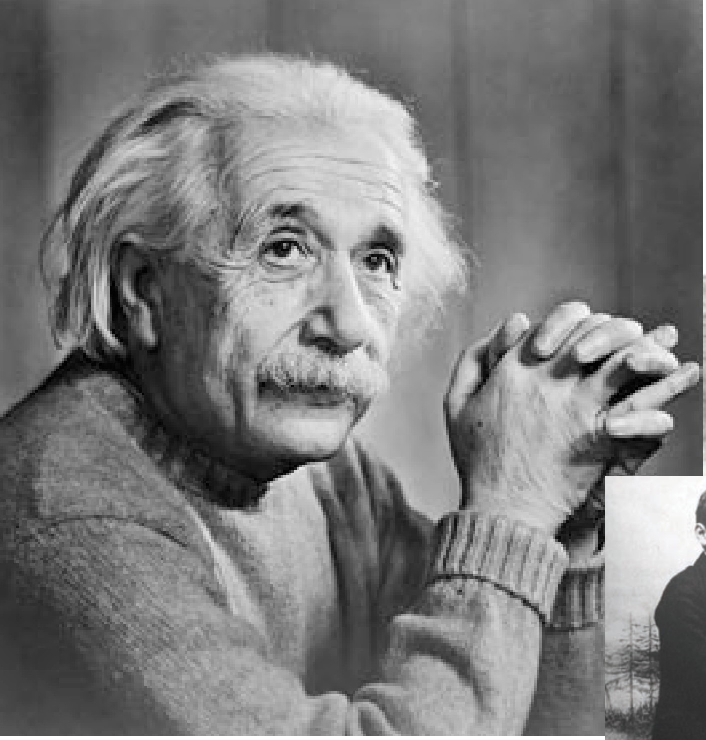
Einstein's *Miraculous Year*



As 2005 draws to a close and newspapers, magazines, MTV, and VH1 reflect on the year's hottest bands, best music videos, worst movies, and weirdest new fashion trends, we will look back 100 years to the year 1905. (*Cue dreamy harp music and fade into hazy past …*)

It's 1905 and two years ago, the Wright brothers flew the first airplane in North Carolina. Last year, the New York City subway system had its first passengers. World War I is still nine years in the future, and women will not have the right to vote in the United States for 15 more years. The Popsicle was invented by 11-year-old Frank Epperson, and a young physicist named Albert Einstein wrote and published three articles that would rock the world of science for decades to come.

By Doris R. Kimbrough

By 1905, many people felt the behavior of the physical world had been thoroughly studied, explained, and understood. Sir Isaac Newton had invented calculus over 200 years earlier to mathematically describe various laws of force and motion. There were just a few niggling problems that were not yet understood. One of those problems was the photoelectric effect. In 1905, scientists had observed this effect, but no one could explain it. It seemed to contradict the Newtonian laws of motion. Another area of controversy was the nature of matter at its most basic level. By 1905, the existence of atoms was well established, but the details of the nature and structure of atoms were certainly not well understood.

The third area that Einstein tackled was the space-time continuum, ultimately leading to his special theory of relativity, which would eventually lead to the understanding of many of science's secrets from nuclear energy to black holes.

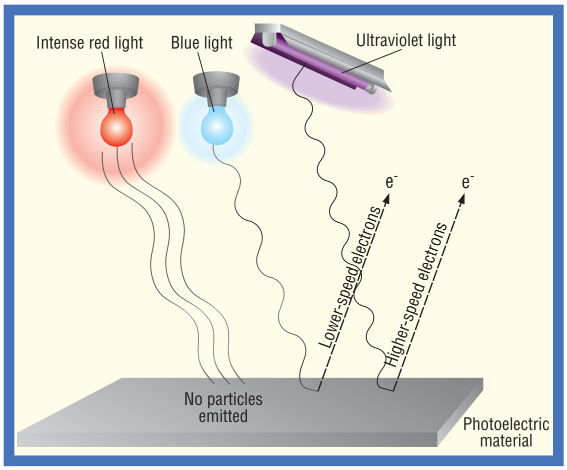
Photoelectric effect

In 1887, Heinrich Hertz first described the photoelectric effect. It occurs when you shine light on a metal surface and electrons fly off. The photoelectric effect is used in many modern conveniences, such as your supermarket's automatic door openers, motion detectors, and night vision goggles, and its applications extend to solar-powered calculators and your friend, the television.

