The Microscopic

*{**Abstract** – In this first segment of our "How small is it" video book, we cover the microscopic world.*

We start with optical microscopes and take a look at some of the things that you can see with light. We also cover light diffraction and show how it sets a limit on the size of objects we can see.

To understand how we can go further than light can take us by using electrons, we cover wave-particle duality. For that we cover particle momentum and wave interference. For a closer examination of waves, we show the famous Young Double Slit experiment that illustrates the wave nature of light. We also cover Airy Disks as a wave effect to further illustrate the limits of light microscopes. Then we go deeper into the nature of electromagnetic radiation. Here we show how it is the very nature of empty space with its permittivity and permeability that determines the speed of light in a vacuum.

For the particle nature of light, we cover Blackbody Radiation, the radiation catastrophe and how Planck solved the problem by showing that light is created in integer multiples of a constant now called Planck's constant. We then cover Einstein's photo-electric effect that showed that light was absorbed in the same multiples of light quanta. We now call these light quanta photons.

To reconcile these two views of light, we return to Young's double slit experiment and fire photons one at a time. The interference pattern appears over time. We cover how Louis Broglie extended this wave-particle duality to include electrons and other particles, and calculated the Broglie wavelength. The conclusion is that objects interact at points like a particle, but travel through space as a wave.

We then dig a little deeper into the nature of an electron starting with J.J. Thompson's discovery using a mass spectrometer. We then cover how Robert Milliken found the charge of an electron. With the electron's mass and charge known, we calculate its wavelength and find it much smaller than an optical photon's wavelength. This makes it ideal for breaking through the diffusion limit to see much smaller objects.

We end by covering how a scanning electron microscope works and using it to view very small things - down to a carbon atom!}

Introduction

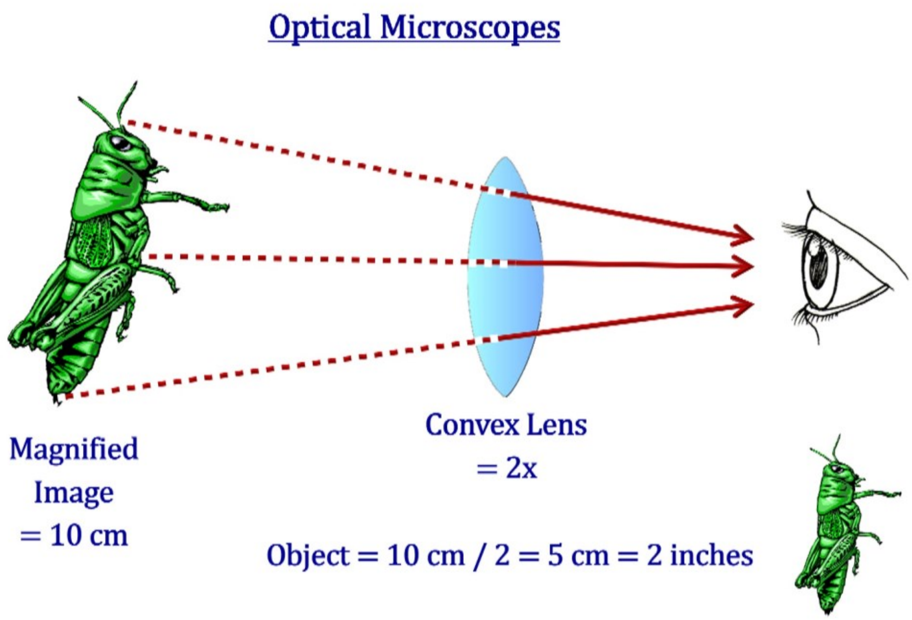
Hello and welcome to the first segment of our video book "How small is it". Here we'll examine the size of things from where we see them around us – very day things down to the smallest things that exist. For that we'll be using a meter stick. A meter is roughly the same size as a yard. It's just 3 inches longer. In addition to how much space an object might take up, we'll going to be looking at how little its mass and energy might be. For that, take a look at the apple - a hundred grams roughly. And to raise a hundred-gram apple one meter is the energy of one Joule. We'll get much smaller than that as we move into additional segments.

We see things because light bounces off an object and into our eye. But the smaller things get, the harder they are to see. A human hair is about one tenth of a millimeter.   A millimeter is a thousandth of a meter. In order to see things this small, or smaller, we use lenses. Like this lens here, to get a better look at the size of a hair. But how far can we go bending light. And just how small can things get. We'll be using microscopes   various kinds of microscopes to see down to the nanometer level. A nanometer is one billionth of a meter.   There are 25,400,000 nanometers in an inch. So, let's get started with optical microscopes.

> **[Music @02:38:** *Tchaikovsky – "Swan Lake" – This 1876 ballet was fashioned from Russian folk tales and tells the story of Odette, a princess turned into a swan by an evil sorcerer's curse. Its variety of melodies fit the themes of science and beauty in our opening chapter.***]**

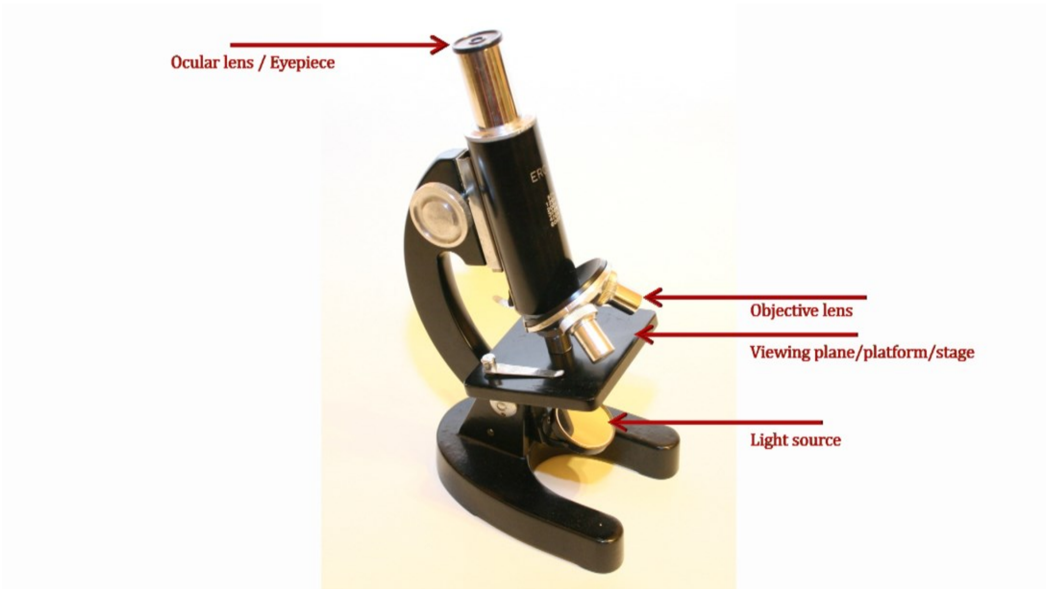
<u>The light microscope</u>

Magnifying tools use lens combinations to bend light at an angle to increase the size of the image that's sent to the eye. The eye traces the light rays back to a virtual image larger than the actual object. The more we bend the light, the larger the image appears. We use x after the number to represent the expansion factor of a microscopic image. For example, the magnifying glass we used in my backyard can double the size of an image, so it would be designated 2x. Therefore, if we divide the apparent size of the image by the magnifying power of the lens, we get the object's actual size.

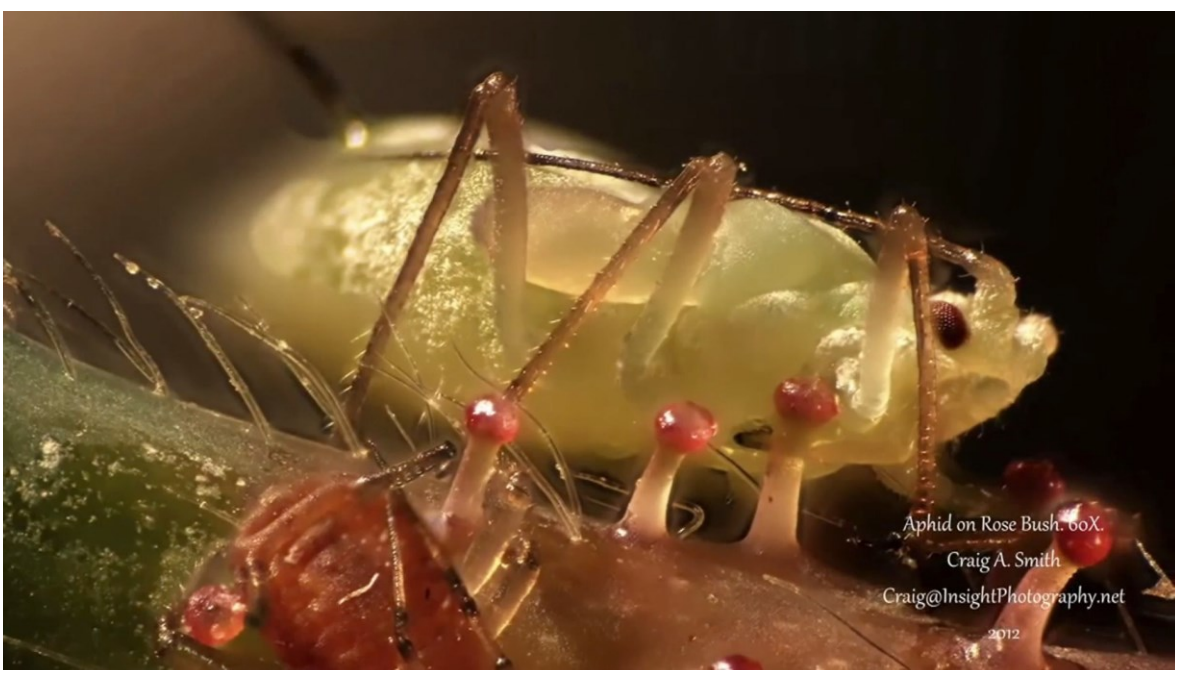


Evidence points to the first microscope appearing in the Netherlands in the late 1500s, probably an invention of eyeglass makers. We know that Galileo used them in the early 17th century. The discovery of things like blood cells and micro-organisms in the late 1600s really accelerated interest and development.

There are a wide variety of optical microscopes, but they all have these basic parts: A quality light source with focusing capabilities; a focal plan for the specimen, the key magnifying lens called the objective and the eyepiece.

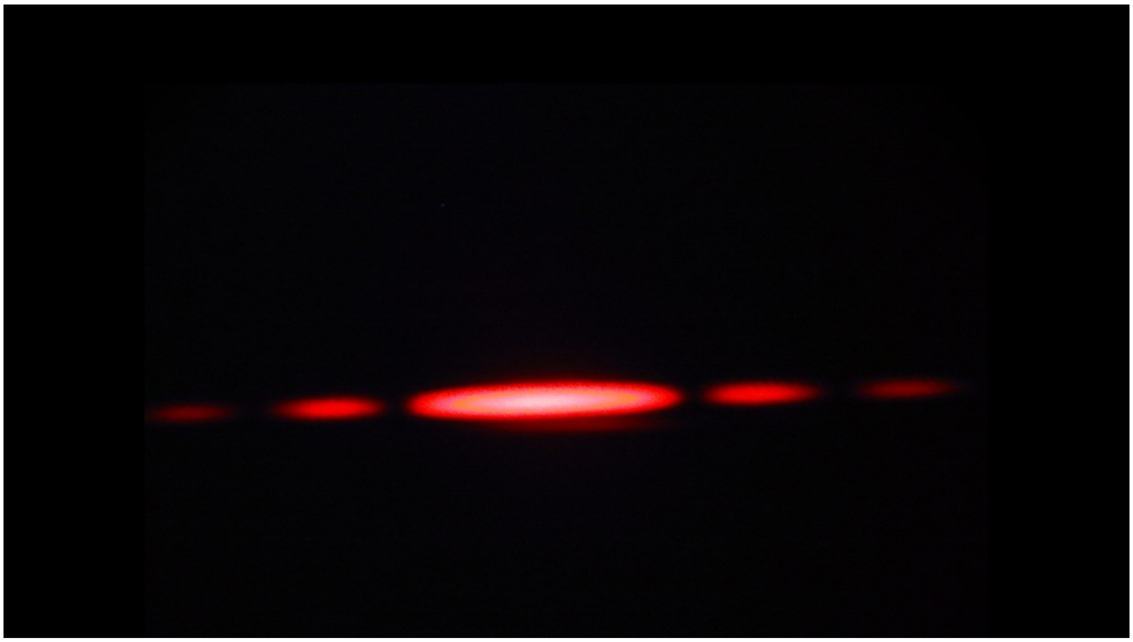


Thanks to Graig A. Smith, we have a fantastic microscopic look at what's in a backyard. **[**You'll find contact information for Graig and additional links in the Credits and Research segment at the end of the video book.**]**



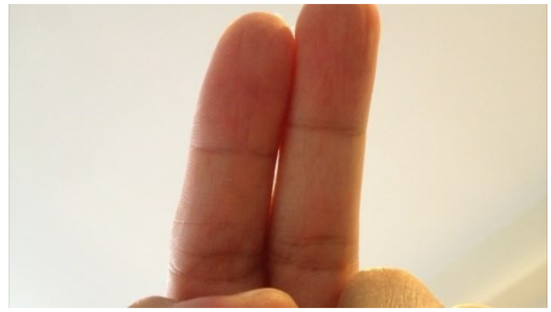
Diffraction

With standard microscopes we can see things as small as 0.2 µm. That's .2 millionths of a meter. Along with factors such as lens size and quality, the limit is hard wired due to a light effect called diffraction. Diffraction of light occurs when a light wave passes by a corner or through an opening or slit that is approximately the size of the light's wavelength.



