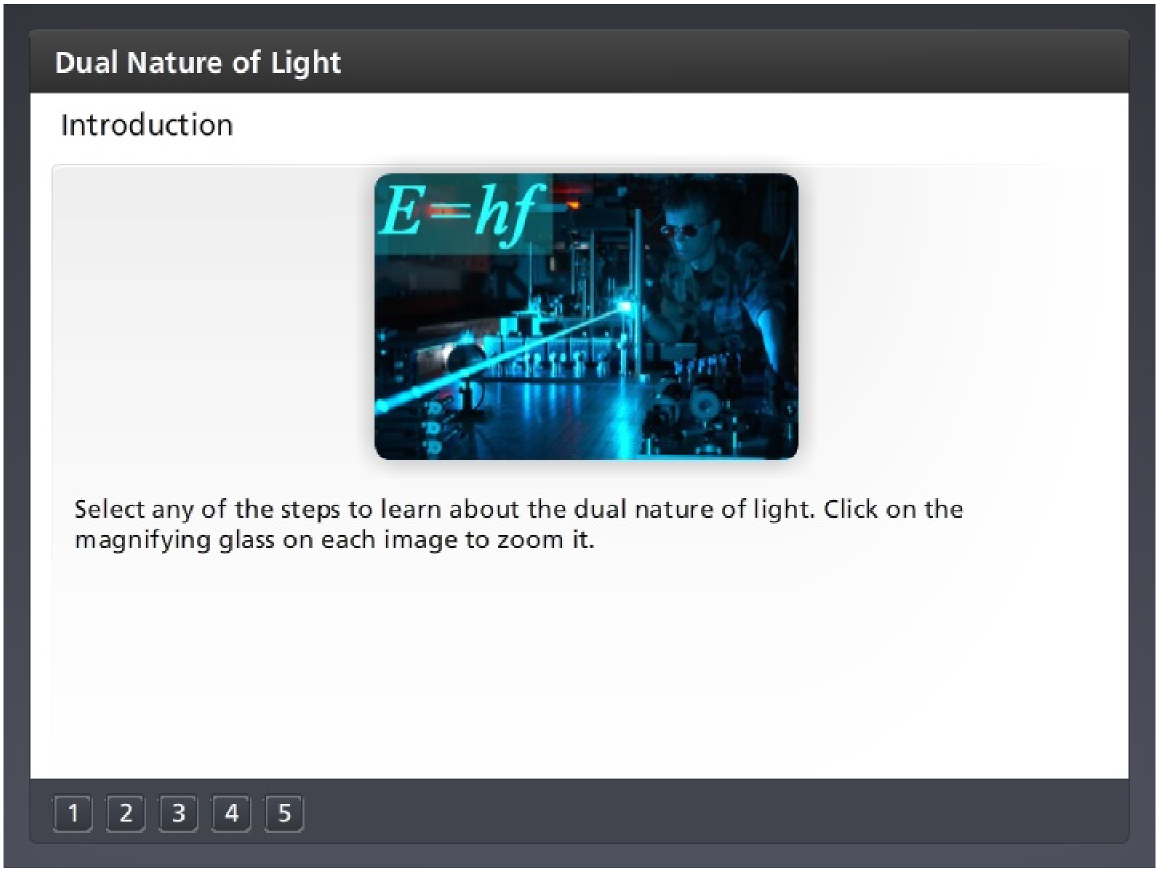
Module 8: 20th Century Physics
Topic 1 Content: Dual Nature of Light

Introduction



Select any of the steps to learn about the dual nature of light. Click on the magnifying glass on each image to zoom it.