Scientists describe "light" as far more than just what illuminates your room at night from a light bulb. It includes the radio waves that bring you the latest hits from a local station, the microwaves that cook your popcorn, the infrared waves that make you sweat on a hot summer's day, the ultraviolet rays that burn you when you forget the sunscreen, and the x-rays that your doctor used to decide that, "No it's not broken, it's just a bad sprain." According to the laws that Newton determined, which kind of light you shine on that metal surface to cause the photoelectric effect shouldn't matter; it should only matter how intense that light is. Newton's laws predict that the more intense the light, the better chance that electrons are ejected from the metal surface.

The problem was that all of the experiments showed that the frequency (i.e., the color) of light, rather than the intensity, was responsible for the electron ejection. Let's say you are a 19th century physicist studying the photoelectric effect. Here is the type of experiment you might have done and what you might have discovered.

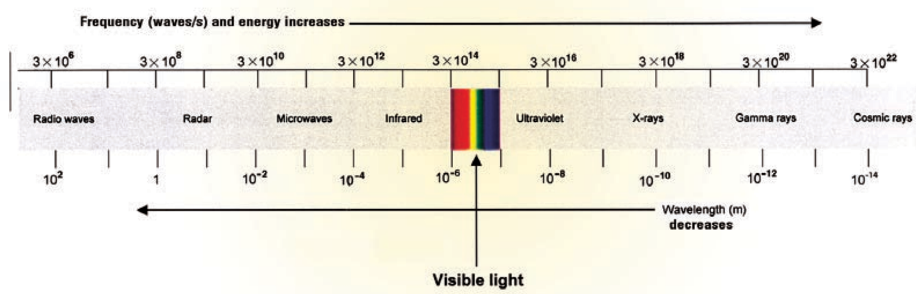
You have a clean metal surface and you are shining a beam of light on it. You have a device that can measure whether or not electrons are being ejected from that surface, we'll call it the electron-measuring device (EMD). You start your experiment by shining low-frequency infrared light on the metal surface and nothing happens. You increase the intensity and nothing happens; no matter how much you crank up the intensity, the EMD just sits there mocking you. You look for something else to experiment with and decide to carefully increase the frequency, without changing the intensity, still nothing. You increase the frequency even more, so that now you are in the visible region. Still nothing—this is starting to get really boring. You yawn and keep increasing the frequency. All of a sudden, the EMD goes crazy! Whoa, the electrons coming off the metal caught you mid-yawn, so you wake up and decrease the frequency a little to make sure something really happened, and the EMD goes quiet. Tweak the frequency up, EMD goes nuts again. Turn it down, EMD shuts off. This is kind of fun: frequency up, EMD-full of life; frequency down, EMD-silent. You carefully write down the frequency at which all of the commotion starts up. This frequency is called the threshold frequency for the photoelectric effect.



For the photoelectric surface shown here, even intense, bright red light will not eject electrons from the surface. But at blue light frequencies and higher, electrons are emitted at higher and higher speeds. Note—different materials exhibit the photoelectric effect when struck with lower frequency light (like materials in infrared sensors).

You do some other experiments with other metals, and you discover that other metals behave the same way but that each type of metal has its own unique threshold frequency. You also notice that if you continue to increase the frequency beyond that threshold, the electrons come off the metal surface faster and faster. Hmm … this is not what Newton's laws would have predicted. The other puzzling thing that you discover is that the intensity of the light does have an effect but not the one predicted by Newton's laws. Higher-intensity light causes more electrons to be ejected, and lower-intensity light means fewer electrons as long as you are above that threshold frequency.