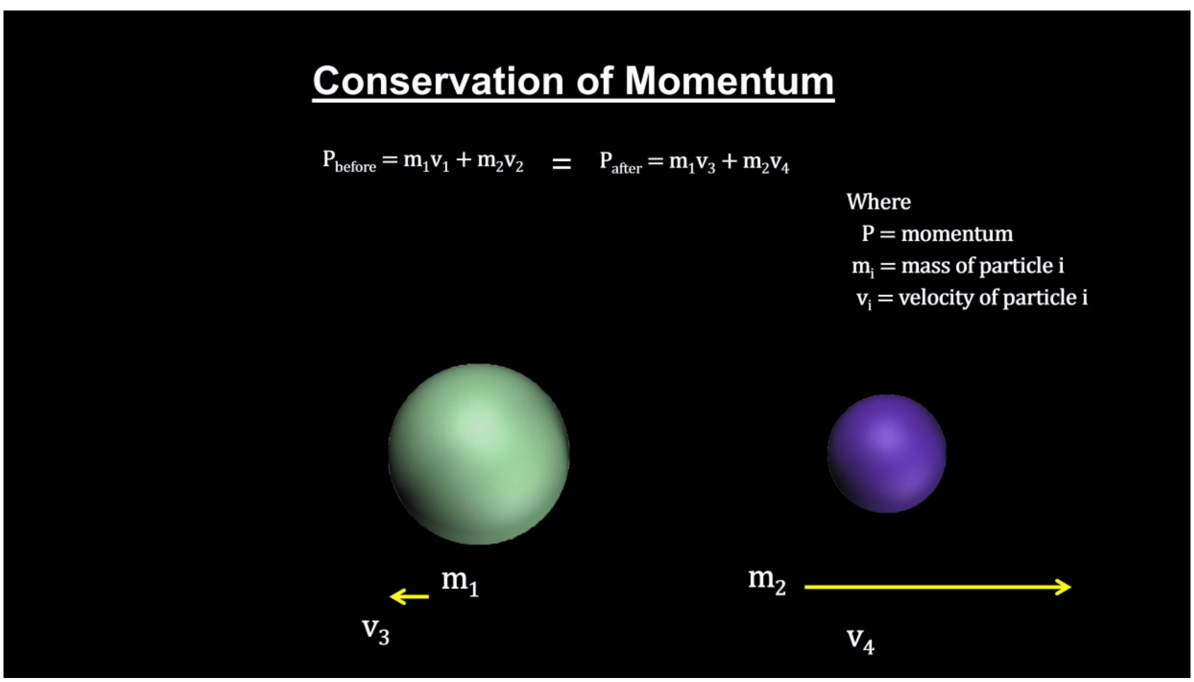
We see this in daily life all the time. For example, diffraction through clouds causes this common yet beautiful sight.

A very simple demonstration of diffraction can be conducted by holding your hand in front of a light source and observing the light transmitted between the fingers. As your face approaches your fingers, you begin to see a series of dark lines parallel to the fingers. The parallel lines are actually diffraction patterns. To understand how this works, we need to take a look at the difference between particles and waves.



Microscope Resolution Power

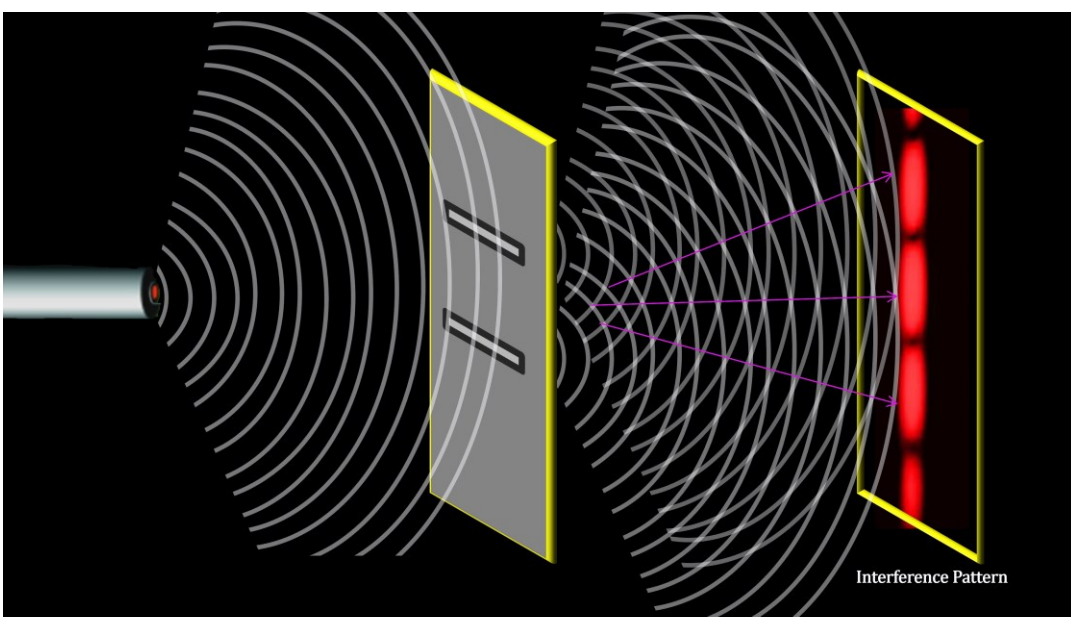
Particles are localized and bounce off each other. An important aspect of collisions between particles like these is that the momentum of the system is the same before and after the collision. Momentum is the mass times the velocity. In nature, this quantity is conserved. We'll use this law of nature later on when we start colliding particles to see what happens.



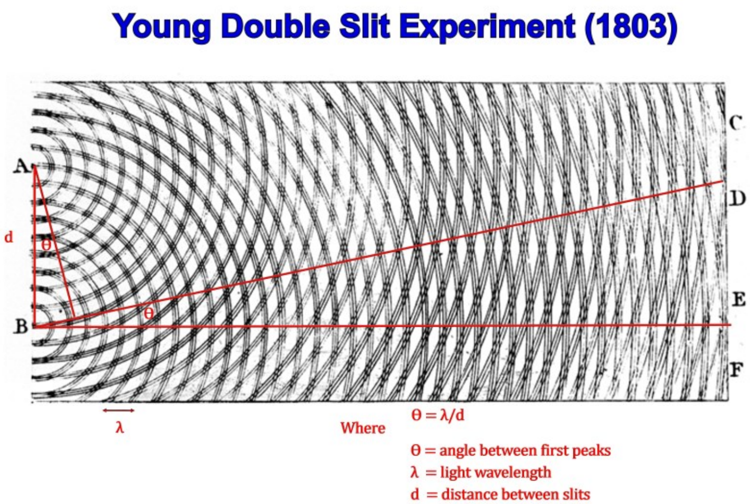
Waves are spread out and pass right through each other. When they move through each other, they interfere with each other. They can even interfere with themselves creating interesting patterns.

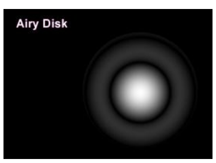
Newton thought light was a particle because he never witnessed light diffraction. The wavelength of light was too small for the experiments he ran. For decades, his view was never questioned.

But in the early 1800s, that changed based on experiments by Thomas Young. Here we see light traveling through two slits and then interfering with itself on the other side. An interference pattern is etched onto the back screen. This is the famous double slit experiment.



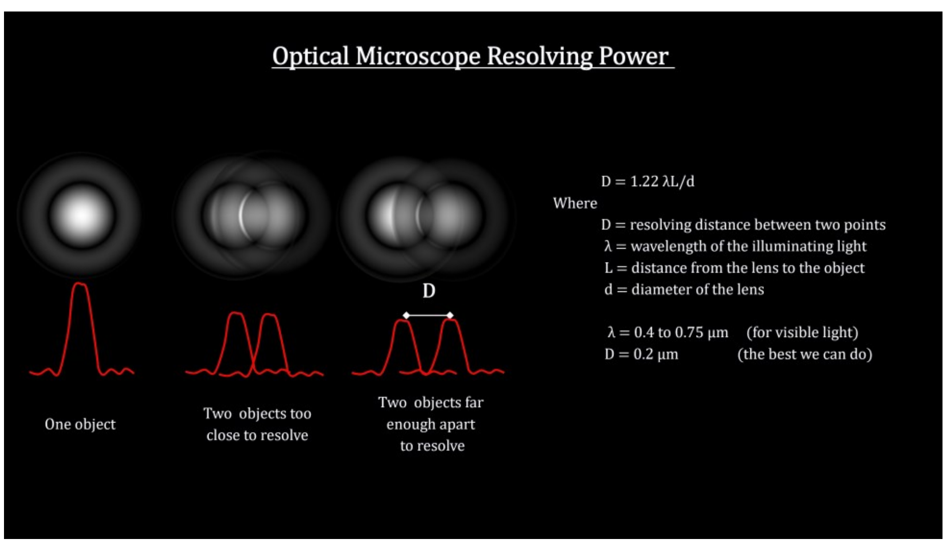
When Thomas Young did his double slit experiment, he showed conclusively that light diffracted and therefore was a wave. Here's his sketch of two-slit diffraction that he presented to the Royal Society in England in 1803.





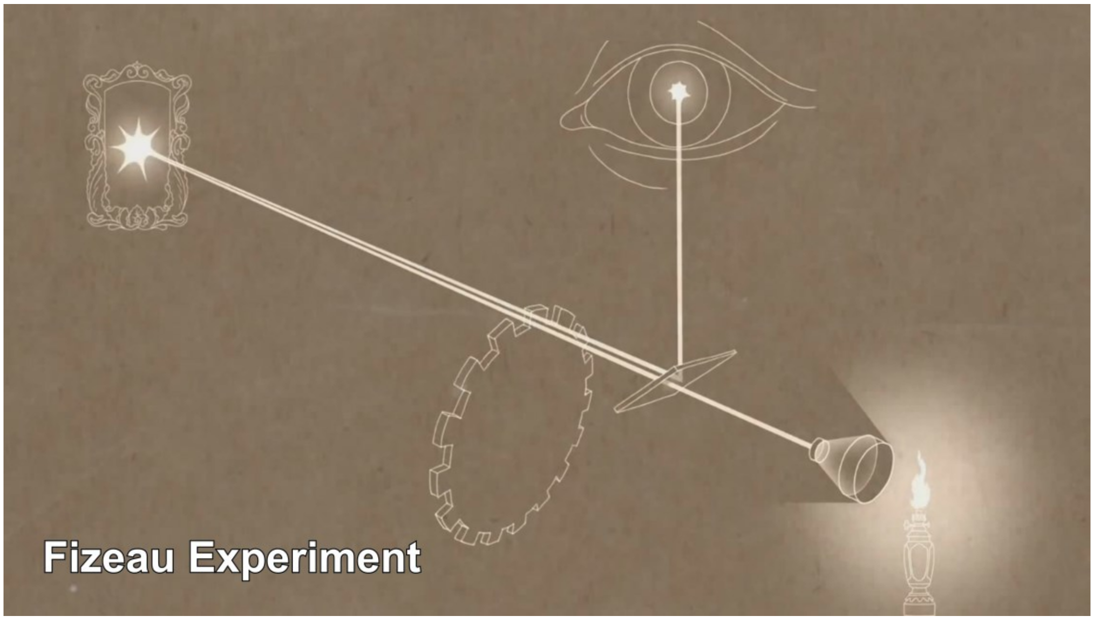
Because of diffraction, instead of seeing points, each point is spread out into a disk called an Airy disk.

The resolving power of any optical instrument is its ability to produce separate images of two adjacent points. This resolving power of optical microscopes is about 0.2 micrometers. The bottom line is that you can't see a thing that is smaller than the wavelength of the light used to illuminate it. If we're going to do better than 0.2 micrometers, we'll need to use something else to do the illuminating. And for that, we'll need to get a better handle on the nature of waves vs. particles.

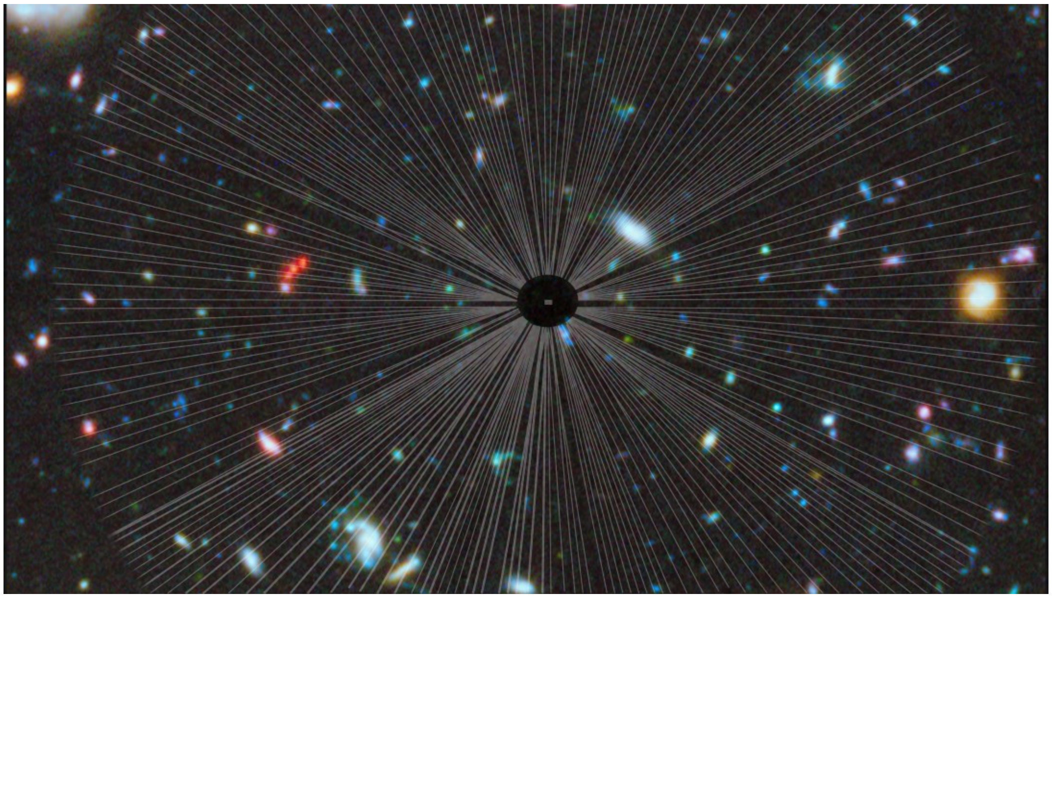


Electromagnetic Radiation

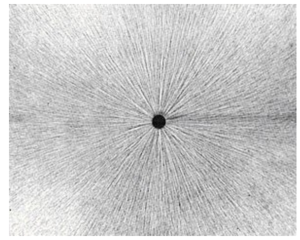
Forty-two years after Young proved that light traveled as a wave, the French physicist Hippolyte Fizeau measured the speed of light to be just under 300,000 km/s (That's 186,000 mi/s). We cover how he did it in the "Speed of Light" chapter of the "How Fast Is It" video book.



