What is Quantum Mechanics?

Quantum mechanics is the theory, or picture of the world, that physicists use to describe and predict the behavior of the smallest elements of matter. It turns out that when physicists examined atoms and the particles that make up atoms, these particles behaved in ways that were complete unexpected and unexplained according to classical physics (Newton's mechanics and Maxwell's theory of electromagnetism). Examples of this strange behavior that we will encounter in this course include

- **The stable orbit of electrons in atoms.** Electrons are charged particles, and according to Maxwell's theory of electromagnetism, charged particles should emit energy in the form of light when they are accelerated or move in curved paths. Electrons orbit atoms in circles. If the electron emitted energy as it orbited, as it should according to classical physics, then the electron would spiral into the nucleus of the atom. But atoms are stable and electrons do not in fact spiral into the nucleus. Thus classical physics is wrong when describing electrons in atoms.

- **The behavior of light.** Light is electromagnetic radiation (waves in an electromagnetic field, that is) and in most circumstances is correctly described by Maxwell's classical theory of electromagnetism. But when very small light levels are considered, and when light interacts with matter, light does not behave like waves, but rather like particles. For example, at very low light levels a CCD in a camera will build up a picture one pixel at a time. This is difficult to explain in terms of waves but easy to explain if light is a particle.

- **Correlations of particles.** In special circumstances, particles interact with each other, seemingly over space and time, with no apparent signal being passed between them. The specific behavior of particles in these circumstances looks for all the world like the interference of waves, yet it does not work to treat the particles as waves.

- **The apparent ability of particles to jump from one place to another without passing through any points in between.** These "quantum jumps" occur when an electron changes its orbit in an atom and when electrons "jump" through non-conducting material. This latter phenomenon is now semiconductors work, so anytime you use a computer you are using devices based on quantum mechanical engineering.

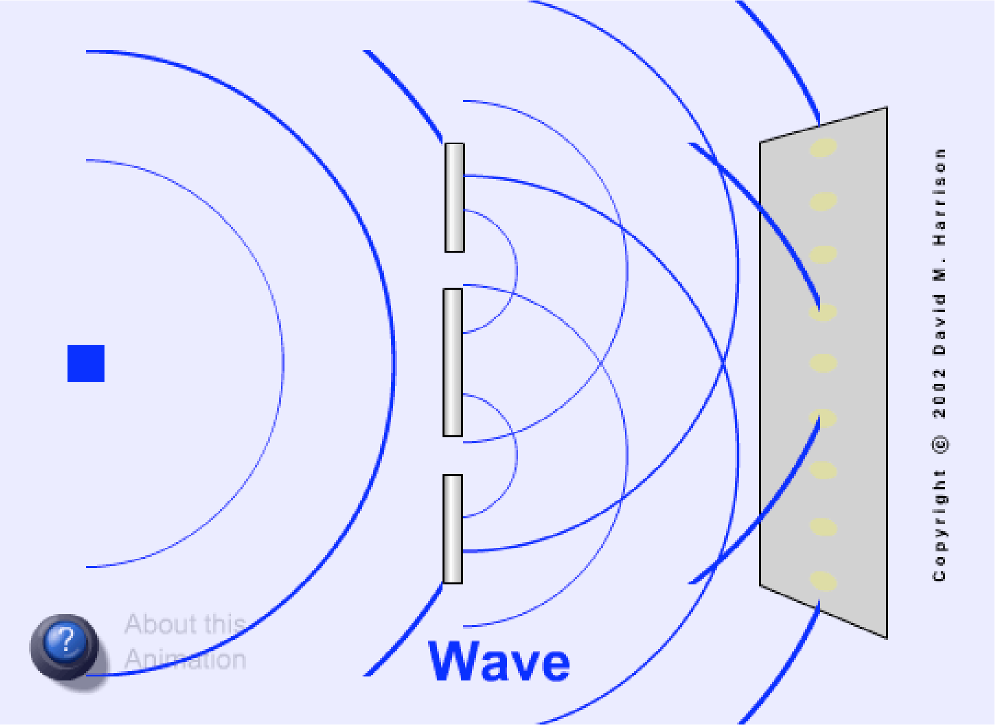
These strange phenomena show up in a conceptually simple experiment showing wave interference:

Wave Interference: The Double Slit Experiment

The standard example of the wave behavior of light is *interference*, or the ability to add together two light waves and get a new wave that looks very different from the original two waves. In fact this type of experiment was observed by Thomas Young in 1803, and was used to *prove* that light was waves.