So you have discovered that the frequency of the light, not the intensity, causes the electrons to leave the metal, and higher frequency makes the electrons leave faster. Increasing the intensity of the light makes more and more electrons leave the metal rather than just a few. Having studied Newton's laws very carefully, you and your fellow 19th and early 20th century scientists are very puzzled because this doesn't make sense at all!

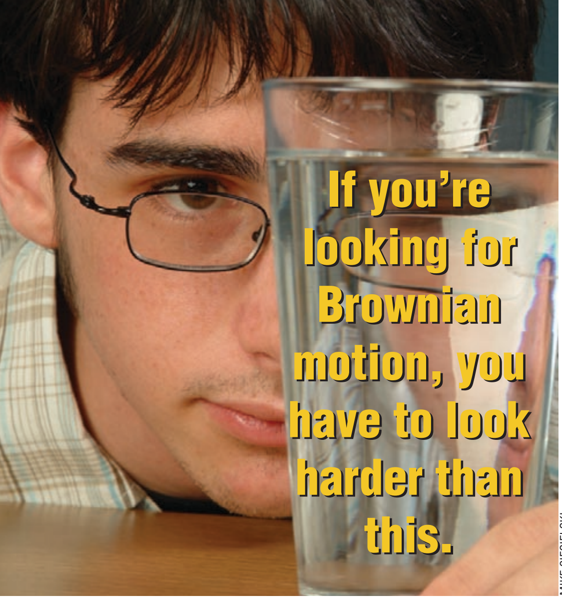


Enter young Albert Einstein, super-physicist! His first paper, published in March of 1905, focused on explaining the photoelectric effect. He suggested that when light interacts with matter, it doesn't work to think of it as a wave. Instead, we should think of it as a stream of particles, each particle a little bundle of energy that can interact with an electron. He explained that if the frequency is at or above a certain value (the threshold frequency), this little bundle of energy (later called a photon) has enough energy to boot the electron out of the metal. If the frequency is below that amount, no dice. Einstein suggested that when we increase the frequency above the threshold frequency, that additional energy is transferred to the electron, so it is moving faster and faster when ejected. He also explained the effect of increasing the intensity (more electrons). He suggested that intensity corresponded to the number of these little photon energy bundles. Increasing the intensity of the light means more photons, so more electrons are kicked out of the metal.

Einstein's explanation of the photoelectric effect was rooted in the notion that light of different frequencies has different energies, a radical idea proposed a few years earlier by Max Planck. This explanation seems obvious and logical to today's scientists and science students who have grown up with a strong foundation in atomic theory. However, in 1905, it was extremely revolutionary and produced a feverish burst of experimental activity in the scientific world, as scientists tried to prove or disprove his explanation. Einstein's explanation triumphed, and he eventually won the Nobel Prize for his efforts.

Atomic theory

By 1905, a number of scientists had considered the possibility of atoms and molecules, but there was no direct proof that they existed. This missing proof meant that there were still a considerable number of scientists who did not believe in the existence of atoms. This may



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seem impossible to those of us who have grown up with the notion that all matter is composed of atoms, but scientists are peculiar that way: they need proof to be convinced.

Some of the fans of the notion of the atom thought its existence could explain something called Brownian motion, which was first described in 1828 by botanist Robert Brown, who observed the apparently random motion of pollen particles suspended in a liquid. Those who believed in atoms and molecules suggested that the Brownian motion of particles in liquids could be explained through the collisions of bazillions of molecules with those particles.

Einstein thought that even though atoms were too small to be observed, their impact on larger objects, like Brown's pollen, could lead to a physical proof of their existence. Einstein analyzed the motion of dust particles in water under a microscope, and through careful calculations, he computed the dimensions of an atom! He went on to publish other papers on Brownian motion, and his work combined with other experimental evidence eventually led to the acceptance of atomic theory by even the most stubborn of atomic nonbelievers.