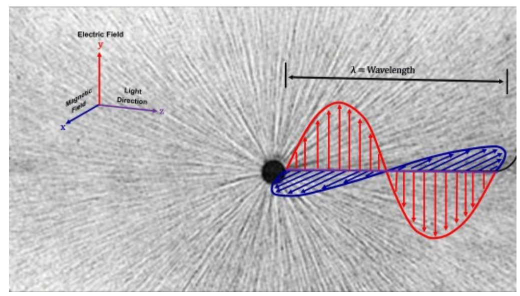
Over that period and into the 1860s, people like Michael Faraday, Andre Ampere and James Maxwell and others were studying electric and magnetic fields. Because waves were known to need a medium to propagate through (like water waves or sound through air), it was assumed that all space was filled with a massless substance that was given the name aether. Then in the mid-1800s, Maxwell proposed that the existence of an electric charge filled empty space with an electric field.



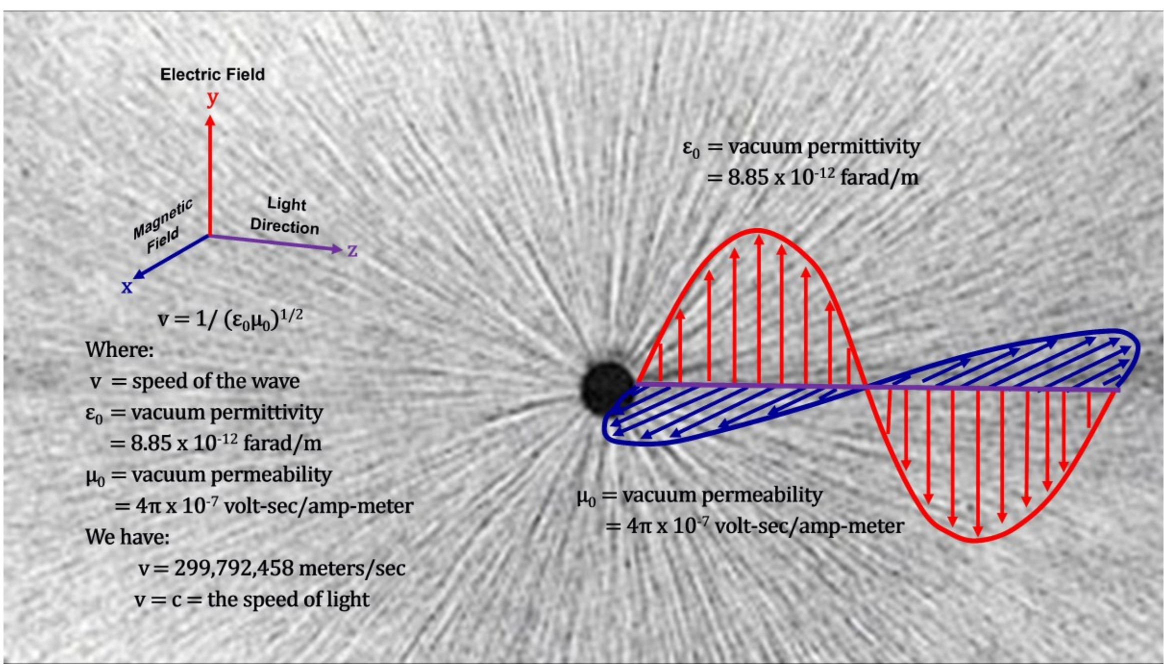
Here's a NASA picture of small threads suspended in an oil aligned with the electric field of a charge.



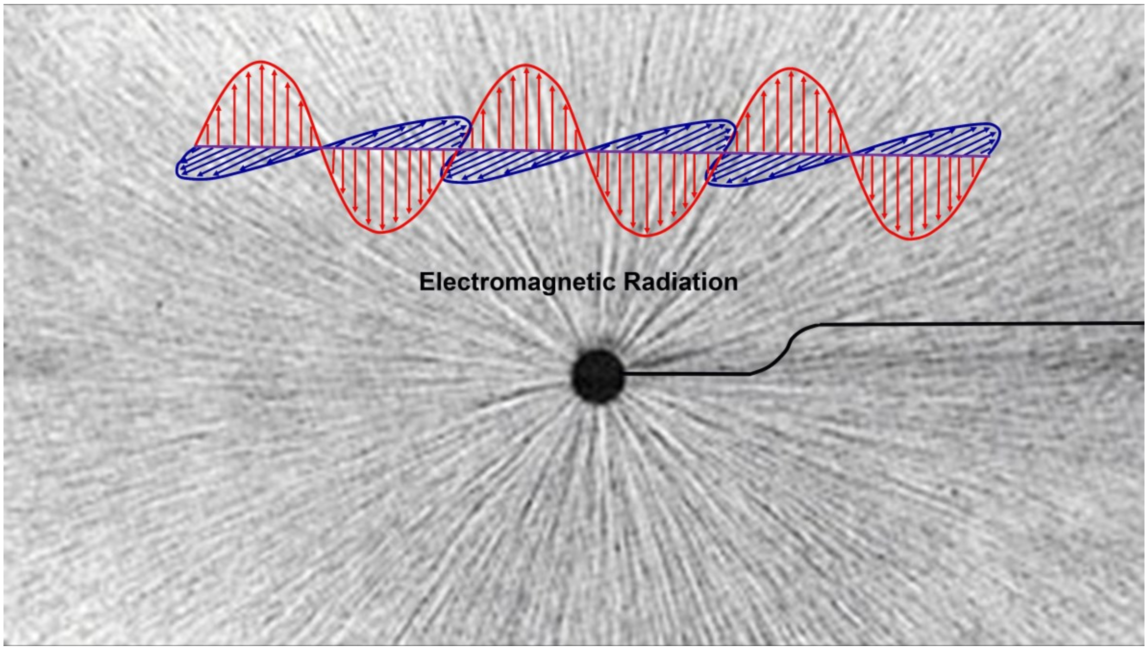
Accelerating the charge causes the electric field to change. Furthermore, he showed that a changing electric field created a magnetic field. And a changing magnetic field created an electric field. So, the accelerated electron creates a disturbance in the electric field that propagates itself through space as an electromagnetic wave.



Earlier, Faraday had measured the resistance of empty space to the forming of an electric field called permittivity and Ampere had measured the resistance of empty space to the forming of a magnetic field called permeability. In 1864, using their numbers, Maxwell calculated the speed of his waves. He found that his velocity was in agreement with Fizeau's for light! He had demonstrated that light is indeed an electromagnetic wave!

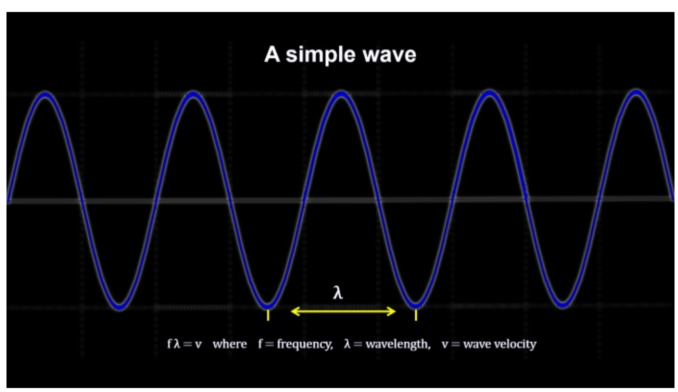


The idea of an aether filling otherwise empty space was rendered un-needed for light propagation once electromagnetic radiation was understood. So, it faded from our vocabulary - replaced by the idea that empty space supported magnetic and electric fields and light represented a disturbance in the electric field. The exact characteristics of so-called empty space will be a recurring subject for us as we approach our segment on the Higgs Boson.



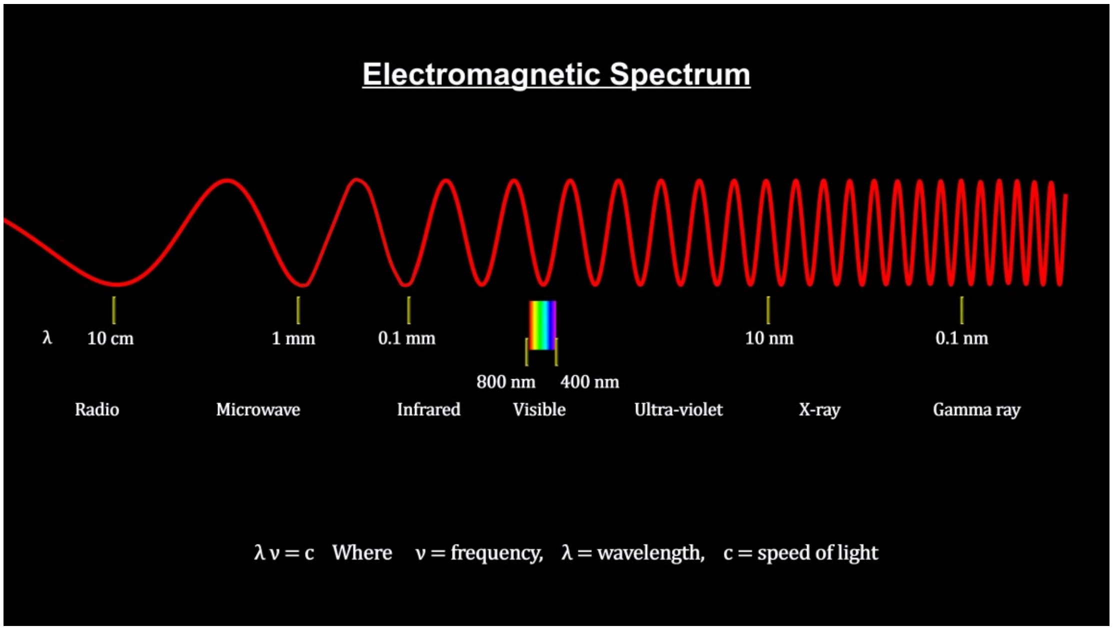
Here's a simple wave. It has:

- a repeating cycle
- a wave length;
- and a frequency in cycles/second



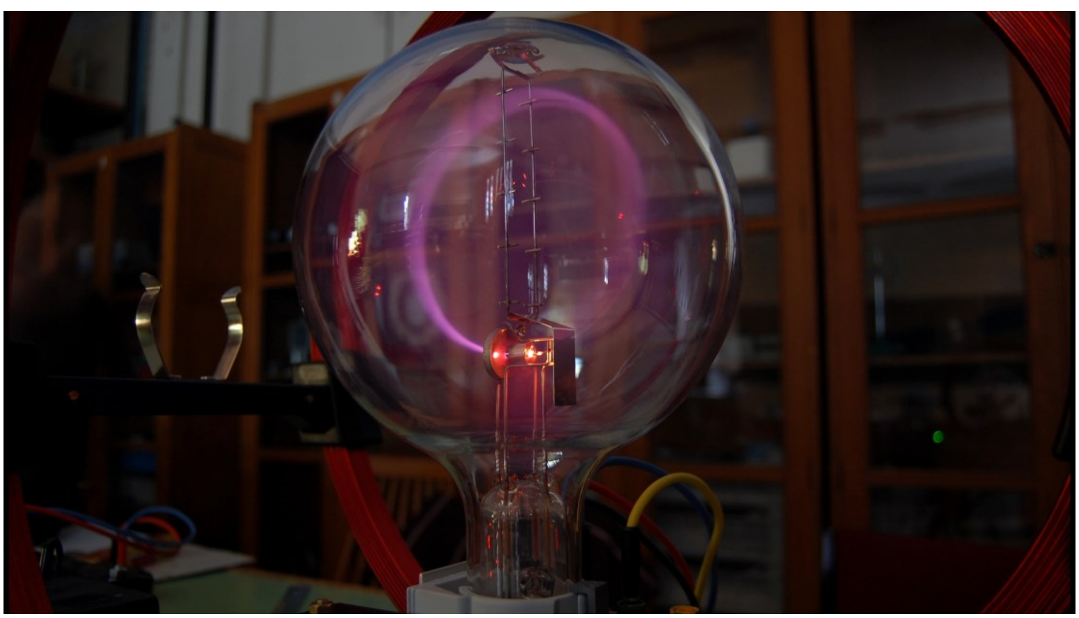
Here we see the full electromagnetic spectrum with visible light in the middle; light with longer wavelengths and smaller frequencies than red light is called *infrared*; radiation with longer wavelengths than infrared is called *microwaves*; and still longer wavelengths are called *radio waves*.