The easiest way to see wave interference is in the classic **double slit experiment.** In this experiment a single light source is sent through two small slits that are very close together. The light passing through the slits interfere to produce a pattern like this:

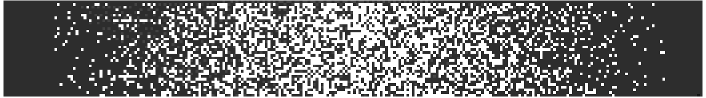
Note the alternating dark and light bands. What is happening here is that the light passing through the two slits is adding together. Where the high part of the wave from the left slit meets the low part of the wave from the right slit the waves cancel and there is no light, while if the high parts from both waves meet the wave is twice as high and the light is bright. Here is a top view of such an experiment, where the high parts of the wave are shown by lines and the low parts of the waves are between the lines:



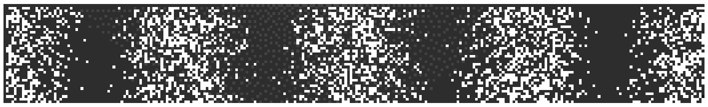
The important idea here is that the alternating dark and light lines appear because of the waves going through *both* slits at the *same time*.

We will be saying a lot more about wave interference in a later class.

Now what happens when we repeat this experiment with particles? If imagine throwing balls randomly, one at a time, at the screen with the slits, some balls would cleanly go through the holes, some would go through but bounce off the edges of the slits, and most would hit the screen. Now imagine that on the back screen we mark where the balls hit. If the slits were close enough together we'd expect to see a pattern like this:



But when we do the experiments with real electrons (which we know are particles, right?) we get



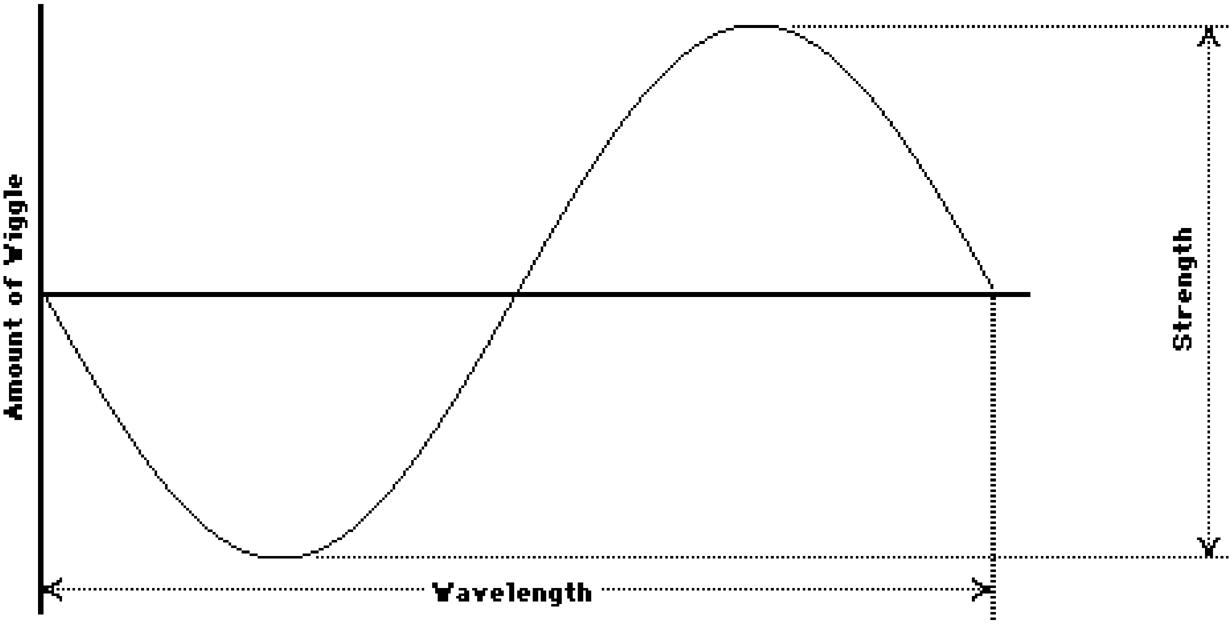
This experiment was first done by Davisson and Germer in 1927. There is no easy way to explain this pattern without invoking some kind of wave phenomenon. In particular there is no way to explain this pattern at all in terms of particles alone that went through one slit or another at different times.

