Wave Particle Duality: The Double Slit Experiment

What makes a wave a wave?

An *oscillation* is the back and forth motion of a something around a centre point. If we attached a marble to the end of a spring, and then stretched the spring out along an axis, the little marble would be whizzed back and forth along the axis:

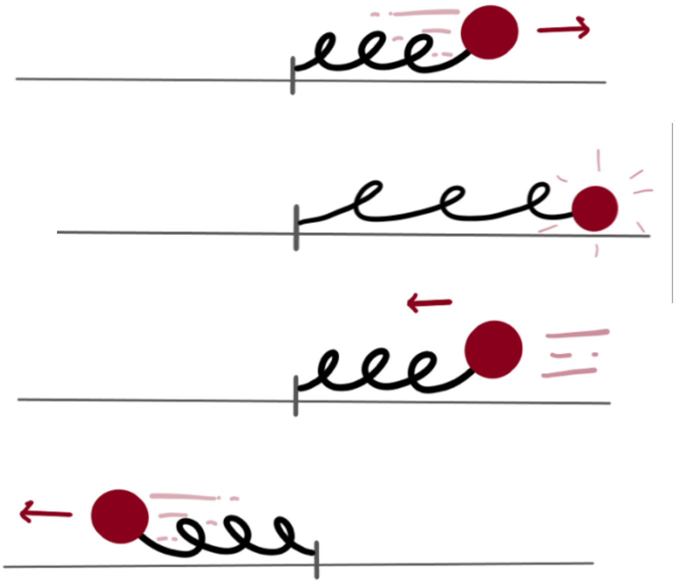

Diagram 1

Each time the marble changes direction, it passes through a centre point, or an **equilibrium position**. The equilibrium position is the point along the axis of motion where the spring is momentarily *not* experiencing a stretch:

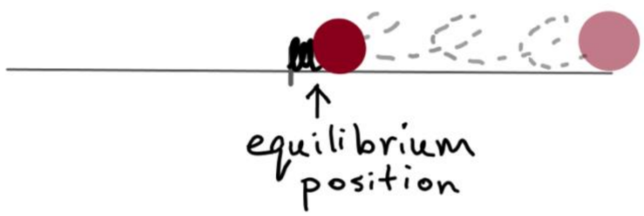

Diagram 2

Nevertheless, because our marble is in motion and has kinetic energy, the marble will keep moving through the equilibrium position. As the spring is stretched more and more by the marble's motion, the marble is forced to slow down. At the instant the marble experiences a change in direction, all of its kinetic energy has been converted into *spring potential energy*: the spring, stretched as much as possible by all the kinetic energy available, has all the energy stored up, ready to snap the marble back in the other direction.

A *wave* can be understood as a series of oscillations strung together. For example, imagine a string made up by single particles all in a row:

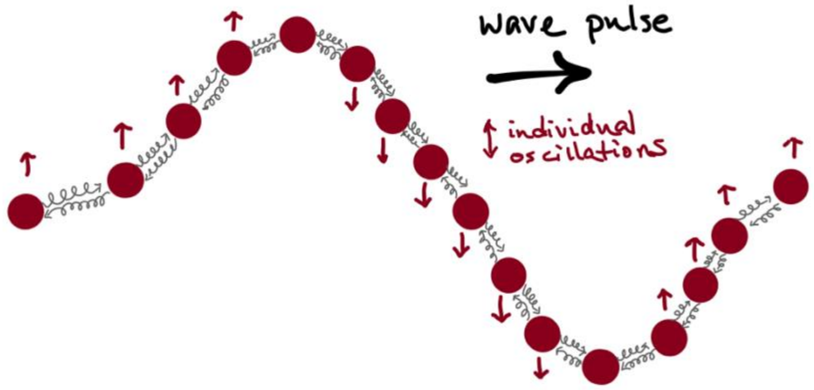

Diagram 3

The intermolecular forces between the particles means that if one particle moves, its neighbours will also be forced to move in the same direction, but with a time delay. As a result, the oscillation of the first particle causes the oscillation of the second particle, and the oscillation of the second particle causes the oscillation of the third, and so on. The larger effect on the whole string is the creation of a series of *wave pulse*s.

Energy and momentum are therefore transferred between the individual particles in our string. A wave is thus **a disturbance in a medium that results in the transfer of energy and momentum, without the overall transfer of matter.** We call the medium that the wave travels *through the medium of propagation*.