Moving up the energy scale, radiation with shorter wavelengths than violet light is called *ultraviolet*; still shorter wavelengths are called *X-rays* and the maximum energy radiation is called *gamma Rays*.

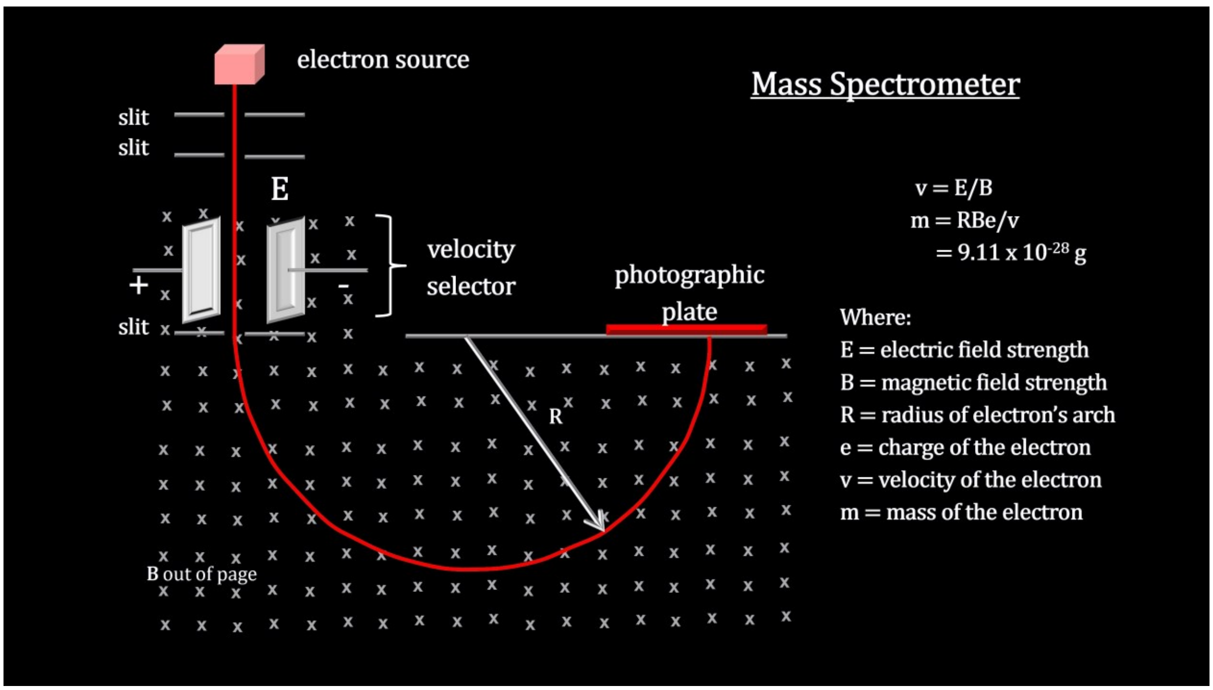


Electron Mass

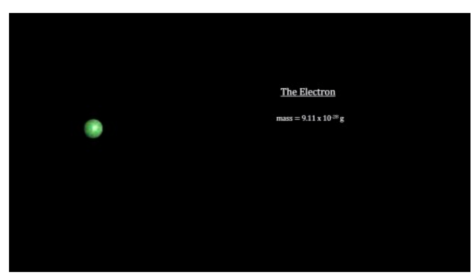
In the early 1800s, most people thought that the atom (the most fundamental unit of matter) was indivisible. Also, a lot was known about electricity, but no one knew what was carrying the electric current. For example, highly charged cathode rays were produced inside vacuum tubes in the mid-1800s, but it wasn't until the late 1800s that anyone figured out what was carrying the charge.



In 1897, J.J. Thompson used a mass spectrometer to measure the mass of cathode rays. Here's how it works. Acceleration is a change in an objects speed or a change in its direction. From Newton, we know that force equals mass times acceleration. So mass equals force divided by acceleration. If we exert an exact amount of force on a particle and carefully measure its acceleration, we'll know its mass. So, we: 1) Fix the particle velocity with an electric field, 2) measure the radius of the resulting curves as it moves through a magnetic field, and 3) use the basic electric, magnetic and centripetal forces equations to calculate mass.



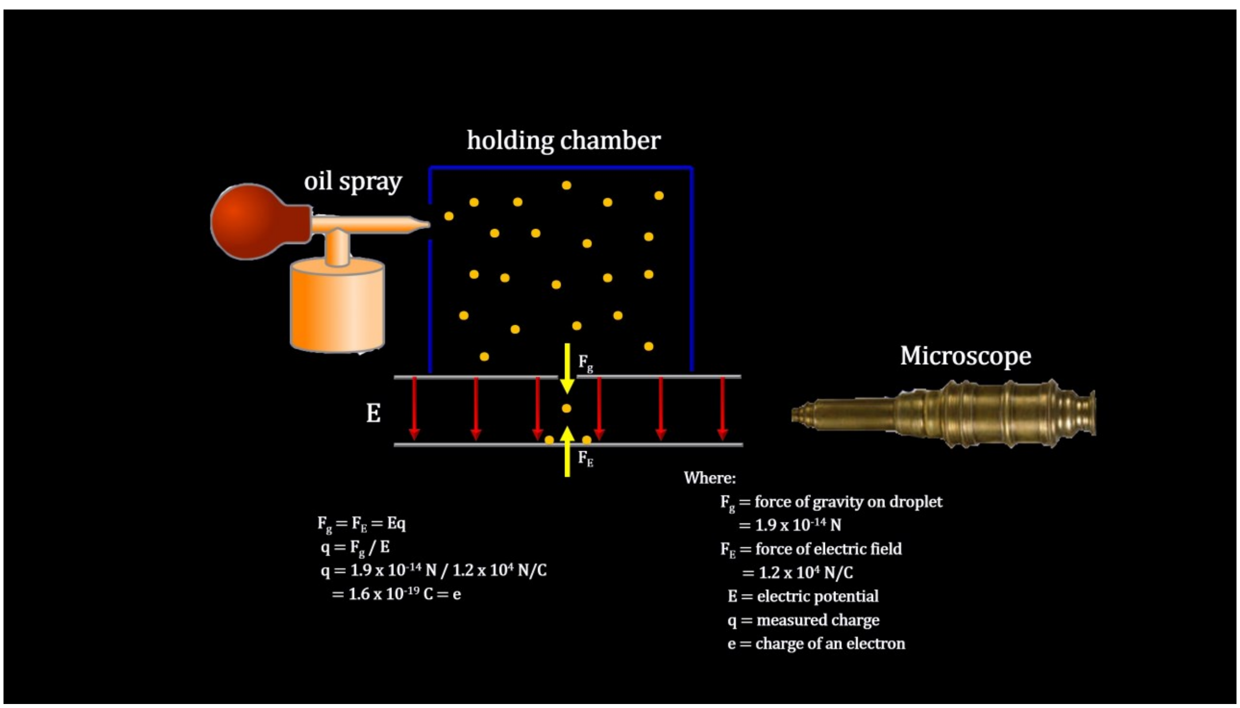
Thompson showed that the rays were made of particles that were around 9.11 x 10^{-28} g. That's 1,800 times lighter than the lightest atom (hydrogen) that had also been measured with mass spectrometers. Therefore, the particles were not atoms. He had discovered a new particle, later named - the electron.



Electron Charge

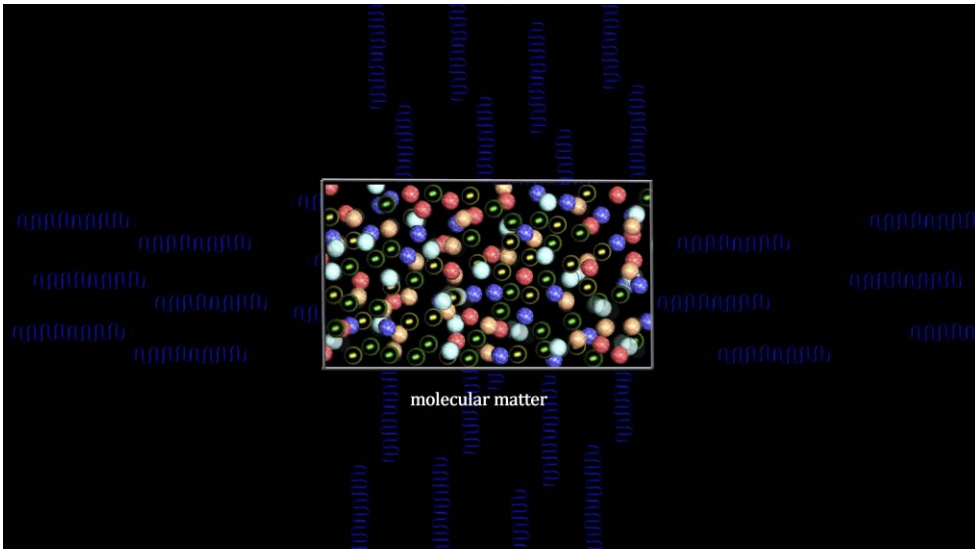
With the mass known, Robert Millikan, a contemporary of Albert Einstein, found a way to measure the charge of an electron. This is the original equipment he used in 1909.

The experiment was performed by spraying a mist of oil droplets into a chamber above two metal plates. Some of the oil droplets become electrically charged by friction as they were sprayed through the nozzle into the holding chamber. A few droplets would enter the space between the parallel plates. Controlling the electric potential across the plates would cause any charged droplets to rise or fall. Finding the voltage that causes a droplet to be suspended above the bottom plate indicates that the downward force of gravity was equal to the upward electrical force. Once Millikin had arduously and meticulously determined the weight of a droplet, he could solve for the charge on the droplet. It was not known just how many electrons would attach to each droplet, maybe one, maybe more. So, the experiment was carried out a large number of times. The smallest charge found was 1.6×10^{-19} C. And all the other charges on oil drops were found to be whole number multiples of this one indicating that it was the charge on a single electron.



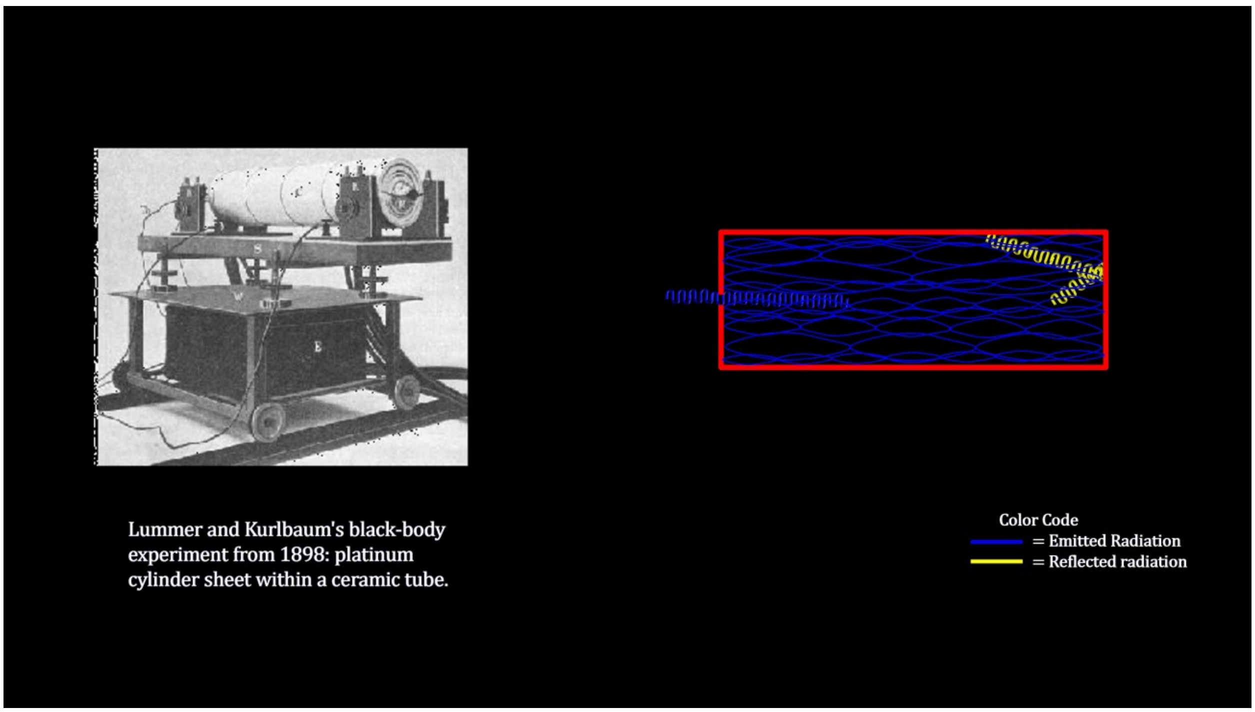
Blackbody Radiation

With the knowledge that the electric charge was carried by the electron, our first elementary particle, Once we understood that light was electromagnetic waves with a wide range of frequencies created by accelerating electric charge, a great deal of research went into studying the nature of this radiation as it related to matter and temperature. Because all matter above absolute zero contains vibrating or oscillating molecules colliding with each other, all matter radiates.



Take a look at this iron rod. At the ends, where it's cool, its radiating in the infrared so we can't see it. Its gray color is based on reflected light. As it heats up it turns red, then orange, yellow and at the hottest is it white. If we could get it hot enough, you'd see it turning blue. These colors are emitted, not reflected.

