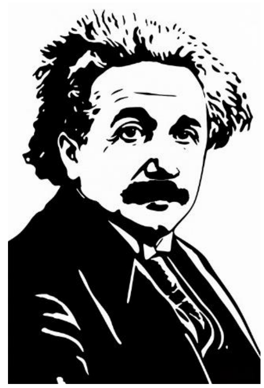
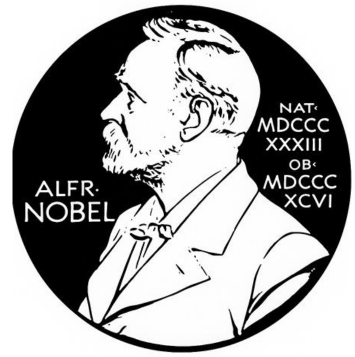
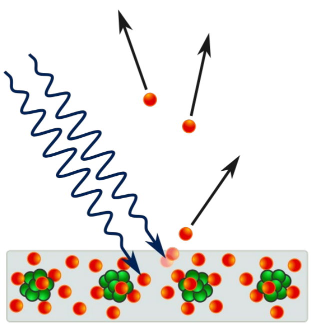
1-1: PhET Photoelectric Effect

Link: https://phet.colorado.edu/en/simulations/photoelectric





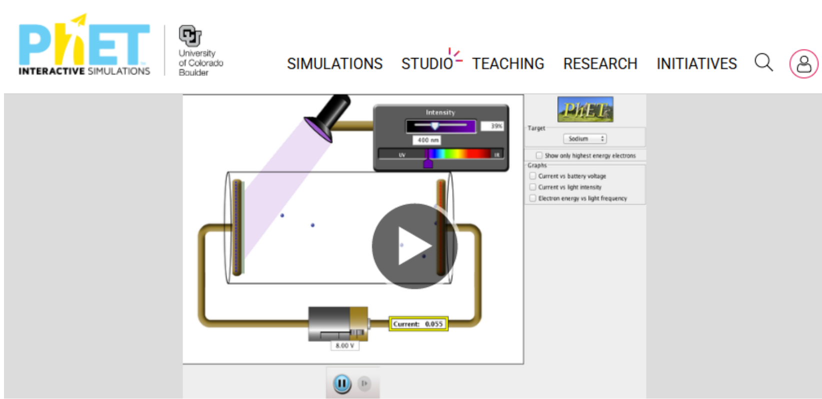
In 1921, Albert Einstein won the Nobel Prize in Physics for his work on the photoelectric effect. That work was part of his "miracle year" in 1905, during which he demonstrated that the photoelectric effect implies that light acts like particles, which were later named photons. The photoelectric effect is relatively simple—shine light on a metal in a vacuum, and it will emit electrons, which can be counted by collecting them on a metal plate and measuring the current flow. The interesting things are how this behavior changes as we change the frequency and intensity of the light, and how the current varies with the voltage between the metal surface and the collector plate.



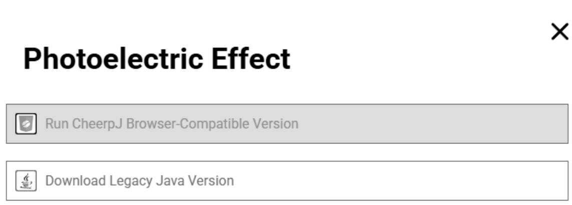
The PhET simulation, created by the University of Colorado Boulder, offers a visual and interactive way to explore the photoelectric effect shown through the schematic in the figure on the left. The schematic is not intended to be a realistic visualization, but you may find it helpful in formulating your mental model for how the experiment works. In a real photoelectric experiment, the process is entirely invisible. Light shines onto a metal surface inside a vacuum tube, and the only evidence of the photoemission is a measurable current detected by an ammeter connected to the collector plate. There are no visible particles, and there is no intuitive way to observe the photon-electron energy transfer. This disconnect means you may leave the simulation with a superficial understanding, thinking you've "seen" the effect when you've only seen a symbolic model. So be careful! We will explore the photoelectric effect in detail, as it is the entry toward understanding what a photon is and how we can detect it.

Starting the Simulation

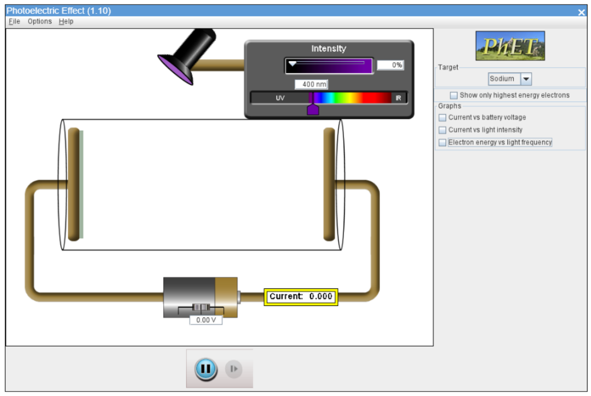
(1) Go to the link or search “PhET Photoelectric Effect” on Google and click the first link.



