

Photoelectric Effect

1st ed: Chapter 38

2nd ed: Chapter 39

Quick Quiz 82

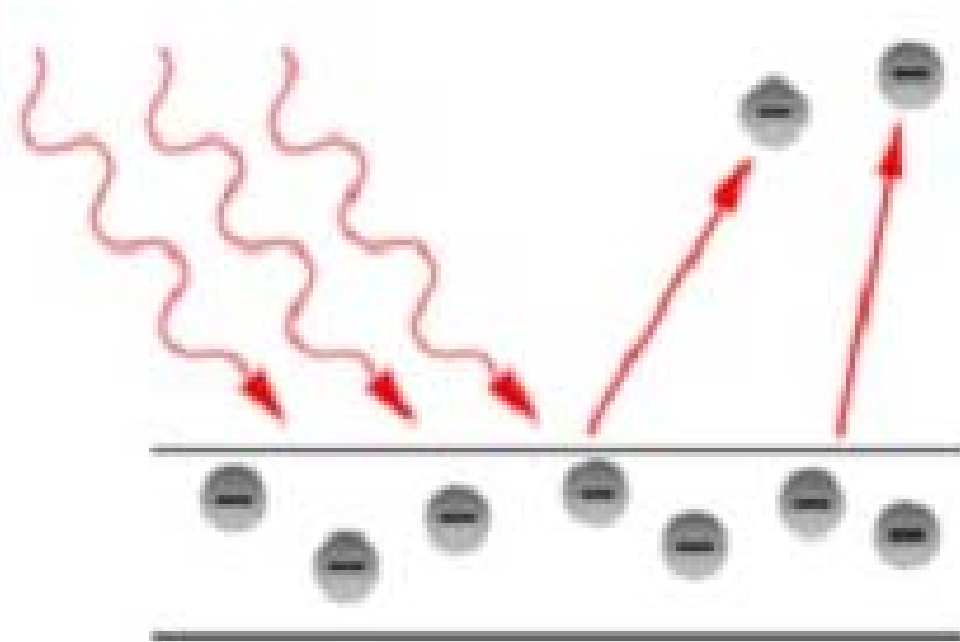
With respect to red light, blue light:

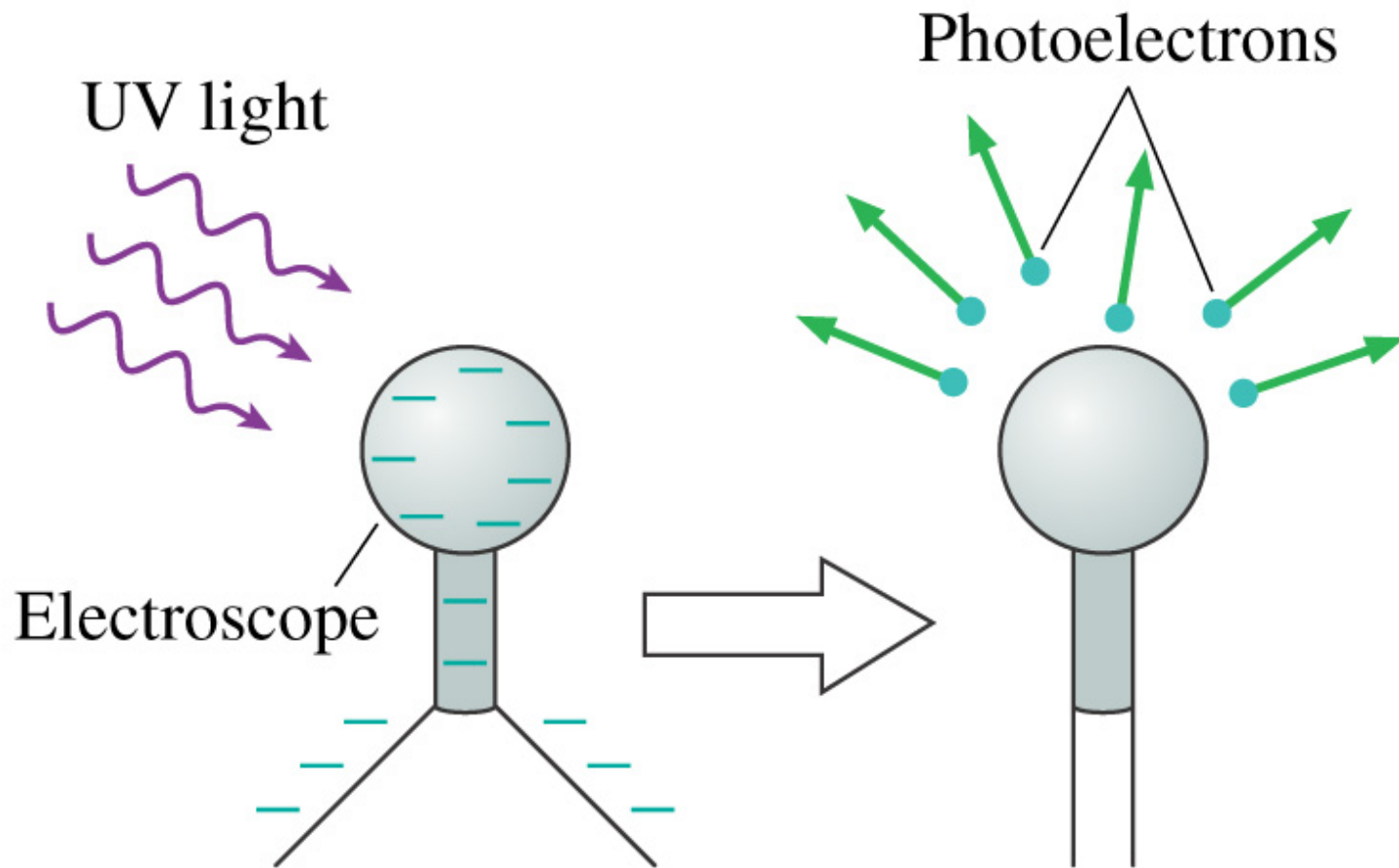
- A. carries more energy
- B. carries less energy
- C. carries the same amount of energy