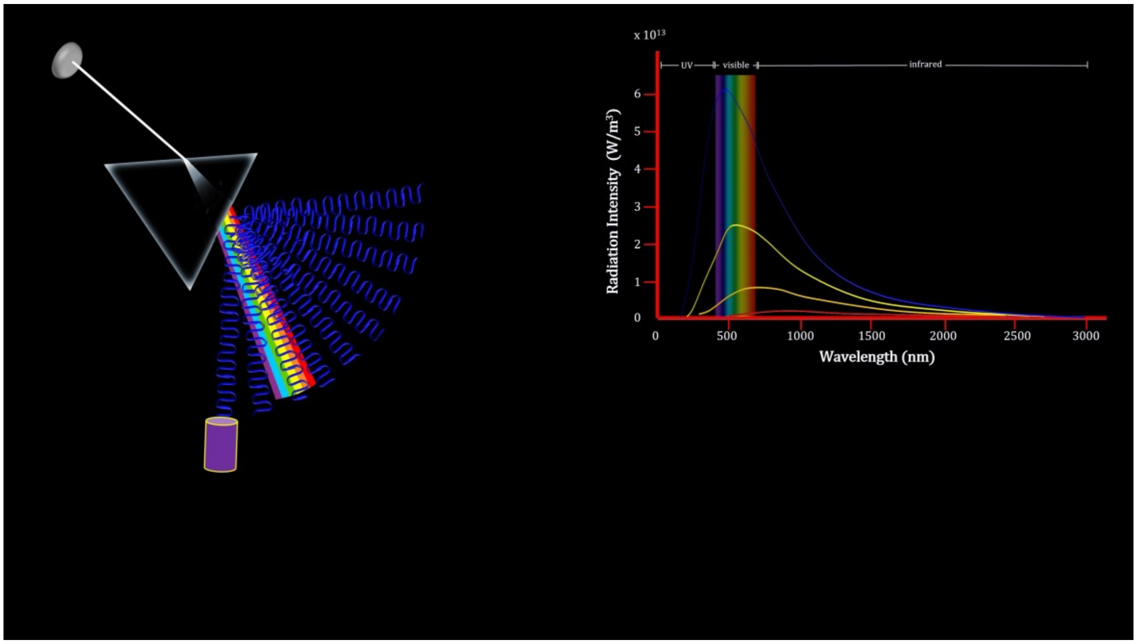
The problem with studying the emitted radiation is that you can't separate out the reflected radiation. What you need is a body that emits without reflecting. Such a body is called a blackbody and its radiation is called blackbody radiation. Here's an example of an early construction of such a device. It's a closed container with platinum interior walls and a small hole at one end. The ceramic exterior keeps the temperature constant throughout the device. Inside, it is literally filled with a wide array of 3-demensional standing waves emitted by the hot platinum walls. Any radiation entering the device through the small hole will have little chance of finding its way back out through the hole. So, for all practical purposes, all the radiation that leaks out through the hole will be radiation emitted by the platinum walls of the device. This makes the hole itself a blackbody.



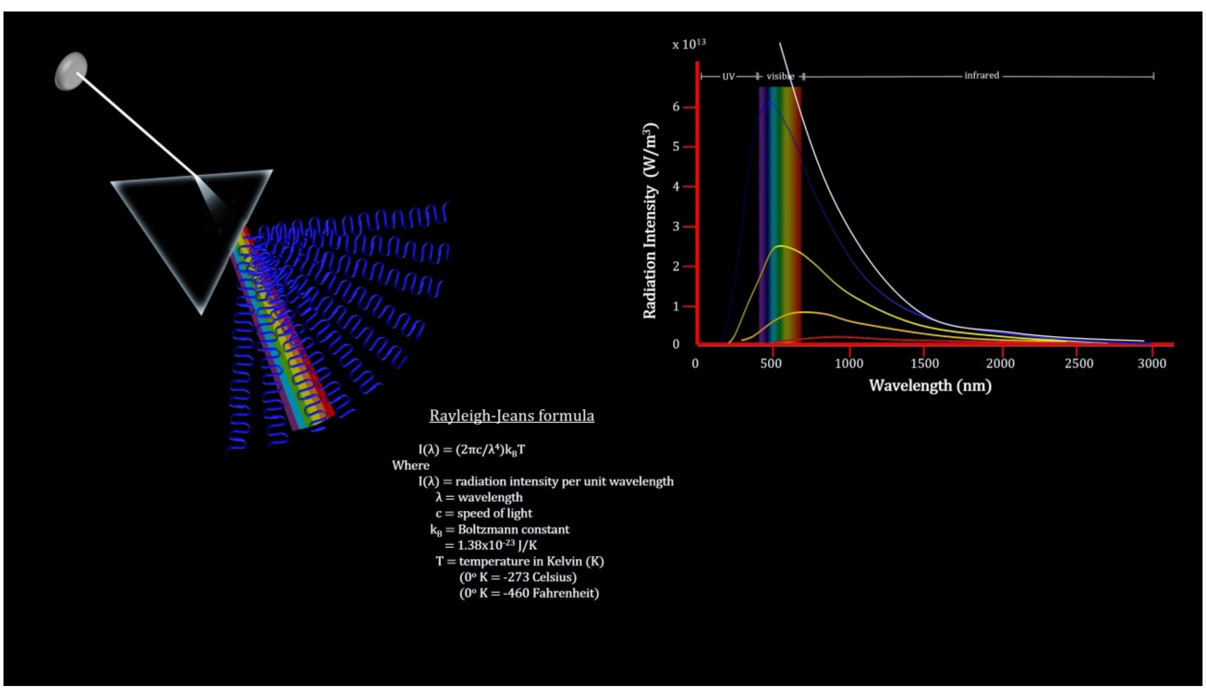
Lummer and Kurlbaum's black-body experiment from 1898: platinum cylinder sheet within a ceramic tube.

We knew that the amount of radiation, its intensity, goes up with temperature. The question was do all frequencies or wavelengths increase in intensity at the same rate. Here's how this is measured. A blackbody is heated to a known temperature. It radiates a beam out the opening. We then pass this beam through a prism to separate the various wavelengths. As we move a detector across the output, we measure the intensity at each selected wavelength. Then, repeat the process with ever increasing temperatures. We see that three things happen:

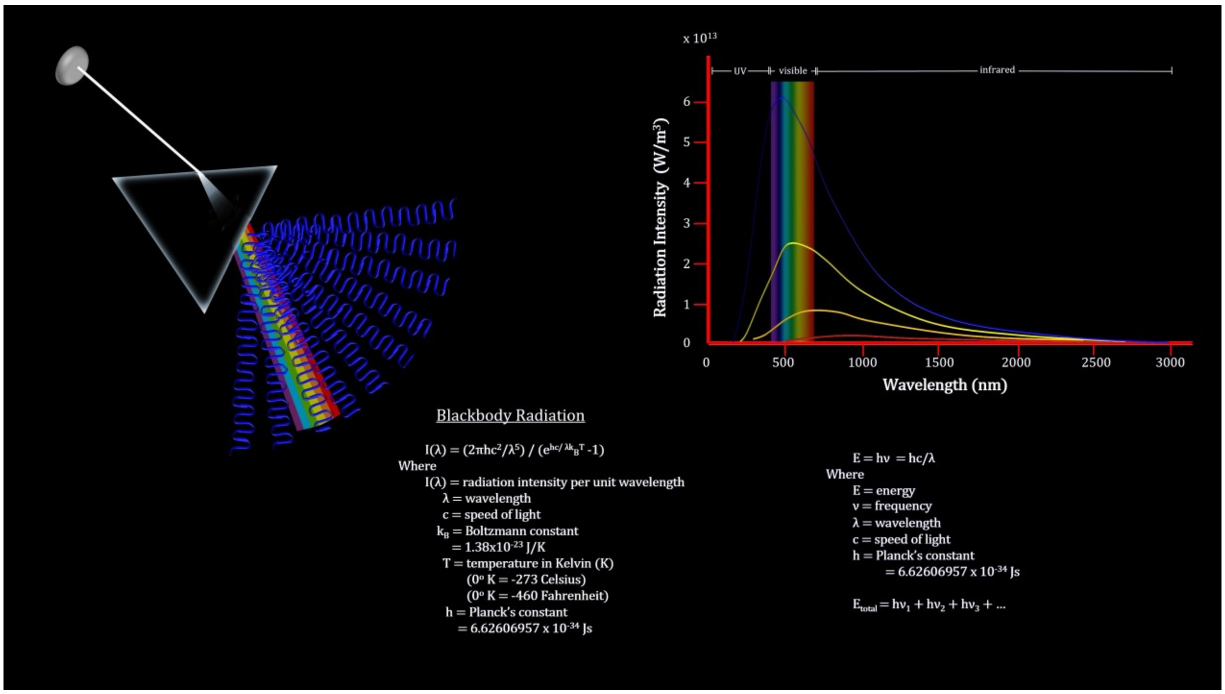
1. The object emits more radiation at all wavelengths.
2. The peak emission frequency shifts toward shorter (blue) wavelengths.
3. The intensity drops precipitously as the wavelengths enter the ultra-violet range.



Using Maxwell's equations and the laws of thermodynamics, physicists developed the equation that should describe blackbody radiation behavior. It's based on the assumption that each wave contributes equally to the total radiation energy and the electromagnetic spectrum is continuous. But the equation predicts an increase in intensity in the ultra-violet range – not the drop-off we see. This dramatic inconsistency between the theory and observation became known as the "ultraviolet catastrophe." Something was dramatically wrong with our understanding.



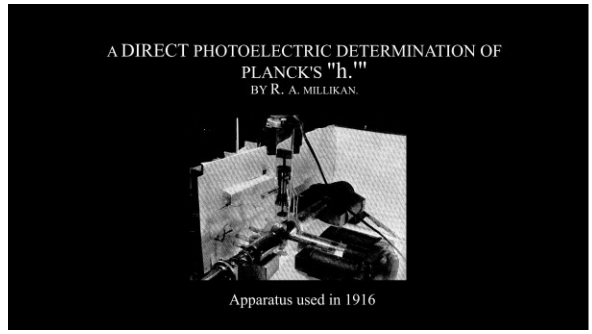
In 1900, Max Planck came up with a solution for blackbody radiation that fit the observations, but he had to brake with two universally accepted fundamentals. He proposed that electromagnetic wave energy was not averaged over a range. Instead, it's a function of each wave's frequency. And he proposed that electromagnetic waves emitted by oscillating atoms are not continuous. Instead, they come in discrete multiples of a minimum quantity. In particular, he proposed that wave energy was described by the simple formula Energy equals a constant times the frequency. The new constant h is now known as Planck's constant, the fundamental constant in quantum mechanics.



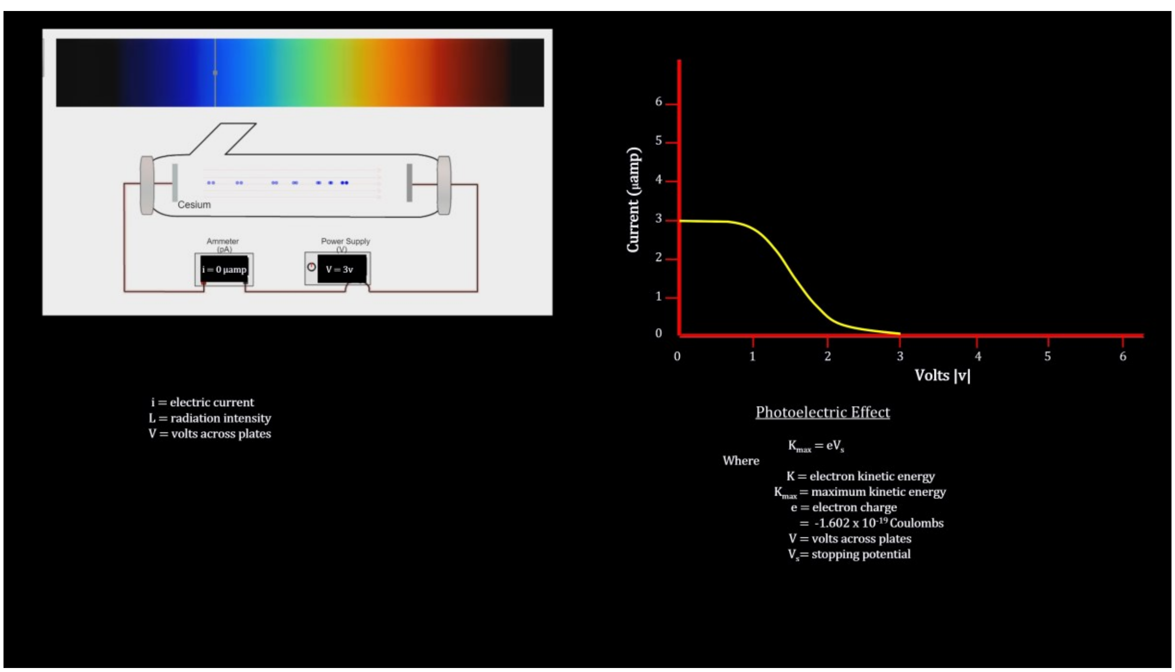
Unlike the speed of light, that's a really big number, Planck's constant is a really small number. Remember that a Joule was the energy needed to lift an apple one meter. Planck's constant is 66 billion trillion trillion times smaller than that. That's why we don't see the effects in everyday life.

Photoelectric Effect

The Photoelectric effect is the ability of light to dislodge electrons from a metal surface. The effect was discovered in 1887 and the emitted electrons are called photoelectrons. In 1915, Robert Millikan developed an experiment to study this effect.