Quantum mechanics explains the above strange phenomena through the use of "quantum mechanical waves". Just what this quantum wave is and whether it really exists in the same sense that particles exist is a subject of debate and contention in physics. The purpose of this course is to survey the various points of view on this issue. For this session, however, we will simply introduce the way in which quantum mechanics uses waves to describe particles.

An Introduction to Quantum Mechanical Waves

The most fundamental insight of quantum mechanics is, roughly, that the behavior of all particles is determined by a wave associated with that particle. As we'll see in this course, it turns out that the strength of a wave determines whether or not a particle may be present and the wavelength (or frequency) of a wave determines the particles velocity and energy. We will not worry right away about what these waves are waves **in**, as that is the main question for this course. For now we need to learn about how waves are described and learn what physicists have discovered about the relationship between particles and waves.

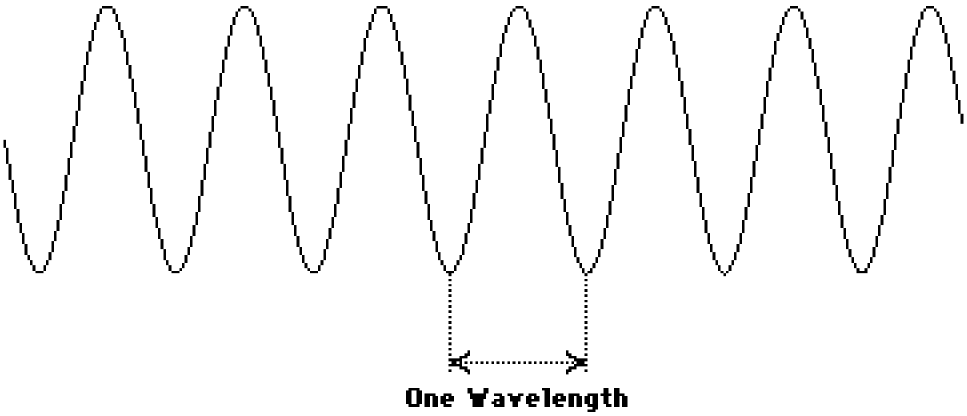
By a wave, I mean any regular back and forth motion or wiggle. Thus a wave is not really an independent thing itself, it is more something that other things **do**. We visualize waves by plotting their motion in space or time. We then draw this plot which can look something like this:



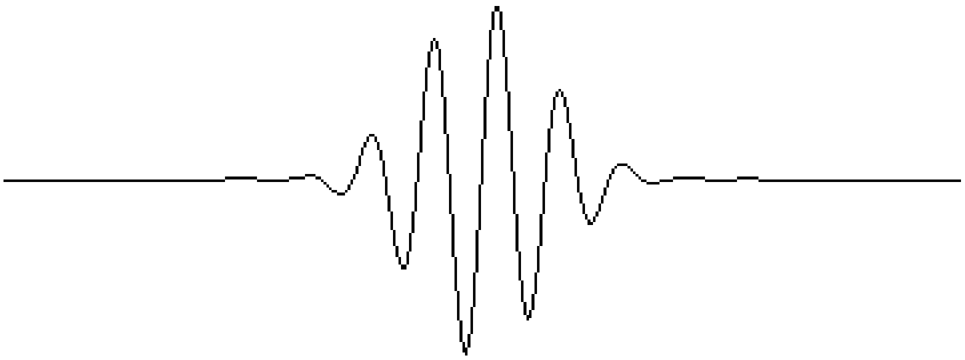
In this plot, two important characteristics of the wave are shown: The **wavelength** and the **strength** of the wave. These are actually very simple concepts. The **strength** of the wave is simply how far the wiggling thing swings back and forth. The **wavelength** is the distance in time or space between complete wiggles. The Another concept that is used to describe a wave is the **frequency** of a wave. The frequency is the number of times the wiggling object will wiggle in a certain time period (i.e. a second).