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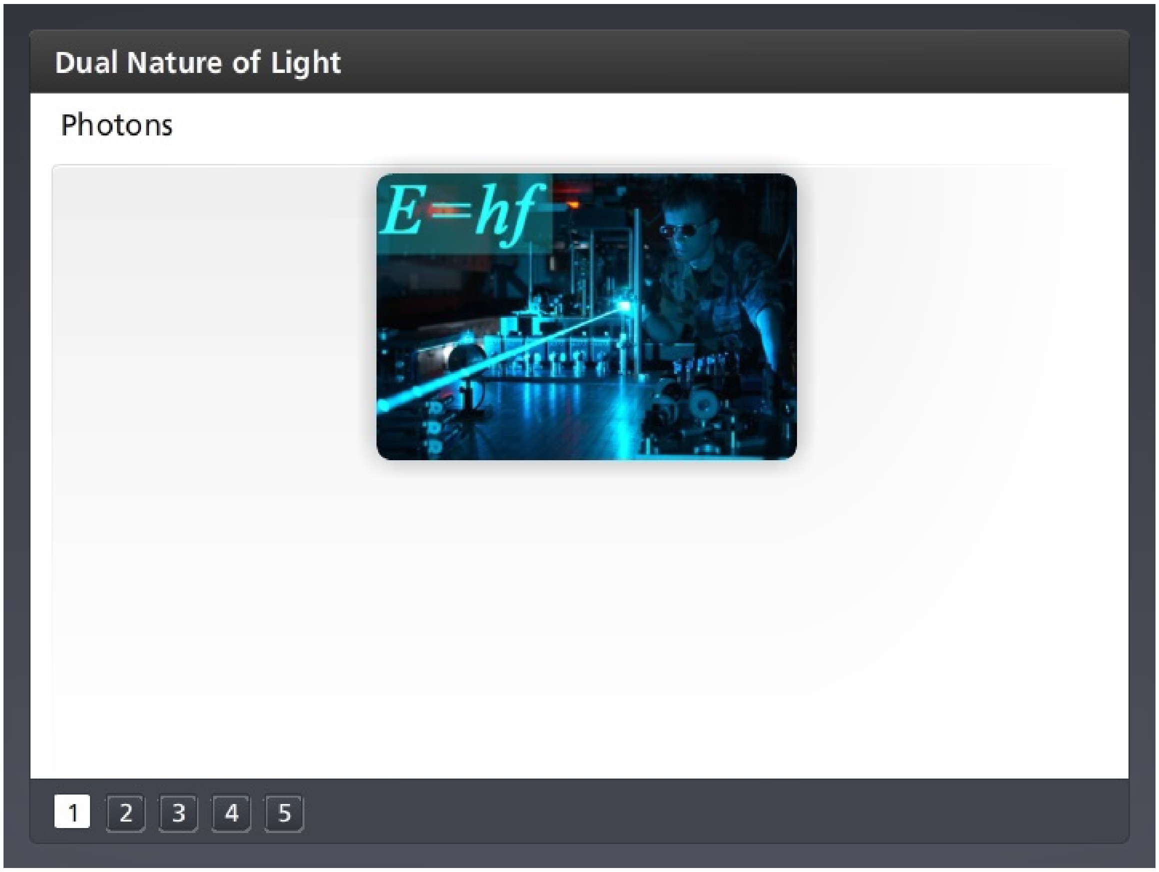
Topic 1 Content: Dual Nature of Light