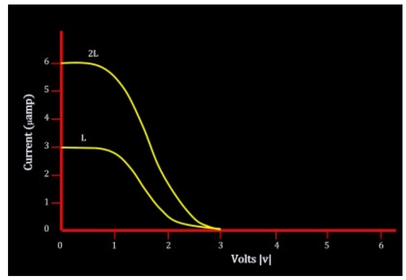


Here's a virtual reproduction of his photoelectric effect experiment. A vacuum tube contains two plates connected to an external circuit that produces a voltage between the plates to oppose the flow of electrons. When a light source shines on the emitting plate, energy is transferred from the light to electrons in the plate. If an electron gains enough energy to overcome the plate's binding energy, it will be dislodged. Furthermore, if such an electron has enough additional kinetic energy left to overcome the voltage, it will reach the other plate. This is then measured as an electric current. At very low voltages, we get plenty of electrons with enough energy to create a current. As the voltage is increased, the number of electrons that can make it across goes down. At some point, the voltage is large enough so that only the most energetic electrons can make it across. Any additional increase will stop all electrons and the current will stop. This is called the Stopping Potential and the energy of those most energetic electrons is the maximum kinetic energy.

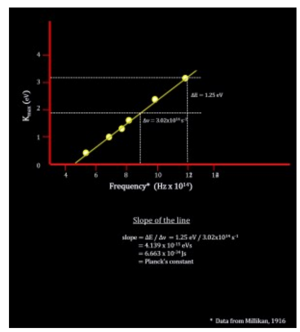


Classical wave theory predicted that light energy would take some time to build up in the electrons before they can escape and the maximum kinetic energy of the electrons would be proportional to the intensity of the light that shines on the metal no matter what the light frequency might be. [That is, as the brightness of the light source is increased, more energy will be delivered to the surface and the electrons should be released with greater kinetic energies.]

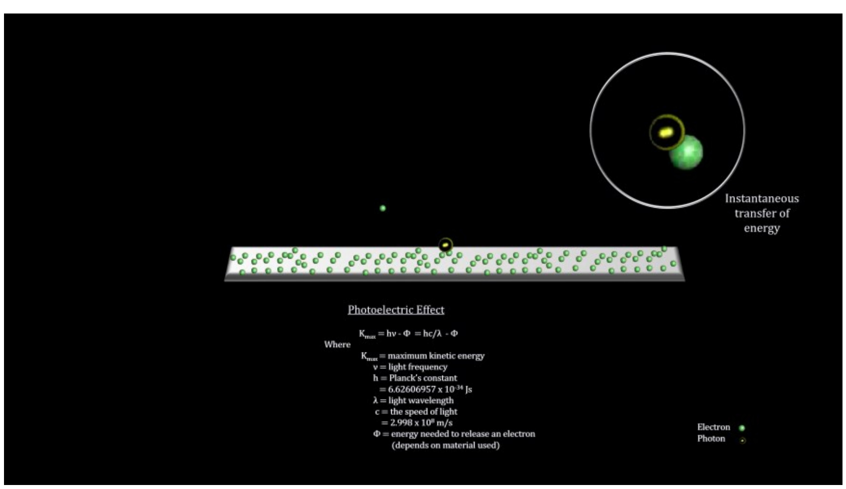
But what we actually see is that although the number of electrons varies with the light intensity, the maximum kinetic energy of these electrons remains the same. In addition, electrons are immitted without any delay except that for really low frequency light, no electrons are emitted at all, no matter how intense the light!



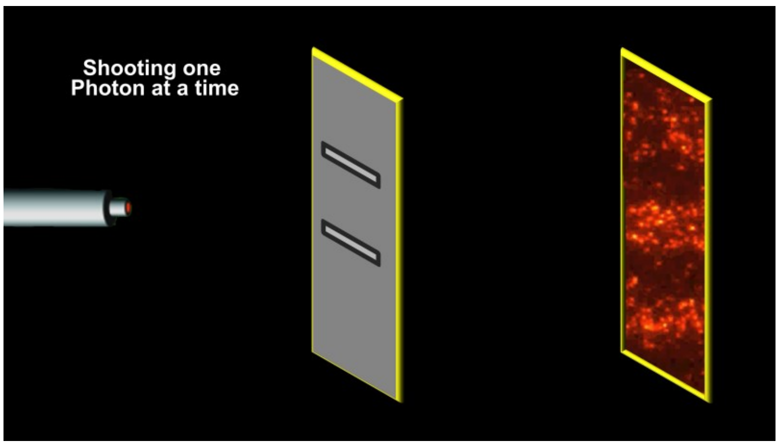
To find out what is actually going on, Millikan measured and graphed this effect for varying light frequencies. Here are his six definitive data points. They create a straight line! The maximum kinetic energy is equal to the frequency times a constant. Careful measurement found that this constant was equal to Planks' constant developed earlier from blackbody radiation.



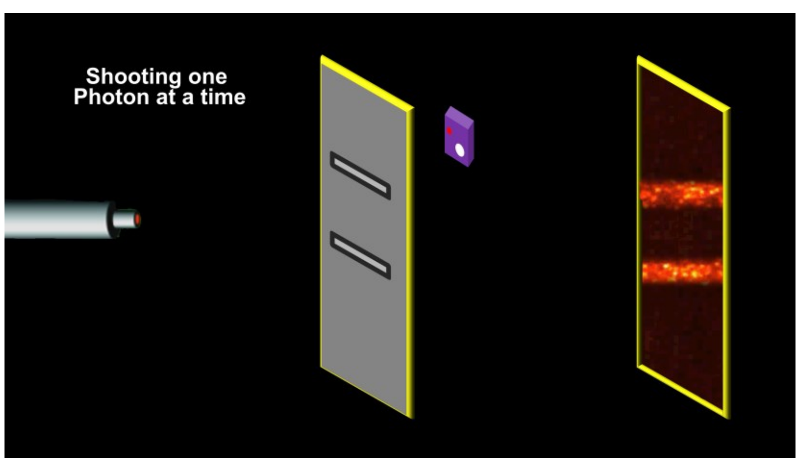
10 years earlier, in 1905, Einstein had proposed that the light impacting the plate was quantized into chunks he called quanta or photons. A photoelectron is released as a result of an encounter with a single photon. The entire energy of the photon is delivered instantaneously to a single photoelectron. If the photon energy is large enough, the photoelectron will be released. If the photon energy is too small, the photoelectric effect will not occur. This explained all the photoelectric effect observations. Millikan (much to his own surprise) proved that Einstein was correct.



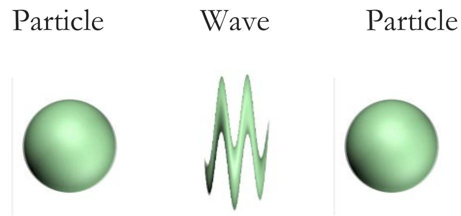
Wave Particle Duality **[Music @25:57** Dvorak – "Symphony No 9 The New World" **]**
Light starts out quantized (as demonstrated by blackbody radiation) and is absorbed quantized as demonstrated by the photoelectric effect, so it stood to reason that it travels quantized as well. In other words, it's a particle – not a wave! But what about the earlier proof that light was a wave? For that we revisit the Young double slit experiment. We've seen Young's diffraction pattern that told us light was a wave. So now let's fire photon particles one at a time at the slits. What happens is that for each photon, the detector registers a hit at a single point. And at first, with a small sample, the hits seam random. But over time, we see that the interference pattern re-emerges! This reminds me of the H-R diagram that looked random after a small sampling, but showed a clear pattern with enough data points. It's as if each photon was contributing to the interference pattern even though there wasn't another photon to interfere with. The conclusion is that photons interfere with themselves! It turns out that they only interfere with themselves, never another photon.



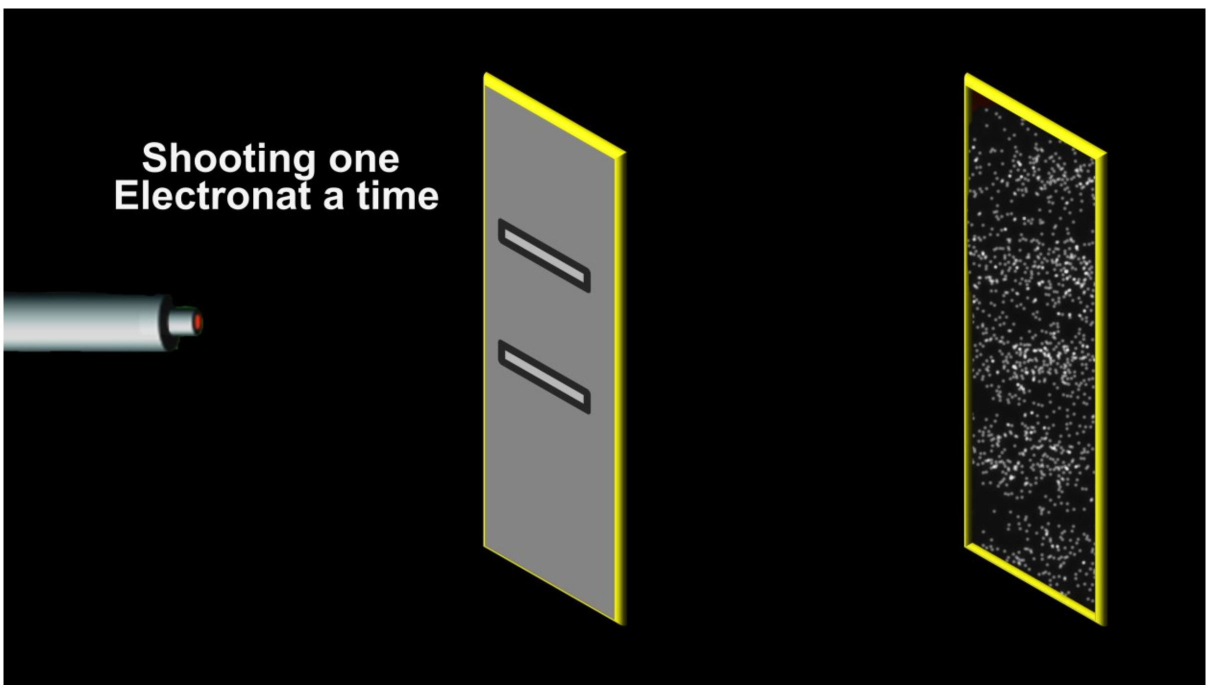
Now look what happens if we detect which slit the photon went through. Here the detector registers yes if the photon went through the upper slit and no if it didn't. The detector sees a photon coming through the top slit around half the time. [The technique for detection uses light polarization and quantum entanglement that we'll cover in an appendix.] We assume that if a photon went through one of the slits, and it was not the top slit, then it must have gone through the bottom slit. The resulting pattern is the pattern for particles! If we turn off the detector, we get the pattern for waves again! This duality puzzled scientists for years, and is argued about to this day.



A good way to look at it is light propagating through space as a wave, but at any time it interacts with something, it interacts as a particle. In other words, it is created as a particle and absorbed as a particle, but travels through space as a wave.



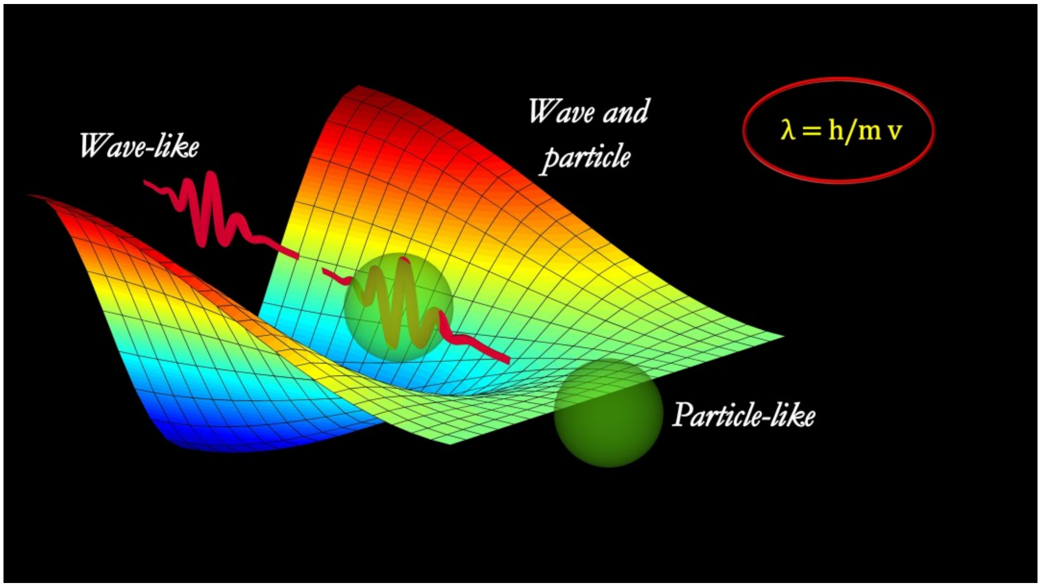
In 1924, Louis de Broglie predicted that this wave-particle duality will work the same for particles like electrons and atoms [and in fact all things]. By 1927, this had been demonstrated for electrons and atoms. With today's equipment, we can even see it for large 20 atom carbon molecules. **[**Anything larger than that has a wavelength too small to detect.**]**



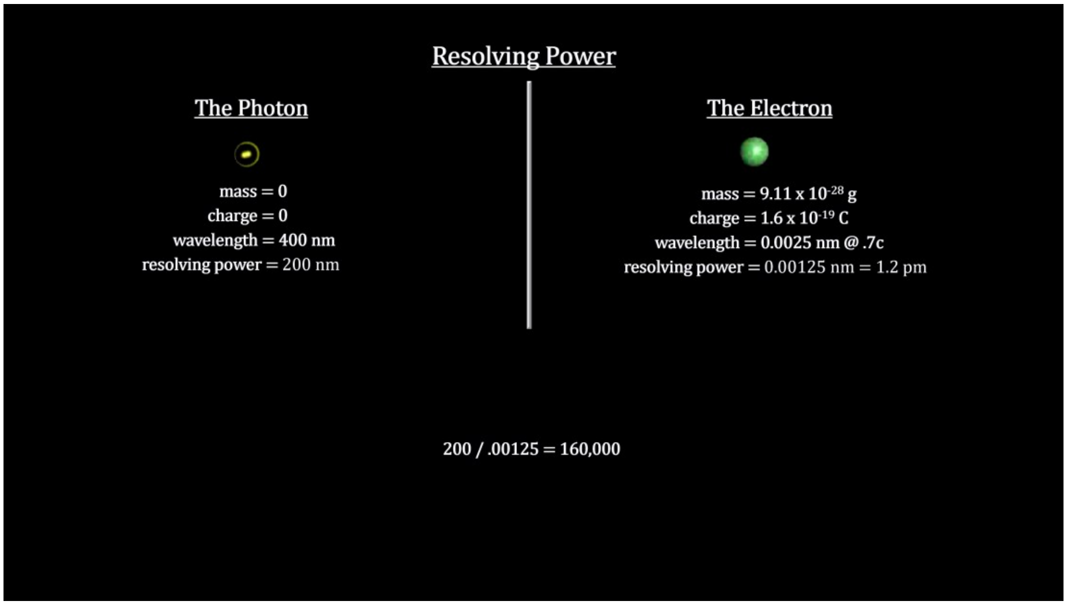
So, we have light waves acting like particles and particles acting like waves. We call it particle wave duality, and it is a fundamental aspect of quantum mechanics and these were the experiments that started it all. Once we understood that electrons travel as waves, they will have a wavelength. Here's the simple derivation conducted by de Broglie.