(2) Click on the play symbol on top of the simulation of the Photoelectric Effect.
A small window should appear as shown below, click on “Run CheerpJ Browser-Compatible Version.



(3) Example of starting screen for simulation shown below:



(4) Current settings. Locate where all of these are and check that you know how to manipulate all of these parameters. Once you confirm, you can change these and reset them to their original settings.

a. Intensity - 0%
b. Wavelength - 400 nm
c. Voltage - 0.00 V
d. Target - Sodium

(5) For now, let's have the graphs open. Click the 3 boxes next to the 3 graph options: 1) Current vs Battery Voltage, 2) Current vs Light Intensity, 3) Electron Energy vs Light Frequency

(6) To start, let's turn on photon visualization. In the top left corner, under the Options tab, click the box next to "Show Photons".

<u>You are now ready to explore!</u>

Photons emit electrons with a frequency threshold.

Why this is important: Unlike waves, where the amplitude determines the energy transferred, or a resonance condition where frequencies must match and drive to threshold, photons distribute energy to electrons proportional to their frequency. This is quantum, not classical behavior.

To do: Use the PheT simulations to demonstrate this behavior. You may need to adjust several different parameters to establish this (frequency and intensity—keep the voltage at 0).

Record your results: After verifying that this phenomenon holds, write a short paragraph explaining what was observed, how you arrived at your conclusion, why the photon frequency determines the electron kinetic energy at emission, and why this can lead to a particle picture for photons. Consider the effect of increasing the intensity of light for a particle picture.

Explore the kinetic energy of the emitted electrons.

Why this is important: Experimentally, we find a stopping voltage, which is the voltage that first prevents any electrons from reaching the collection plate. Describing how this relates to the kinetic energy is important.

To do: Use the PheT simulations to determine the stopping voltage for sodium (Na). You may find that visualizing the electrons helps you find the stopping voltage most easily.

Record your results: Describe what determines the kinetic energy of the emitted electron as the color of light is changed. Explain how the stopping voltage is used to measure the maximal kinetic energy of an emitted electron.

Photons are particles of light.

Why this is important: The photoelectric effect is interpreted as illustrating the particle nature of light. The response to changing frequency and changing intensity is thought only to be interpreted in a particle picture.

To do: Analyze different scenarios using the simulation to show what supports the particle interpretation of light.

Record your results: Write a short description of why one can interpret this experiment using a particle picture for light. Does this establish that light must be a particle?

Caution: PheT simulations illustrate simplified and unobservable phenomena

Why this is important: Individual electrons and photons are invisible. They are quantum objects, which have wave-particle duality and behave in complicated, non-intuitive ways. Nevertheless, PhET displays them as visible moving classical particles.

To do: Think about how a real experiment would work—what can be observed and what cannot. How does one make the conclusions about the particle nature of photons using just the limited information available in an actual experiment?

Record your results: While this can be useful for developing physical models for how the photoelectric effect works, one should always bear in mind that this is a simplified representation and not what will actually be observed. It can also lead to misconceptions, so be careful. Summarize what can be observed and what cannot in an actual experiment, and how it still supports a photon picture.

Want to learn more about photons?

Deep Dive: The photoelectric effect is often hailed as proof that photons are particles. Interestingly, a formal quantum treatment of the problem shows all of this behavior even if one uses a classical electric field for the photons. How is this possible? Quantum mechanics describes the transition of the electron from a bound state in the metal to a free state outside the metal, via a time-dependent transition process. Suppose this transition is driven by a field oscillating at the frequency corresponding to the energy difference between the bound state and the free state. In that case, the amplitude of the free state resonantly grows. But once the electron has a substantial amplitude in the free state, it moves away from the metal and is emitted. So, formally, one does not need the photon to actually describe the photoelectric effect. This takes nothing away from Einstein's work, as the conclusions all still hold. The true story is just more nuanced. In fact, we will describe in more detail how one verifies the existence of single photons and what they really are in a future worksheet.

Take-home message: The photoelectric effect has single-quantum sensitivity—one can send in a single photon with a high enough energy, and it will emit a single electron from the metal. This sensitivity allows the effect to be employed to detect single photons. It requires us to amplify the emitted single electron to many, so we can measure them using classical equipment. This device is called a photomultiplier tube, and it is critical for understanding the properties of photons.