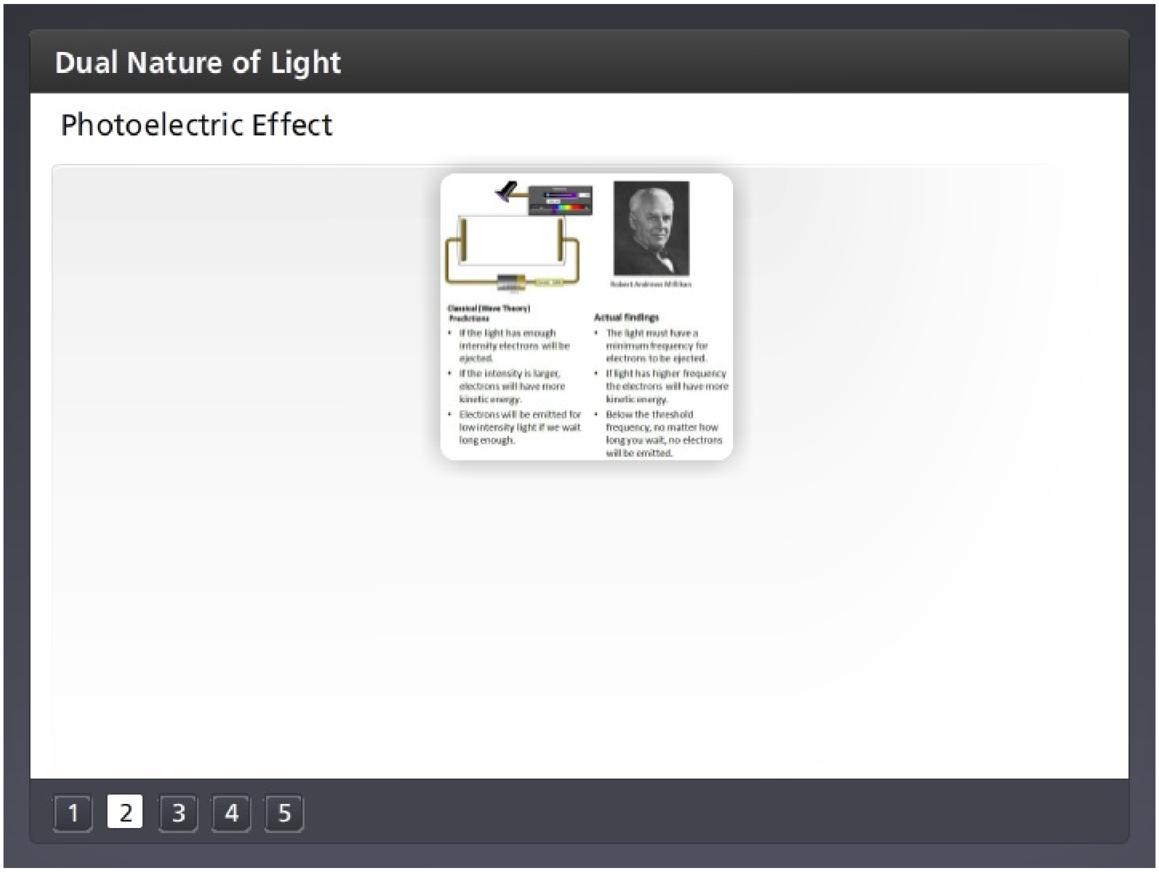
Photons



A light particle is called a photon. You can think of a photon as a tiny bundle of electromagnetic energy. The laser in this picture is emitting a tremendous number of photons each second. Photons are particles, but they also have some wave properties. Just like waves have frequency, each photon also has a frequency. The frequency of the photon is directly proportional to its energy. The equation for the energy of a photon is E equals H times F. E is the photon energy, f is the frequency and h is Planck's constant. Planck's constant is equal to six point six three times ten to the negative thirty four joule seconds.

This equation means that for a given frequency of light, photons can only have energies that are some multiple of Planck's constant. Some values are not possible. The idea of a quantity only occurring in certain amounts is called quantization. The smallest amount you can have of something is called the quanta. For example, American money can only occur in multiples of pennies. The penny is the quanta of American currency and we can say that money is quantized. You cannot give your friend a half a penny. The same can be said of energy.

Photoelectric Effect



Einstein’s theory of the photon that explained the dual nature of light was published in 1905. The photoelectric effect occurs when a metal atom absorbs a photon, then emits an electron. These electrons are called photoelectrons.

Robert Andrews Millikan did not believe that the photon theory of light was correct because there was so much evidence to support the wave theory of light. So Millikan spent ten years working on an experiment to test the theory. His results confirmed all of Einstein’s predictions. This screenshot shows a simulation of the photoelectric effect experiment.