The Photoelectric Effect

- Einstein received the Nobel Prize not for relativity, but for using Planck's hypothesis of the quantization of light to explain the *photoelectric effect*
- Photoelectric effect: light incident upon a polished metal surface will tend to cause the surface to emit electrons

- The basic idea of the photoelectric effect: shining light on a metal causes it to emit electrons

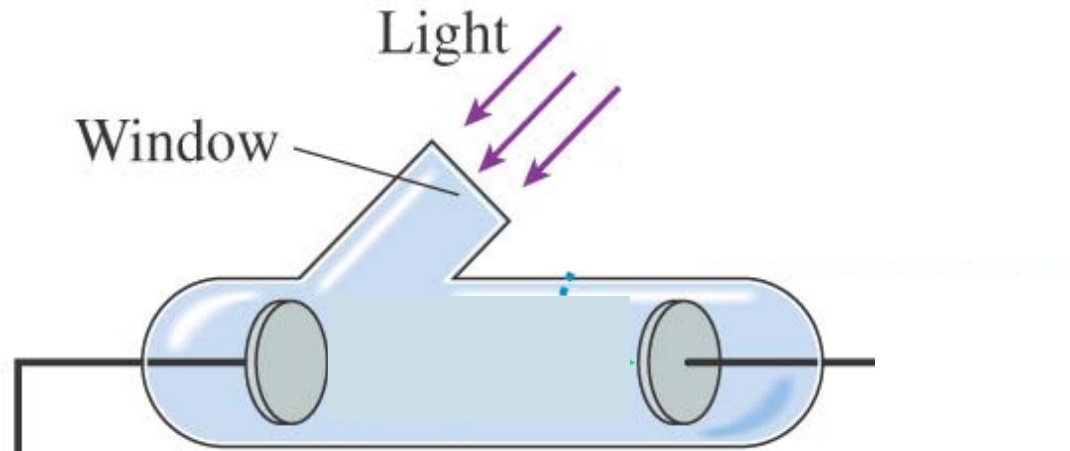