Let's look at a sound wave as an example. Say two people, Person A and Person B, stand at opposite ends of a room. Person A claps their hands, which causes the air particles near their hands to accelerate in all directions. Those particles, forced into motion by the clap, collide with their neighbours, who then in turn collide with *their* neighbours, and so on, until the air particles near Person B's ears hit against their inner ear mechanism. Person B thus hears the clap all the way from the other side of the room.

In this example, energy and momentum are transferred from one air particle to another, but the air particles themselves don't move very far. The air particles collide with their neighbours, but they will also bounce backwards once they hit their neighbours. So even though the air particles do indeed move, there is no large net movement of the air particles, whereas the *sound itself travels to the other side of the room.* Sound is thus a wave, and in this particular example, its medium of propagation is air.

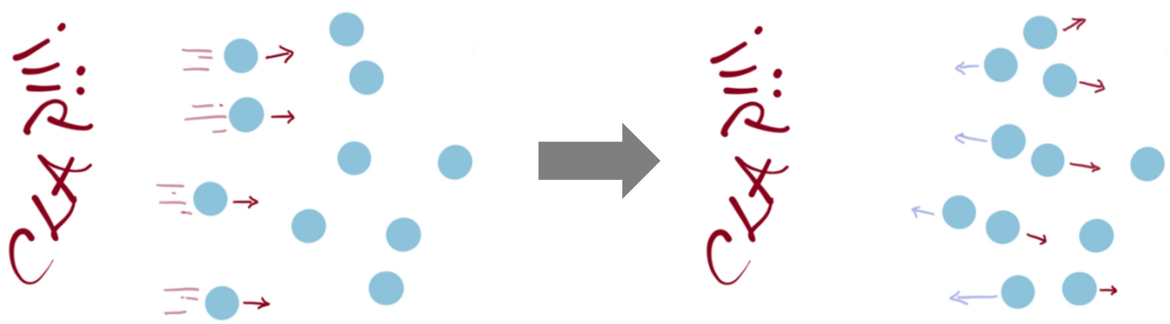

Diagram 4

The Wave Theory of Light and Young's Diffraction Experiment

In the early 17th century, Sir Isaac Newton strongly advocated the idea that light was made up of particles. This was in part due to the observation that light only travelled in straight lines, whereas waves were known to bend around obstacles. Newton devised a *particle theory* of light that explained light phenomena, such why a beam of light refracted when passed from one medium of propagation to another medium.

Around the same time, Christian Huygens developed a *wave theory* of light, which suggested that light shared certain behaviours with sound waves and with water waves. In particular, Huygens suggested that two beams of light could *interfere* with each other.

If, for example, you add two waves together so that their peaks are perfectly aligned, the result will be a new wave, and its peaks will have a height equal to the sum of the two initial waves. If, however, you align the two waves so that one wave's peak aligns with the other's trough, the two waves will cancel each other out. These are two simple examples are cases of *constructive interference* and *destructive interference* respectively.

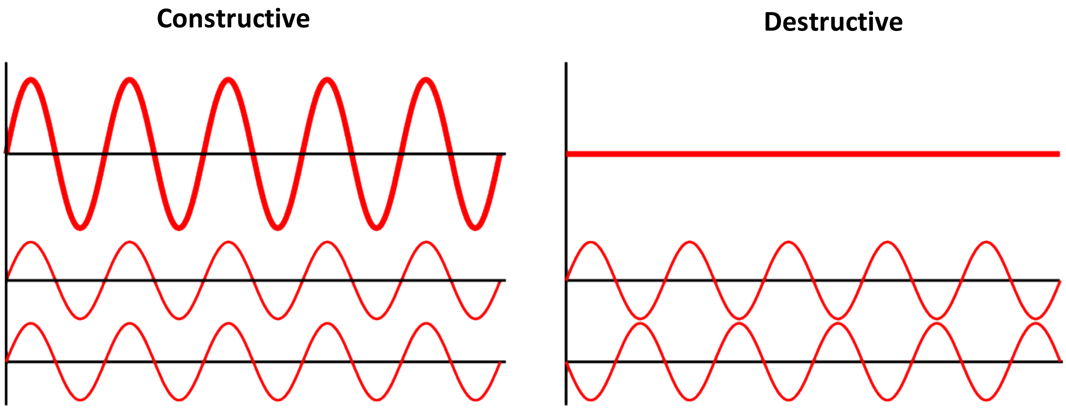

Diagram 5

It is also possible to create more complex interference patterns, in which constructive and deconstructive inference both occur. Here is one pattern, created by the interference of two water waves with each other:

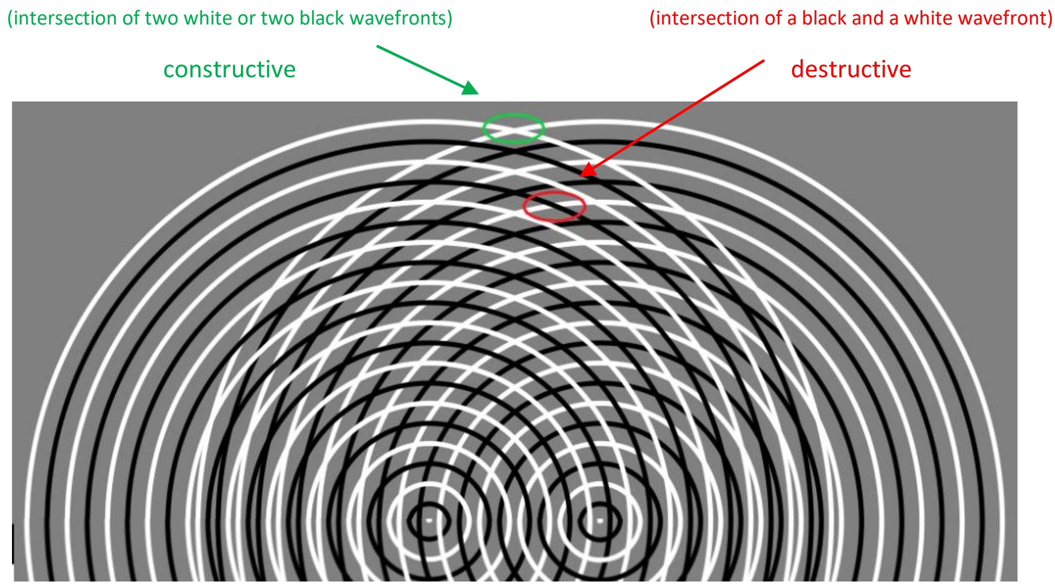

Diagram 6

Newton and his particle theory of light had many supporters, but so did Huygens and his wave theory of light. At the beginning of the 19th century, Thomas Young, a supporter of the wave theory of light, conducted an experiment that showed light created interference patterns, just like waves. Specifically, Young split sunlight into two beams using mirrors and a thick piece of paper. The result was that the two beams of sunlight interfered with each other and created an interference pattern, just like two water waves! The wave theory of light, therefore, was triumphant! Or so it would seem…

Quantum Theory and Davisson and Germer Experiment

After Young's Diffraction Experiment in 1803, the wave theory of light became the accepted theory, and Newton's particle theory of light lost its prestige. All the way through the 19th century, the wave theory of light became more and more robust. Visible light was discovered to be only one member of a whole family of waves, called *electromagnetic waves*. These types of waves were all made of oscillating electric and magnetic fields, but differed from each other in properties like *wavelength* (the spatial distance between peaks of a wave) and *frequency* (the number of oscillations a point on the wave undergoes per second). EM waves were believed to propagate through a mysterious, undetectable medium called the *luminiferous aether*, which was ultimately proven not to exist (not a bad thing, since this is what gave way to Einstein's theory of relativity!) All in all, things were looking good for the wave theory of light.

But there was a problem. The higher the frequency of a wave, the more energy the wave carries and transmits. This means that a *black body*, an object that perfectly absorbs and re-emits electromagnetic waves, should in theory be able to emit infinite energy when it emits waves with very high frequencies. At least, this is what the mathematics suggested. In reality, nothing in the physical world can emit infinite energy, and indeed, it was shown experimentally that this was not the case. This discrepancy between the mathematics and experimental reality became known as the Ultraviolet Catastrophe.

Read about the Ultraviolet Catastrophe here.

In 1900, Max Planck postulated that energy was in fact *quantized*. Specifically, Planck asserted that the amount of energy transmitted by an electromagnetic wave is directly proportional to the wave's frequency, but with the caveat that only discrete packets of energy were absorbed or emitted. The energy per 'packet' was proportional to frequency of the wave:

$$E_{packet} = hf$$

h is Planck's constant, approximately equal to $6.63 \times 10^{-34}\ Joule\ seconds$

This implied that if the energy of electromagnetic waves was transmitted in packets, then each "packet" could be in fact be a particle! In 1905, Einstein's description of the *photoelectric effect* suggested that electromagnetic waves appeared to be made of discrete particles, which Einstein called *photons*. And indeed, in 1914, Robert Millikan experimentally confirmed the photoelectric effect.