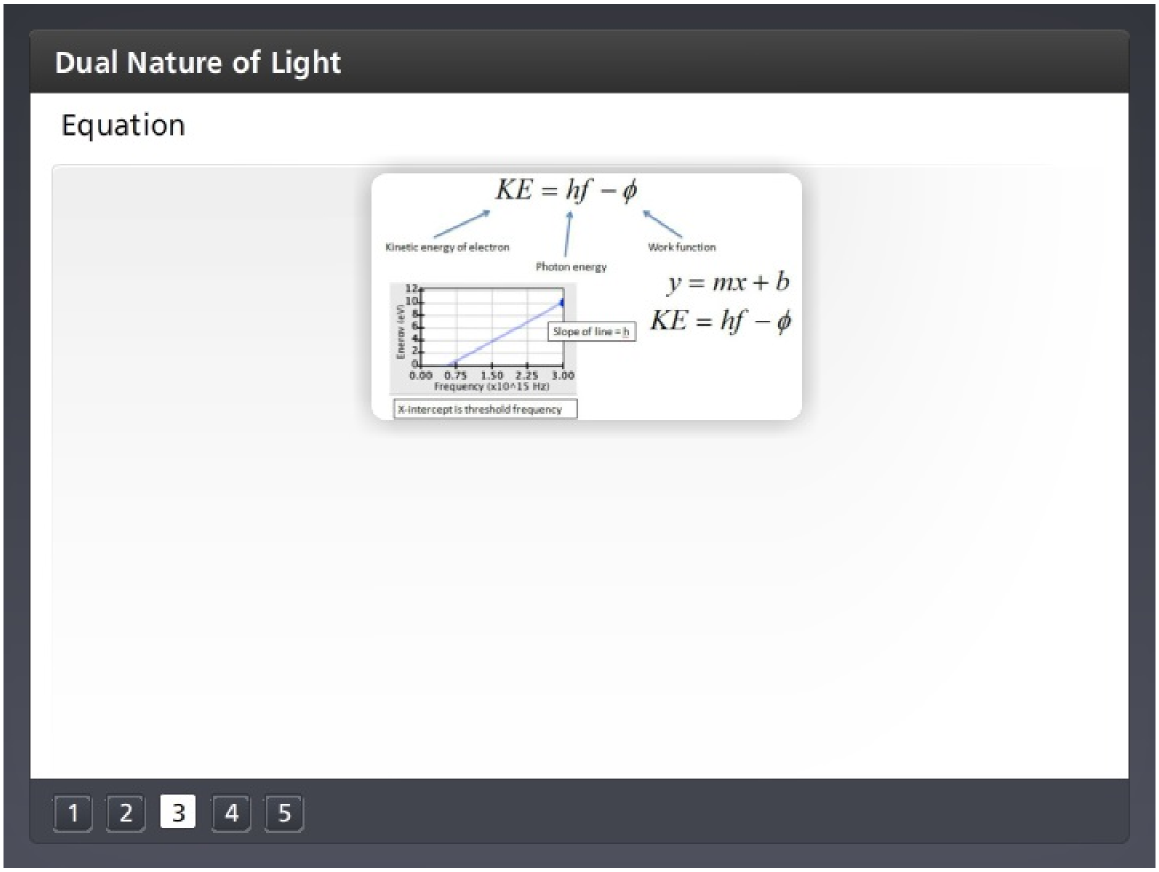
The fact that light can cause electrons to be ejected from an atom does not contradict the principles of classical physics. Light has energy, and if the energy is large enough, an electron could be pulled away from its atom and have enough energy to escape the metal. However, the specific details of the photoelectric effect cannot be explained by the classical theories.

According to classical physics, the energy of a wave increases as its intensity increases. So predictions of how the photoelectric effect should work can be made based on wave theory. We can make three predictions based on wave theory. First, that if the light has enough intensity, electrons will be ejected. Second, that if the intensity gets larger, the electrons will have more kinetic energy. Third, that even at low intensities, if we shine the light long enough, eventually electrons will be emitted.

However, Millikan’s findings did not support the wave theory. What was observed was quite different. The intensity was not the most important property of the light, the frequency was. The frequency has to be a certain minimum value for the electrons to be ejected. The frequency had to be increased to increase the kinetic energy of the electrons. And below the minimum threshold frequency, no matter how long you wait, no electrons will be emitted.

These experimental observations did not support the classical wave theory at all. They completely supported Einstein's photon theory.