- The momentum for light is Planck's constant divided by the wavelength ($p = h/\lambda$).
- So, the wavelength is equal to Planck's constant divided by the momentum ($\lambda = h/p$).

- And we know that for particles, momentum is equal to its mass times its velocity (p = mv).
- So, a simple substitution gives us the wavelength of the particle as Planck's constant divided by the mass times velocity of the particle ($\lambda = h/mv$).



Microscope resolving power in general is limited to about ½ of the wavelength of the illuminating source. We saw earlier that visible photon wavelengths gave us a resolving power of around 200 nm. Using around 200 keV we can accelerate an electron to 70% of the speed of light. With that, we can use de Broglie's equation along with relativistic adjustments for space contraction and time dilation to calculate its wavelength. We get a wavelength of .0025 nanometers for a resolving power that's 160,000 times smaller than light.



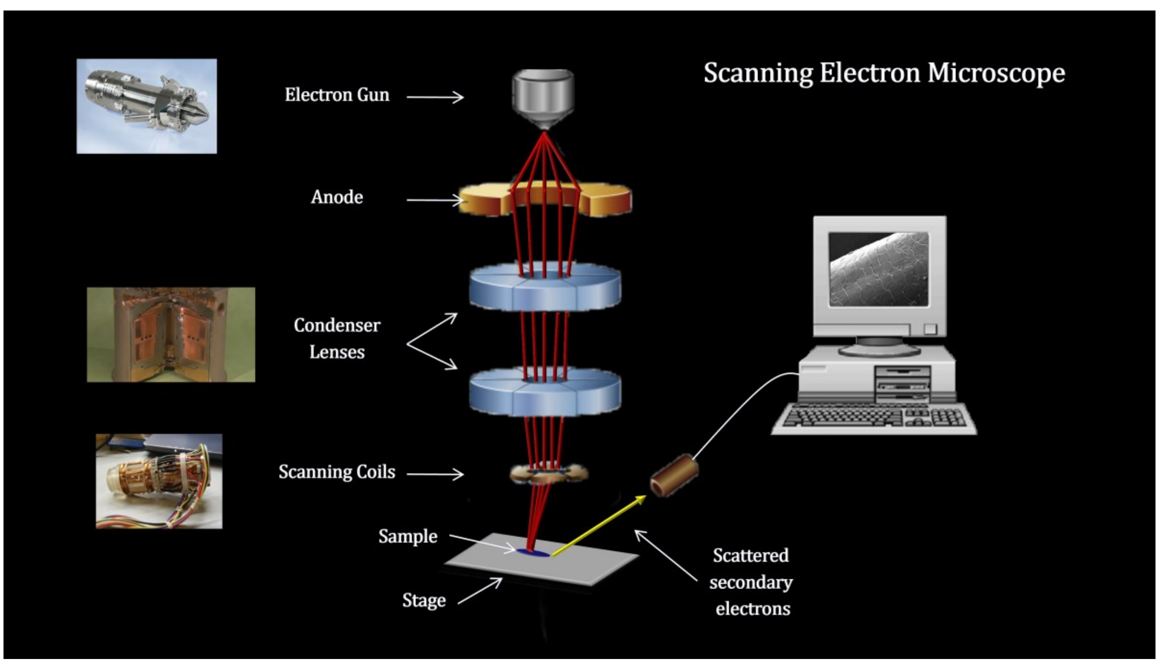
Scanning Electron Microscope

[Music @30:09 Chopin – "Piano Concerto No II Romance" **]**

With such a dramatic increase in resolving power over light, we'll use electrons instead of photons to illuminate the objects.

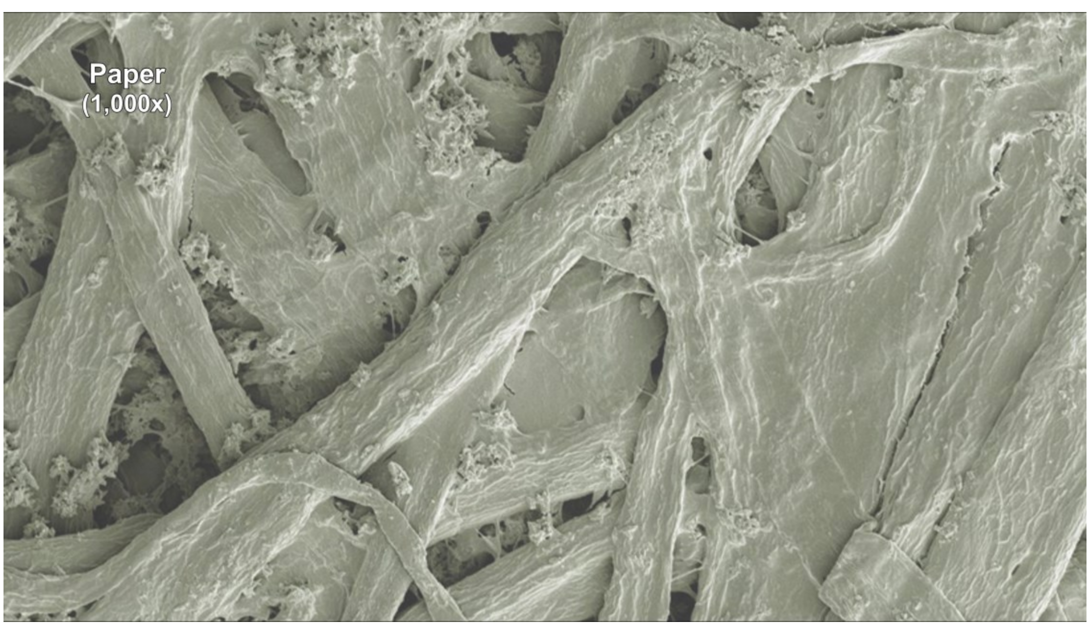
The most common electron microscope is called a scanning electron microscope (SEM).

Here's how they work. An electron gun heats up a metal, such as tungsten, to a temperature where it releases its electrons. An Anode with a large charge accelerates the electrons to a very high speed. Where glass lenses are used in an optical microscope to bend and focus the light, electron microscopes use powerful magnetic and electric field generators bend and focus the electron beam. Scanning coils are then used to focus the electrons onto a tiny spot on the specimen and move it across for a full picture of the surface. Different wavelengths penetrate the surface of the specimen and provide information on its structure. Here we are detecting the secondary electrons that define the surface of the specimen. The results are fed into a computer for processing and color additions.

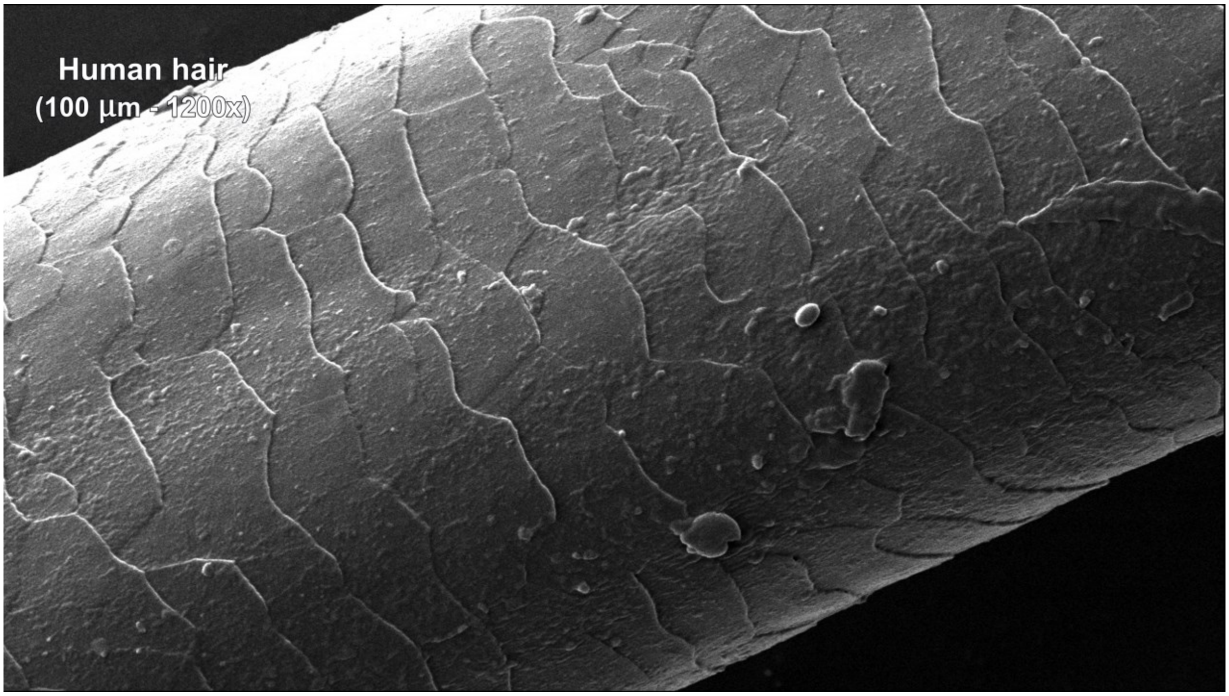


So, let's take a look at what we can see with electron microscopes. Here's an interesting look at bees through an electron microscope magnified 150 times. As you'll see, the resolving power of the electron microscope process provides images with dramatic clarity and detail not possible with optical tools. Because it's not light, there is no color associated with the images. But like we did with astrophotography, color can be added after the image is created by the electron microscope. Here's some honey bee images.

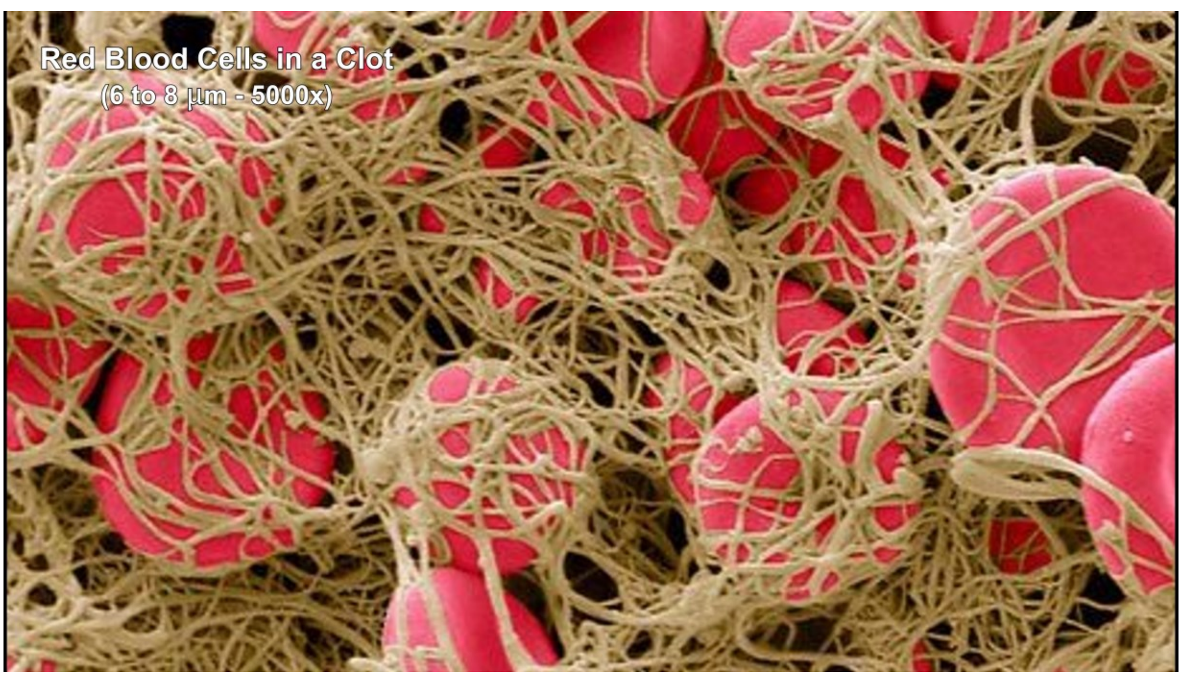
Here's what a sheet of paper looks like at 1000x magnification.