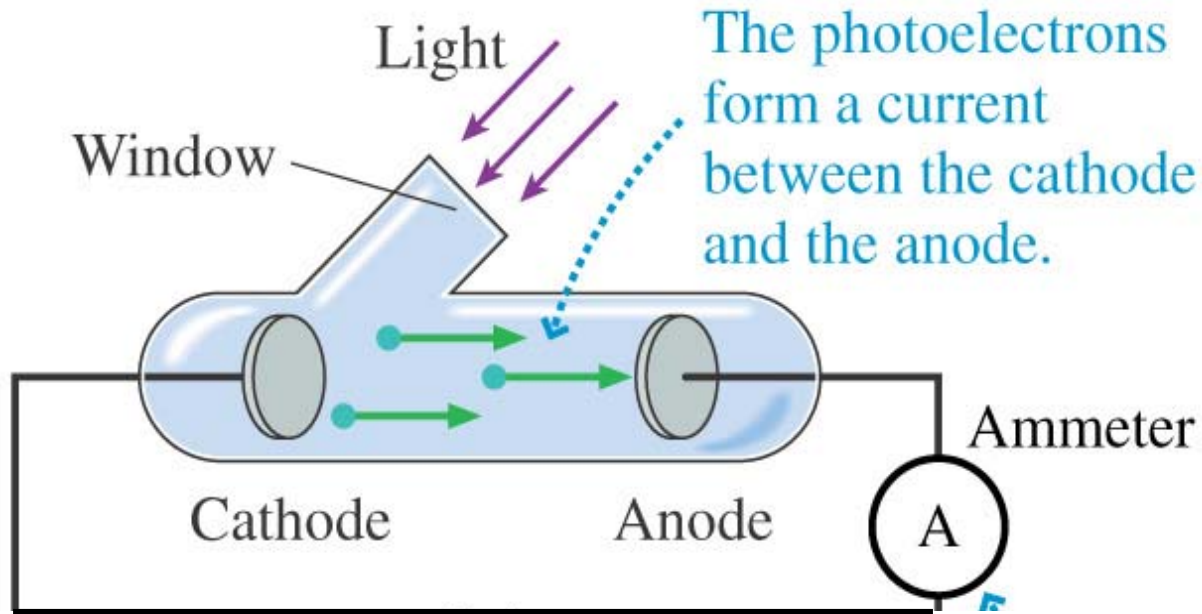
Ultraviolet light discharges a negatively charged electroscope by causing it to emit electrons.

- Classical physics can explain the fact that electrons are ejected
- Classical physics cannot explain some of the subtler details of the phenomenon

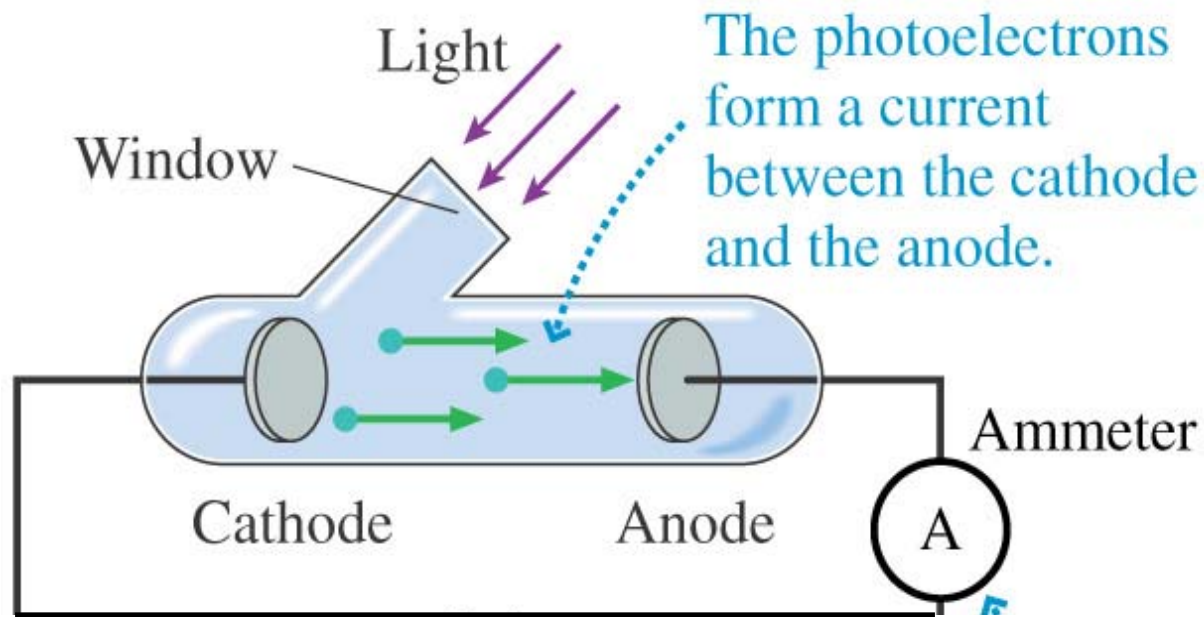
- Consider the following experiment:
 - put metal cathodes and anodes in a closed, evacuated tube
 - shine ultraviolet light on the cathode