Equation



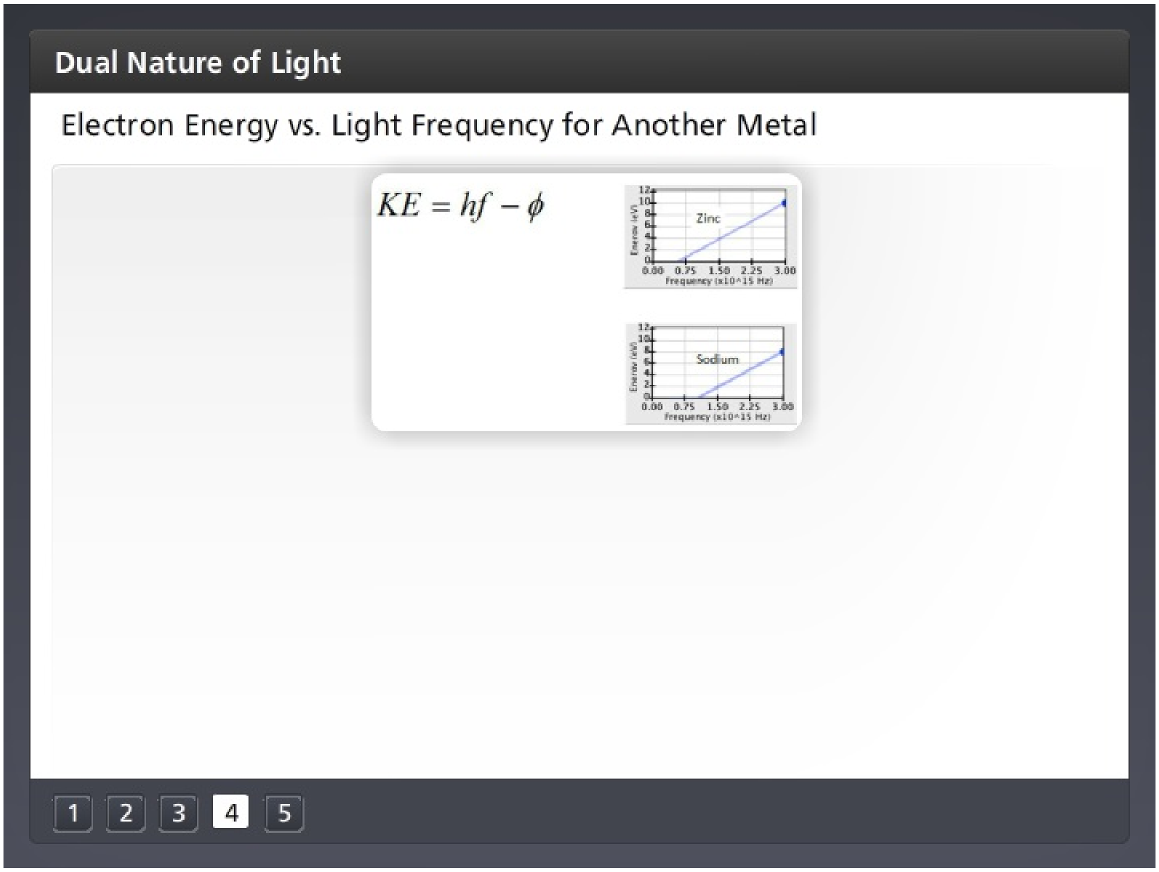
The equation that describes the photoelectric effect is based on conservation of energy.

KE stands for the kinetic energy of the electron, h f is the energy of the photon, and phi is the amount of energy it takes to remove the electron from the atom that is also called the work function. The work function depends on the type of metal, every metal has its own work function.

This equation says that the energy the electron has when it is emitted is equal to the energy of the photon minus the energy it takes to remove the electron.