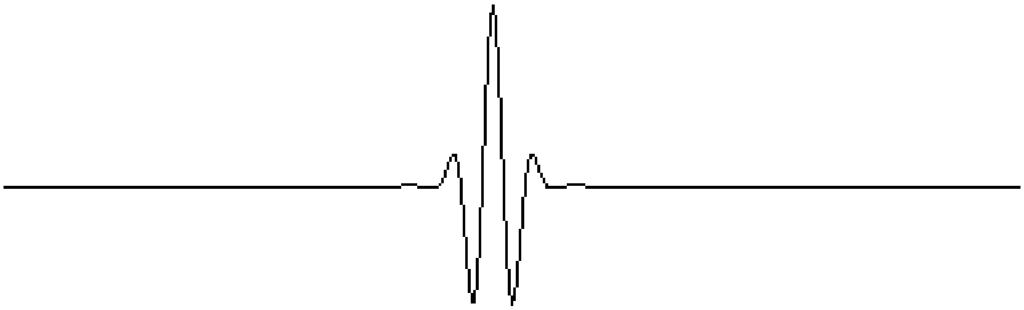
A thing can wave in either space or time. A hand waving is a wiggle in time, as the hand swings back and forth. If the above plot were a representation of the waving of a hand, then the vertical direction would represent the movement of the hand in space and the horizontal direction would represent the passing of time. An example of a wave in space is a snapshot of water waves. Then in this case the vertical direction would represent the displacement above or below the average level of the water, and the horizontal direction would represent the distance from some point. A moving water wave is a wave the wiggles in both space and time.

The above plot is actually a plot of a **sine wave**, which is a very common and natural kind of wave. Sine waves show up very often in nature. The simplest kind of sine wave goes on forever:



More complicated waves, however, do not need to go on forever and ever. They can be localized and be a wiggle only in a small region of space or for a small period of time. Here are two examples of waves that wiggle for only a very short interval of time or space:





Now compare these localized waves with the wave drawn above that wiggles forever and ever. First, the strengths of all these waves are not well defined, as the strength of the localized wave varies. The wavelength of the local waves are also not at all well defined, as there are few waves to measure to detect the wavelength. The fewer the waves to measure the more uncertain the wavelength.

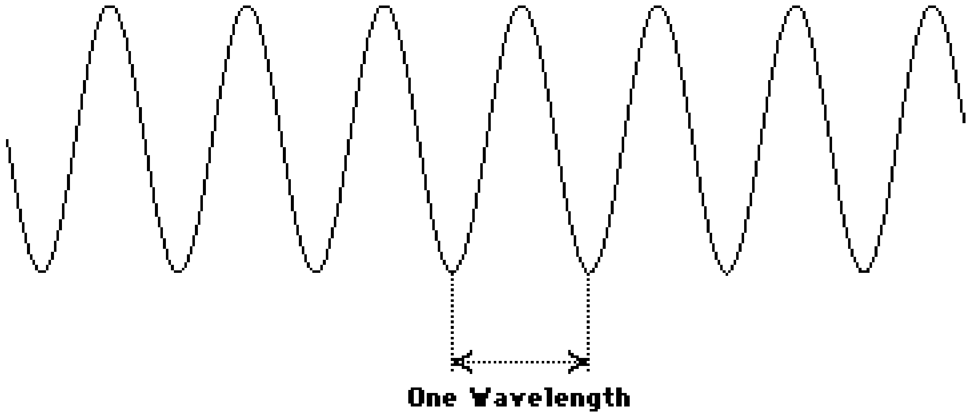
The relationship between waves and particles

The rules relating particles and their associated waves are rather simple, so I will simply state them here:

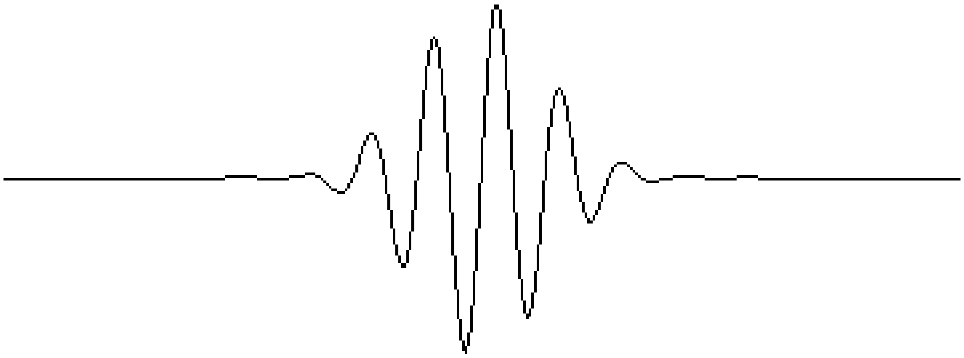
Where the strength of the particle's associated wave is large, there is some probability that the particle may be found. The greater the strength of the wave at some point, the more likely it is that the particle will be found at that point.