In 1924, Louis de Broglie introduced the concept of *wave-particle duality*. Though electromagnetic waves are not made of matter (they don't have mass), they nevertheless have properties characteristic of particles as well. De Broglie suggested that perhaps the reverse was also true: particles might in fact also have properties characteristic of waves! De Broglie hypothesized that an object with mass had an associated wavelength, given by Planck's constant h divided by the object's momentum p:

$$\lambda = \frac{h}{p}$$

In 1927, Clinton Davisson and Lester Germer conducted an experiment in which electrons exhibited behaviours thought to be exclusive to waves, thereby confirming de Broglie's hypothesis. Specifically, Davisson and Germer fired electrons at crystalline substances, which comprised of particles neatly arranged in lattices so that small 'slits' or pathways were available for the moving electrons to pass through.

If we were to throw a ping-pong ball at two holes in a wall, the ball would simply traverse one of the holes, and emerge from the other side. On the other hand, if we were to send a wave at the pair of holes, an interference pattern would emerge, as we saw in Diagram 6.

Before de Broglie put forward his hypothesis, electrons were thought to resemble tiny balls. It was believed that if fired at a series of apertures, electrons would behave just like our ping-pong ball did. So Davisson and Germer's electrons, fired through a lattice of particles, ought to have simply passed through in an unspectacular manner. Instead, Davisson and Germer observed an interference pattern created by the electron. In the experiment, the electron encountered a series of 'slits' in the crystalline obstacle, and then constructively and destructively interfered with itself, just as a wave would have done.

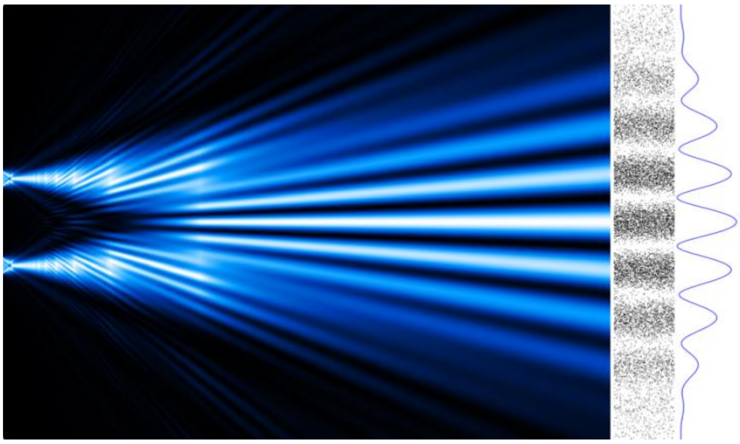

Diagram 7

Remember that Young's Diffraction Experiment, which was taken to prove that light was a wave, worked in exactly the same way. Sunlight was split into two beams, and the result was an interference pattern. By the same logic, the Davisson and Germer experiment proved that electrons, though particles, were in fact also waves!

Wave-particle duality, like many of the strange discoveries that accompanied quantum theory, fundamentally reshaped the way physicists think about the physical world. Wave-particle duality in particular plays a central role in quantum theory, in that it gave rise to a quantum mechanical *wave function*: a mathematical function that embodies the likelihood of possible measurement results in a quantum system. In classical physics, the wave equation is a differential equation that describes how a wave moves in space and in time based on its unique characteristics. With the rise of quantum theory and discovery of wave-particle duality, a similar differential equation could be devised to describe the probability of finding a quantum system in a particular state. This differential equation is known as the *Schrödinger equation*.

Louis de Broglie received the Nobel Prize in Physics in 1929 for what is now called the "de Broglie hypothesis", and Davisson won the Nobel Prize in Physics in 1937 for his earlier successes with diffraction experiments and subsequent follow-up experiment with Germer. George Thomson shared the 1937 Prize with Davisson for independently conducting a similar experiment to Davisson and Germer's, but with thin metal foils instead of crystals. The Davisson and Germer Experiment, like the Young Diffraction Experiment, is commonly referred to as the "Double Slit Experiment", and is often regarded as the experiment quintessential of quantum theory.