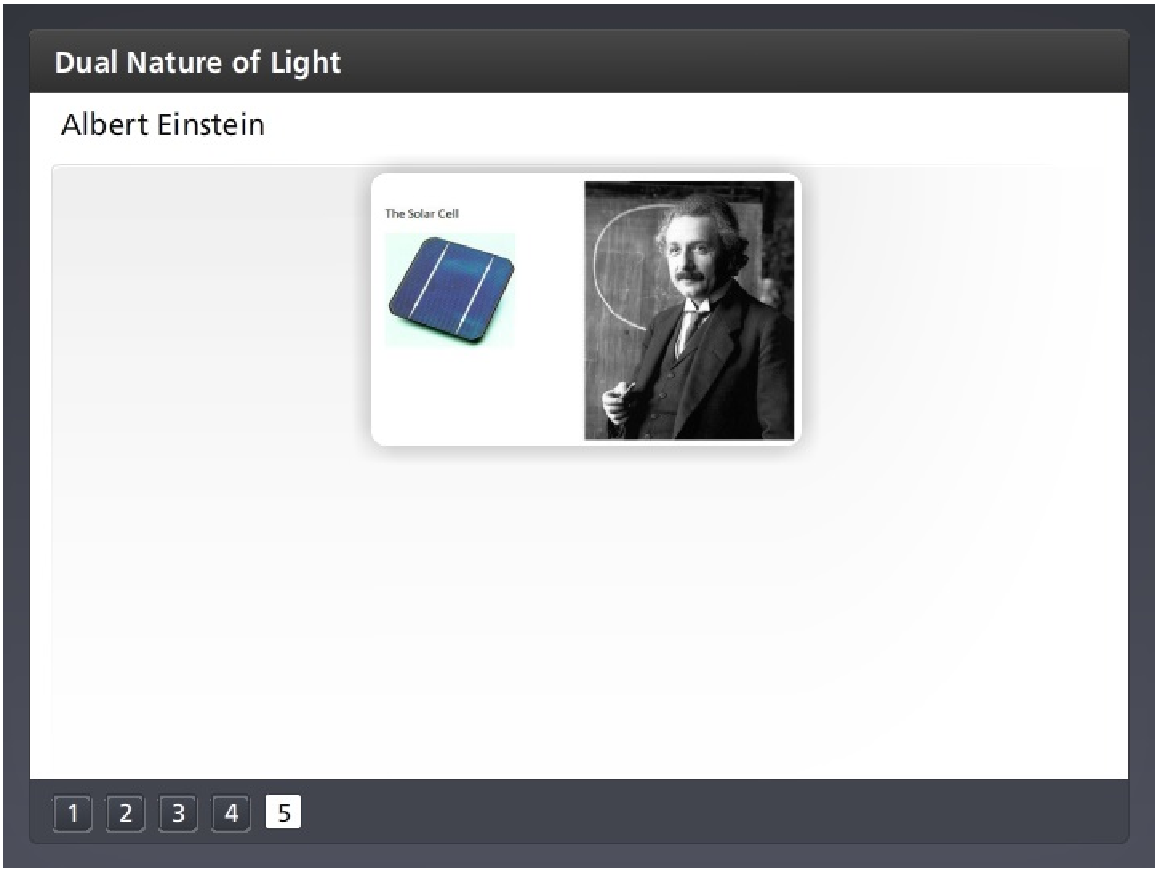
If we graph kinetic energy versus frequency, we get a linear function. We can see how the photoelectric effect equation compares to the slope-intercept form of the equation of a line. The slope of the line is h, Planck's constant. The x-intercept is the threshold frequency for electron emission. The y-intercept is the work function, or the amount of energy it takes to remove an electron from an atom. Since kinetic energy cannot be negative, we do not see this y-intercept in the actual data. However, we could extend the graph to the y-axis and see that the y-intercept would be negative.

Electron Energy vs. Light Frequency for Another Metal



If we compare other metals to the Sodium in our example, how would the graph be different? Let's look at the graph for Zinc. You will notice that the lines are parallel, they all have the same slope. Note that the slope is a physical constant, h, so it does not change when the metal is changed. The x-intercepts are different because each metal has a different threshold frequency. The work function will be different, so the graph will shift vertically, either up or down, depending on the value of the work function. The graph is shifted vertically downward. The lower graph is for Sodium.