Where the wavelength of the wave is short (or the frequency of the wave is high), any particles found there will have a large amount of motion (momentum, to be exact). Where the wavelength of the wave is long (or the frequency of the wave is low), any particles found there will have a smaller amount of motion.

So let us look at the above examples:

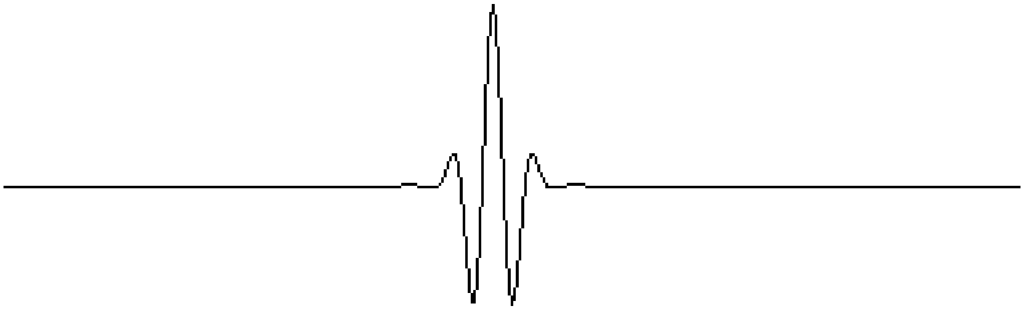


The particle can be anywhere, and wherever it is it has the same amount of motion, as the strength and wavelength of the wave are the same everywhere.



Not Here! Particle is somewhere in here Not Here!

The particle is now more localized in space, but wherever the particle is we are rather uncertain about it's amount of motion, as we can't tell what the wavelength of the associated wave is.



Not Here! Particle is somewhere in here Not Here!

The particle is now even more localized in space, but wherever the particle is we are even more uncertain about it's amount of motion, as it is even harder to tell what the wavelength of the associated wave is.

We are learning a lesson here. **The more localized the wave, the more uncertain we are about the wavelength. The more certain we are of the wavelength, the less localized the wave.** Using the rules relating particles to their associated waves, we have:

The more certain we are about a particle's position, the less certain we are about the particle's state of motion.

The more certain we are of a particle's state of motion, the less certain we are about the particle's position.

This is a statement in words of what is known as the **Heisenberg Uncertainty Principle.** This principle follows from the way a particle's behavior is determined by a wave associated to that particle.

The uncertainty principle raises some very interesting questions. First one may say "Fine. By looking at the associated wave of a particle you have some trouble discovering the position and the motion of the particle at the same time. That just means that the wave is not a good way of looking at the particle. Simply invent some very exact measuring device that looks at the particle directly and measures the position and motion."

If you sit down and try to design such an exact measuring device, you will discover that no matter how clever you are, the way in which you measure the position of a particle disturbs the motion of the particle in an unpredictable way. Similarly, the way you measure the motion of the particle leaves you uncertain about the particle's position. Albert Einstein (a very clever man indeed!) spent much time trying to show the uncertainty principle to be an incorrect description of nature by designing measuring devices to get around this. Every time Einstein thought he had succeeded, however, Neils Bohr showed that Einstein always missed some uncertainty that was really there.

Now just how uncertain is uncertain? It turns out that if you know a particle's position very exactly, you cannot be so exact about the particle's state of motion but you can still be quite exact by everyday standards. Similarly, if you know a particle's motion very exactly, you cannot be so exact about the particle's position but you can still be quite exact by everyday standards.

This is said technically by saying that the product of the uncertainty in a particle's position and the uncertainty in a particle's motion (at the same time) is always greater than a certain number, **6.625×10^{-34} Joules-seconds** (if velocity is measured in centimeters/second and position is measured in centimeters). This is an exceptionally small number, so the uncertainty principle is utterly undetectable directly in everyday life. The fact that this number is not zero, however (that is, there is an uncertainty however small), has tremendous implications for physics.

The point of view that we have been taking in this discussion is that the particle and it's associated wave are related but separate entities and that the wave somehow controls the behavior of the particle. If particles exist, this is certainly the case. We shall soon see in this course, however, that this idea that the particles and the waves are separate things is too naive and will have to be abandoned. Just what we thought were particles really are is a matter of great controversy in physics and is the main point of this course.