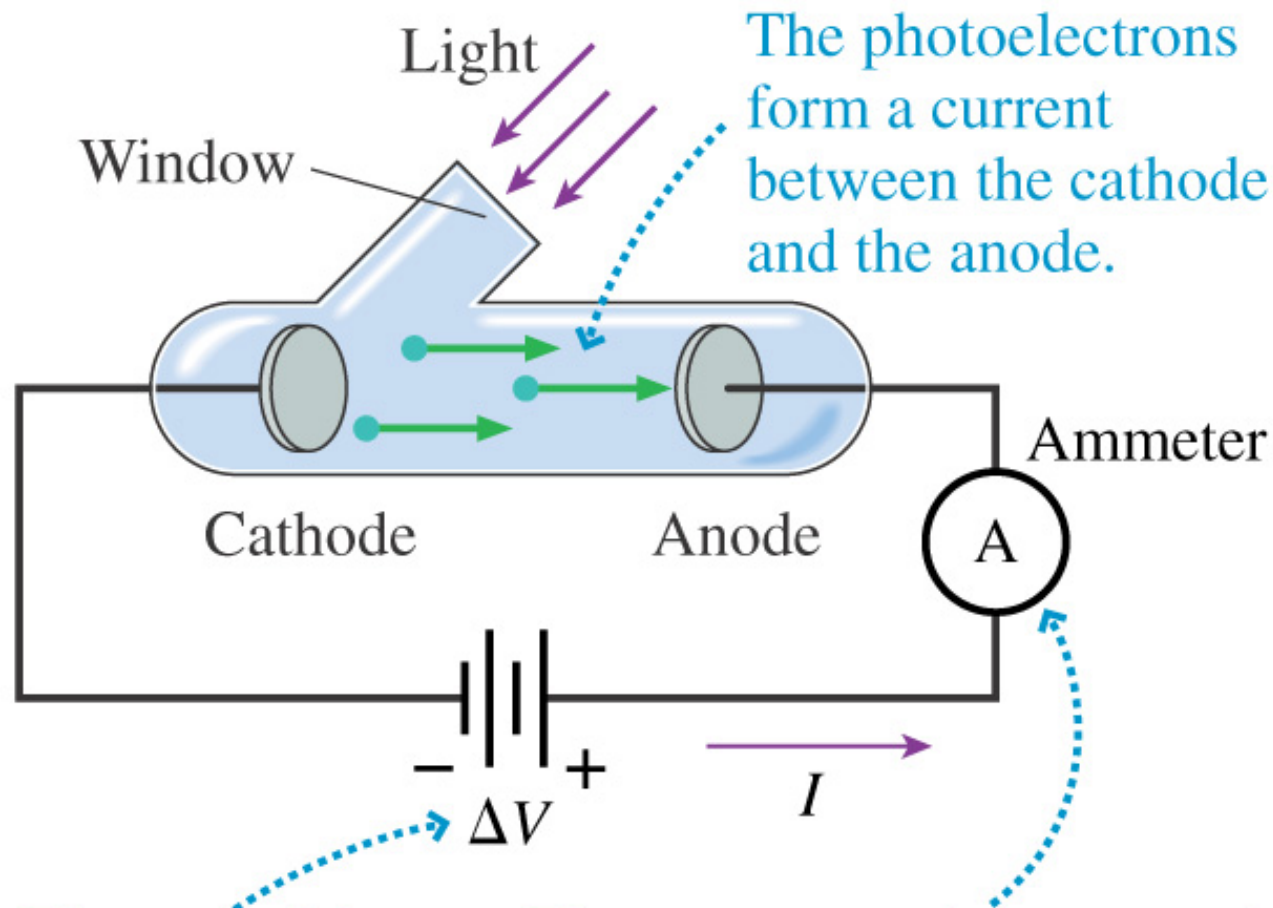
- hook the cathode and anode together with a wire
- measure the current through the wire using an ammeter



- Results:
 - when light is present, the ammeter registers a current
 - when no light, no current
- So light causes electrons to leap from the cathode to the anode



- Now hook a battery into the circuit so that you can create an electric potential difference, ΔV , between the cathode and anode
- Measure the current in the circuit while you vary:
 - the wavelength of the light, λ
 - the potential difference, ΔV



The photoelectrons form a current between the cathode and the anode.