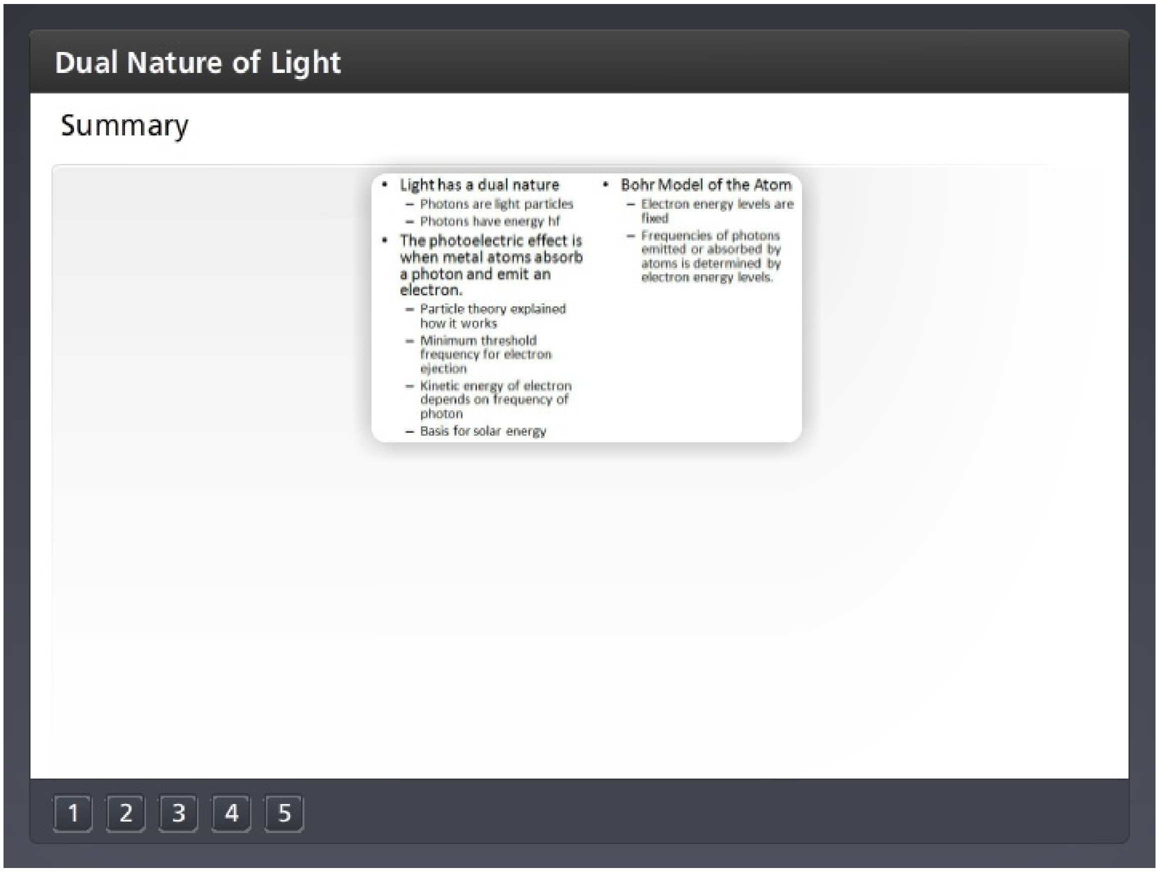
Albert Einstein



Einstein won the Nobel prize in 1921 for this work that explained the photoelectric effect. 1905 was called Einstein's "Miracle Year" because he published several important papers in that year. This accomplishment sets Einstein apart as one of the greatest physicists of all time. The special theory of relativity, the photon theory of light, a proof that atoms exist, and his famous E equals M C squared equation were all accomplished by Einstein in 1905. We will discuss some of Einstein's other work later in this module.

Uses for Einstein's photoelectric effect are still being developed by engineers today. The science of photovoltaics is built around using light to generate electricity. The photoelectric effect is the basic principle behind the solar cell.

Summary



In summary, in this topic you learned about the wave and particle nature of light, called its dual nature. Light particles are called photons and they have an energy equal to the product of Planck's constant and frequency. The photoelectric effect is when a metal atom absorbs a photon and emits an electron. The details of how the photoelectric effect works can only be explained by the particle theory of light. In particular, the fact that there was a threshold frequency below which no electrons would be ejected and the fact that the kinetic energy of the emitted electrons was dependent on the frequency of the photon were only explainable by particle theory.