, the state vector changes to the eigenvector of the eigenvalue corresponding to the observed value. For example, if an observer observes the energy of this object to be $2J$, then the state vector (or wave function) changes to $|2J\rangle$, the eigenvector of the eigenvalue $2J$.

For a more concrete understanding, let me give you another example. Let's say that an object's state vector is $(0.6)|2J\rangle + (0.8)|5J\rangle$. You can see that the square of 0.6 is 0.36 and the square of 0.8 is 0.64 and that the sum of 0.36 and 0.64 is 1 . Therefore, the probability of an observer observing the energy to be $2J$ is 36% while the probability of observing $5J$ is 64% . Also, upon observation, the state vector changes to $|2J\rangle$ with 36% probability and $|5J\rangle$ with 64% probability. If the state vector changes to $|2J\rangle$ and the energy is measured again, the result will be $2J$ with 100% certainty. (This probabilistic interpretation of quantum mechanics is called "Copenhagen interpretation.")

The same is true for all observables, including position, angular momentum, and so on. The state vector of an object is expanded out on the basis of eigenvectors, with the probability of observing a given eigenvalue being the ratio of the square of the coefficient of the corresponding eigenvector to the sum of the squares of the coefficients of all the eigenvectors. (Why the probability is proportional to the square of the coefficient rather than the coefficient itself will be clear when you read "quantum mechanics V." Here, let me briefly mention that the coefficients can take negative values, while their squares can only take non-negative values. As probability must be always non-negative, it would not make sense for the probability to be proportional to potentially negative coefficient. Furthermore, those of you who studied freshman optics may remember that the intensity is not proportional to the amplitude, but rather the square of the amplitude. Think along this line.)

To show you another aspect of quantum mechanics, let me mention that it is known that position operators and momentum operators don't commute, that is, $XP - PX$ is non-zero, where X is a position operator (or matrix) and P is a momentum operator (or matrix). Therefore, as we will see later in another article, we cannot determine an object's position and momentum at the same time. In fact, $XP - PX$ is equal to $i\hbar/2\pi$ where h is the Planck constant, and from this one can derive Heisenberg's famous uncertainty principle.

All calculations in Heisenberg's quantum mechanics are done with the formula $XP - PX = i\hbar/(2\pi) = i\hbar$, while all calculations in Schrödinger's quantum mechanics are done with the assumption that the energy matrix is $-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)$ where $V(x)$ denotes potential energy. For example if the state vector (or wave function) is $\psi(x)$, the state vector multiplied by the energy matrix is $-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2} + V(x)\psi(x)$ (although seems to be a function rather than a vector, it is actually both; I will explain why in my next article).

Surprisingly, it was proven that Heisenberg's quantum mechanics and Schrödinger's quantum mechanics are equivalent, and always give the same result. However, in practice, it is much easier to use Schrödinger's quantum mechanics for most cases. In my third article on quantum mechanics, we will learn about the simple proof of this equivalency, which initially took months for Schrödinger to figure out.

Problem 1. Let's say that an object's wave function is $3|2J\rangle - |4J\rangle$. What will be the probability of an observer observing its energy to be $4J$?

Summary

- An observable is something that can be observed. For every observable, there is a corresponding linear operator (i.e. matrix).
- Observed values are always the eigenvalues of such a linear operator.
- For every object, there is a corresponding vector called “state vector” or “wave function.”
- The probability of observing a given eigenvalue is proportional to the square of the coefficient of the corresponding eigenvector.
- Upon observation, the state vector changes to the eigenvector of the eigenvalue corresponding to the observed value.
- Heisenberg’s quantum mechanics and Schrödinger’s quantum mechanics are equivalent.