The potential difference can be changed or reversed.

The current can be measured while the potential difference, the light frequency, and the light intensity are varied.

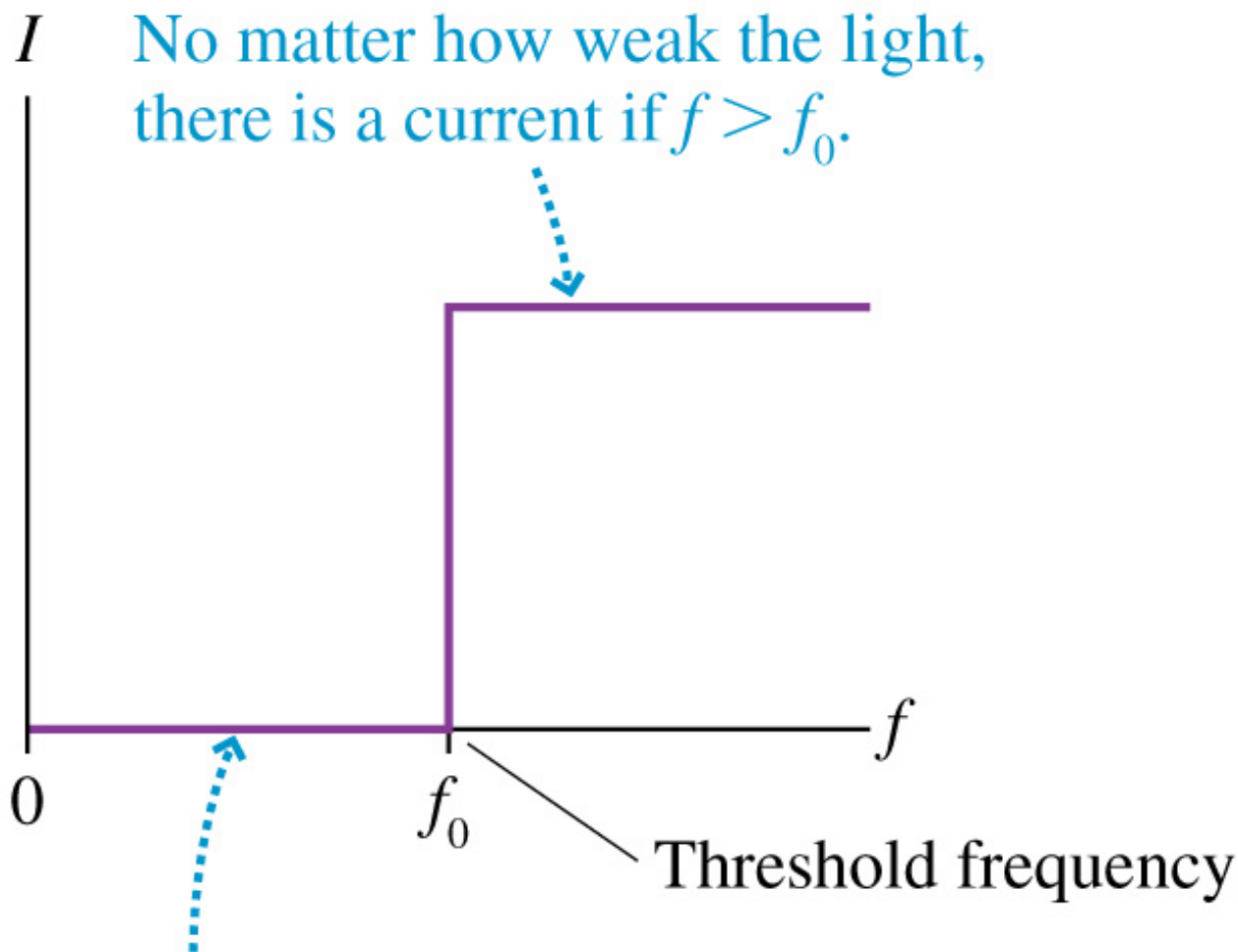
Quick Quiz 82b

If the cathode is made more positive than the anode, what direction is the electron accelerated?