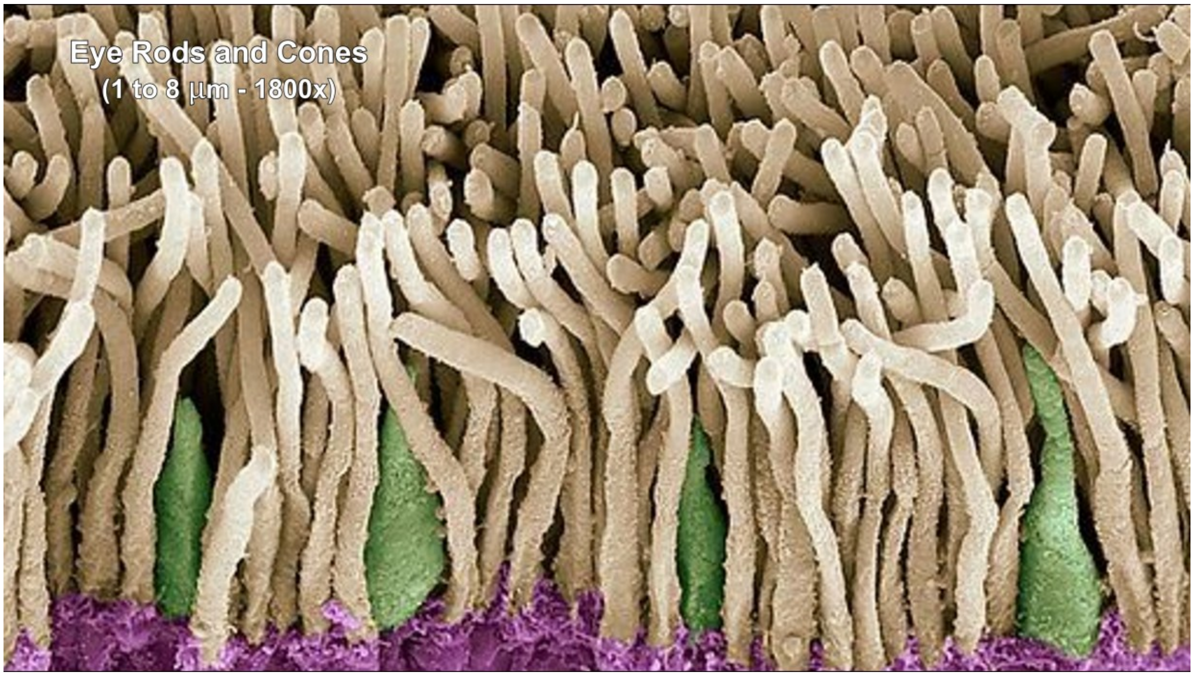
Here's a human hair magnified 1,200 times.



This is a colored SEM micrograph of red blood cells clumped together with fibrin to form a blood clot.

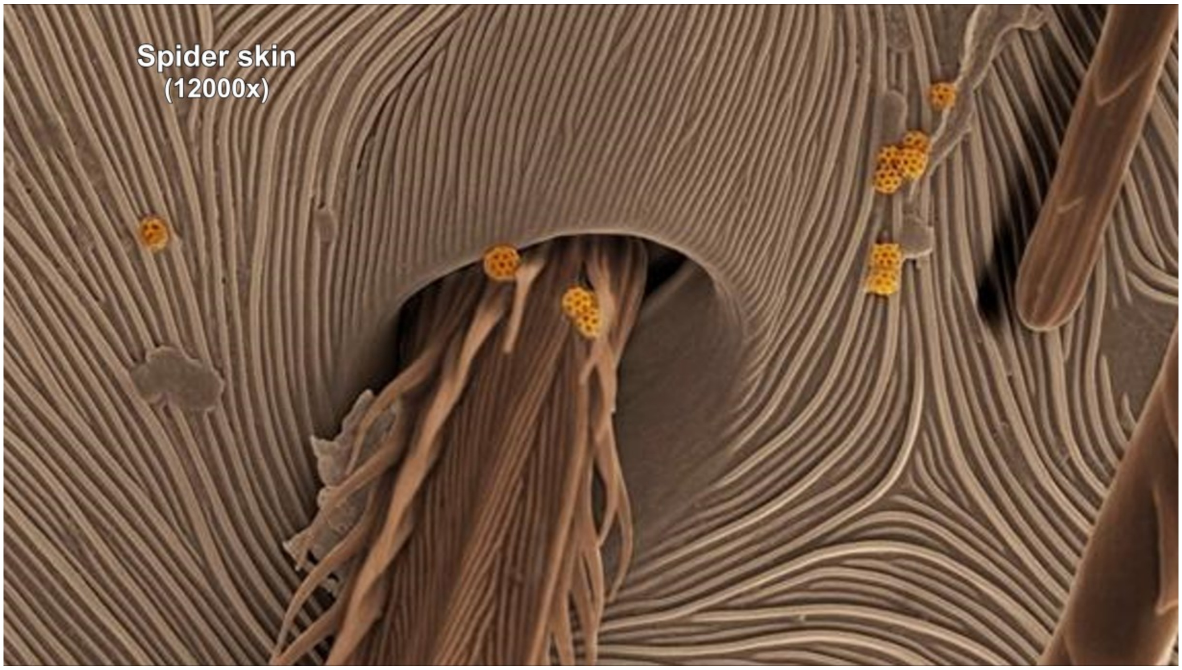


This colored SEM micrograph shows the rods and cones in the retina of the eye. The rods are tan and measure around 1 µm in diameter. The cones are green and measure around 8 µm in diameter.

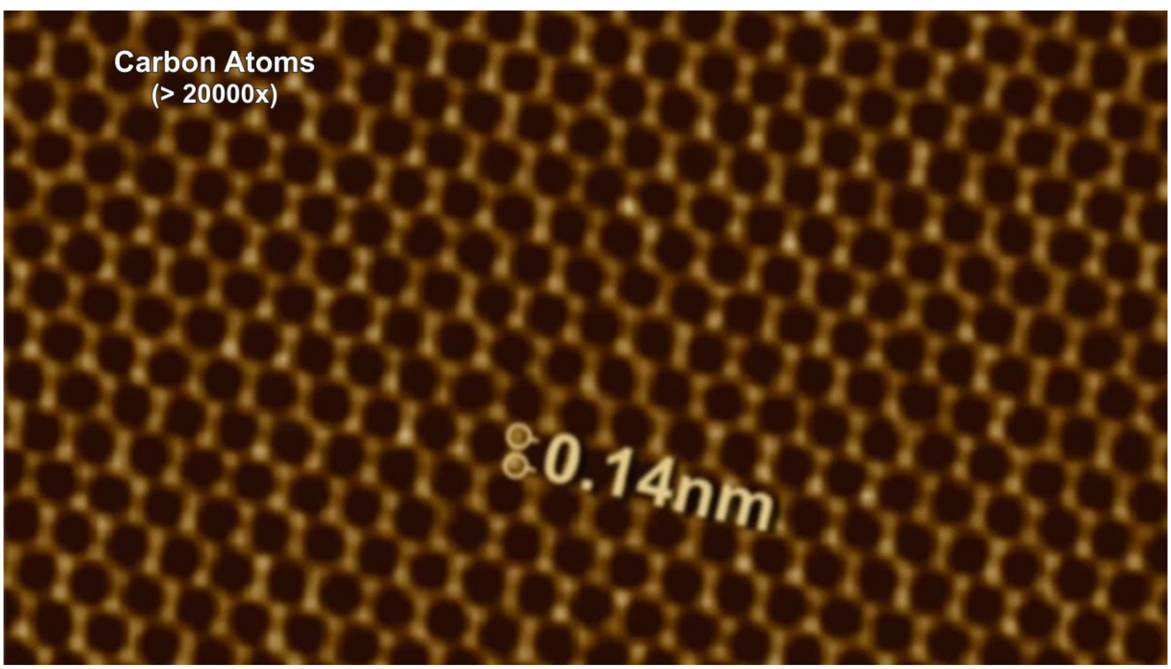


A nerve fiber is a threadlike extension of a nerve cell. Here's a colored scanning electron micrograph of myelinated nerve fibers. The myelin sheath is grey, the nerve inside is pink and the connective tissue is yellow.

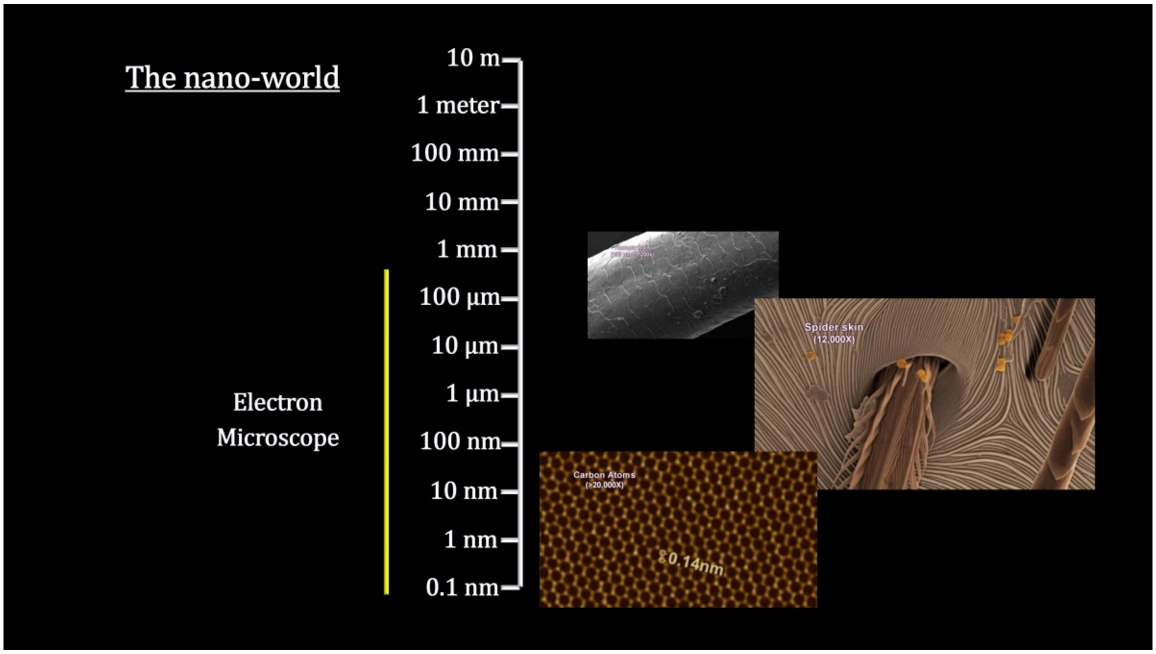
Here is the texture of the skin of a spider, magnified 12,000 times.



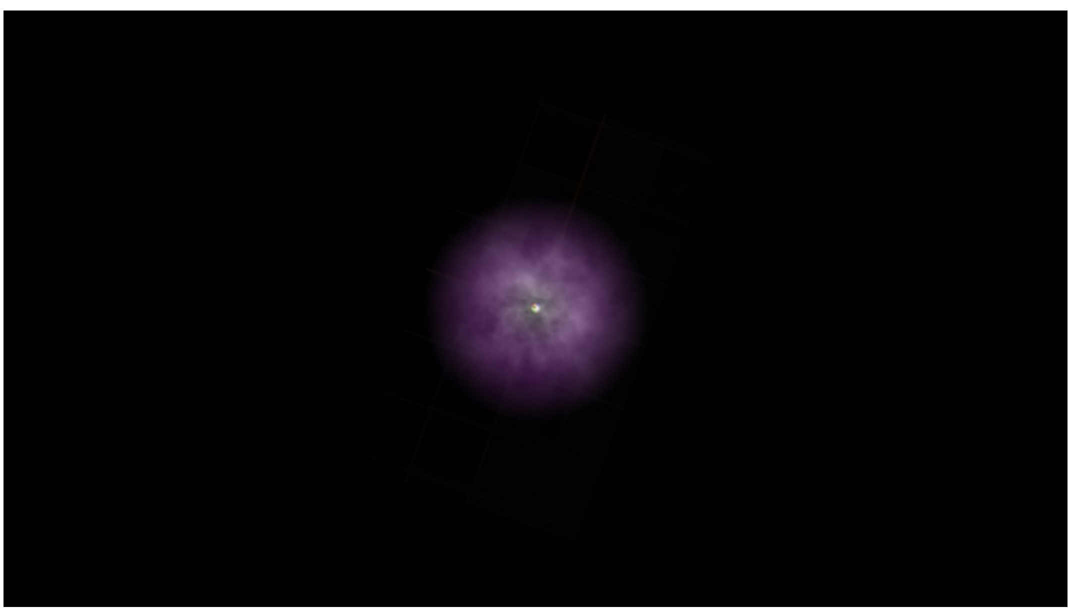
The most powerful electrons microscopes can resolve things as small as carbon atoms. Here's a sheet of carbon atoms with each atom around 0.14 nm in diameter. That's around a billion times smaller than the human hair we saw earlier.



In this segment we've gone from what we can see with the human eye, to what we can see with optical microscopes to what we can see with electron microscopes. Given the electron wavelength, this is about as good as we can do.



In our next segment, we'll take a closer look at atoms and their sub-atomic parts.



Music

@02:38: Tchaikovsky – "Swan Lake": New Symphony Orchestra from the album "Tchaikovsky's Greatest Ballets", 2009

@25:57 Dvorak – "Symphony No 9 The New World": Oslo Philharmonic Orchestra; Mariss Jansons; from the album "Essential Adagios", 2010

@30:09 Chopin – "Piano Concerto No II Romance" : Martha Argerich; Orchestre Symphonique de Montréal; Charles Dutoit; from the album "Essential Adagios", 2010

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

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