Einstein's special theory of relativity

Explaining the photoelectric effect and Brownian motion forged new links between the microscopic structure of light and matter and observable properties. The last paper, describing the theory of relativity, really shook physicists' beliefs about the nature of the physical world and remains deeply surprising even today. In order to even try to make sense of it, we have to revisit the behavior of light. When you look at the clock in the front of your classroom to see how much longer your chemistry class could possibly last, what allows you to see the time is the light traveling from the clock to your eye, which then registers the clock's image on your eye and your brain. The light has to travel from the clock to you, so the actual time you see is what the clock displayed a split second ago. If that isn't weird enough, the time that the front row sees is earlier than the time that the students in the back row will see because it takes a bit longer for the light to get to the back row. Even though these differences in time are too small for us to detect, technically you never get to see the actual time the clock displays, no matter how close you get to it.

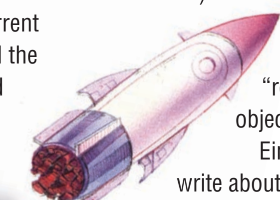
Now let's pretend you are in a spaceship traveling at the speed of light away from that clock. The light from the clock at the current time will never reach you (since you and the light are traveling at the same speed and you left first), so as you travel, the clock will appear to have stopped at whatever time

you left on your light speed journey. Your spaceship only has room for one, so your fellow students are stuck in the classroom with the clock. They watch the classroom clock keeping perfect time, getting closer to the end of class, even though to you it appears stopped. To further confuse you, if you look at the wrist watch that you are wearing in the spaceship, it continues to merrily tick away, time advancing, because it is traveling with you. This clock thing gets even more mysterious when you return to the classroom after your speed-of-light adventure. Even though your watch and the wall clock might have been in perfect synch before you took off, your watch now reads a time ahead of the wall clock. Einstein reasoned that time (and distance and matter and energy) are all relative to your frame of reference.

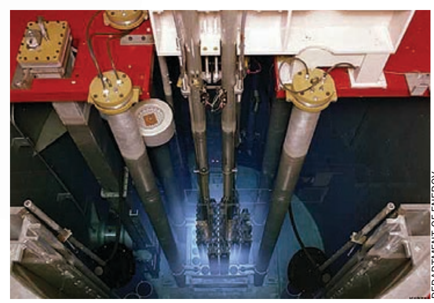
Light traveling through matter goes slower than c (3×10^8 m/s), and other things can potentially exceed the speed of light in a given medium but cannot go faster than light in a vacuum.

Einstein started with the premise that—in a vacuum—the speed of light is a constant and that light moves at the fastest speed in the universe. This contradicted Newton's laws, which say that if you continue to accelerate, you will continue to get faster. Einstein's assumption that light is the universal speed limit, lead to some of the more bizarre revelations of relativity theory. His conclusions are well supported by 100 years of experimental evidence.

He showed that as you approach the speed of light, time and space are compressed such that our measuring devices (e.g., clocks and rulers) become distorted depending upon their frame of reference. Thus, time and space are "relative" states for the same object.



Einstein went on to study and write about each of these three subjects more thoroughly. His special theory of relativity gave rise to a general theory of relativity, which incorporated other aspects of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Faster than the speed of light! The blue glow of this reactor is due to Cherenkov radiation. This radiation is emitted when electrons pass through the reactor water faster than light (Light travels about 25% slower through water.)

the behavior of the universe such as gravity and led to the prediction of black holes and the Big Bang theory of the origin of the universe. His further work in the area of Brownian motion solidified atomic theory and the existence of molecules, and his explanations of the behavior of light and the photoelectric effect fostered the basis for much of the quantum mechanical model of the atom. So 1905 was just a launch pad for young Albert Einstein, but what an amazing liftoff he had!

Doris Kimbrough teaches chemistry at the University of Colorado-Denver. Her last article "More Than Blue" appeared in the April 2004 issue of *ChemMatters*.