- A. Towards the anode
- B. Towards the cathode
- C. Perpendicular to the surface of the anode

- **Results:**

- 1. The current is proportional to the light intensity**
- 2. The current appears instantly, as soon as the light is turned on (<1 ns)**
- 3. Electrons are emitted only if the frequency of the light, ν , exceeds some threshold value, ν_0**
- 4. The value of ν_0 depends on what the cathode is made of**

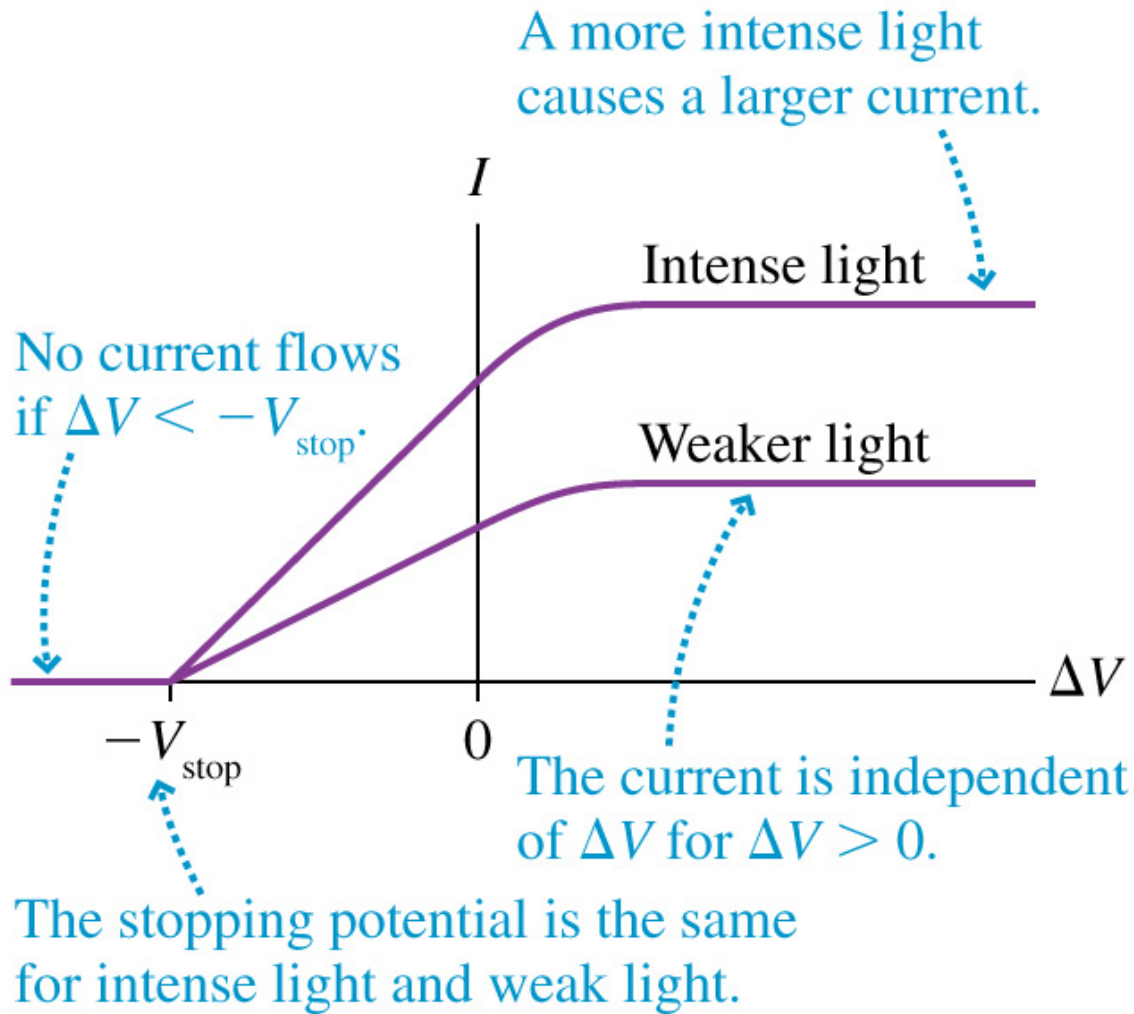


No matter how intense the light,
there is no current if $f < f_0$.

Quick Quiz 82c

If the frequency of light hitting the cathode is above the threshold frequency, the current:

- A. Increases with increasing light intensity
- B. Decreases with increasing light intensity
- C. Is independent of light intensity



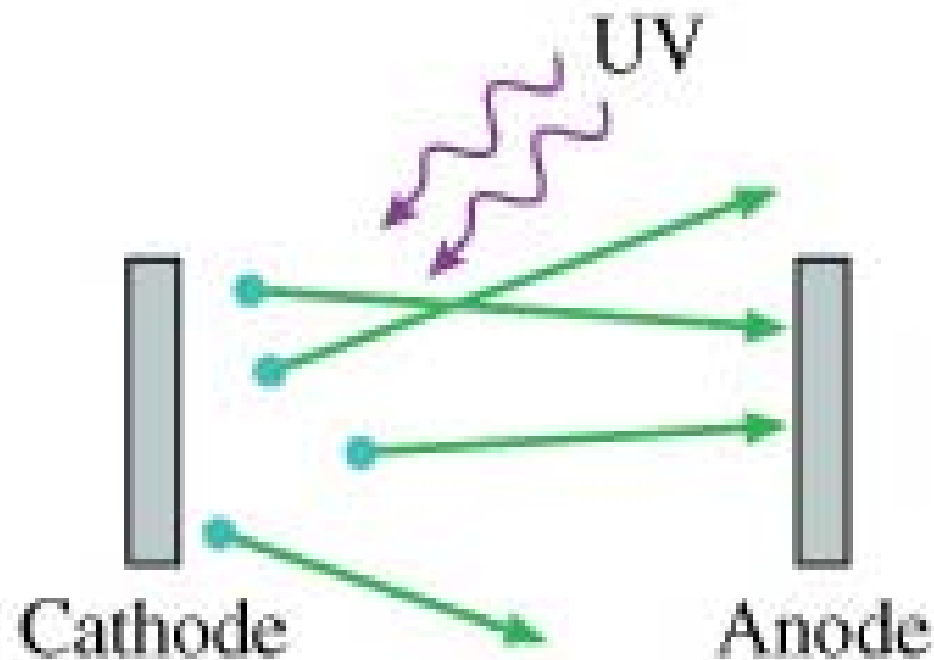
5. ***There is a stopping potential, $\Delta V = -V_{\text{stop}}$, below which the current is zero (no electrons emitted)***
6. ***The value of V_{stop} is independent of the intensity of the light.***

- Let's try to explain these results using classical physics (it will work, in part)
- The electrons are all bound to the metal— if they weren't they'd come flying out with no provocation
- Call the energy needed to extract an electron E_0 , the ***work function*** of the metal
- The work function is the minimum amount of work we have to do to overcome the attractive force of the metal

- Let E_{elec} be the energy of an electron in the metal
- If we do work E_o to get it out, the maximum kinetic energy it can have when it comes out is:

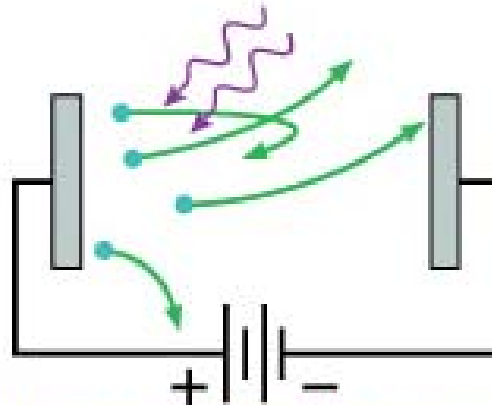
$$K_{max} = E_{elec} - E_o$$

- If we do nothing to affect the trajectory of this electron, it will head out in some random direction



$\Delta V = 0$: The photoelectrons leave the cathode in all directions. Only a few reach the anode.

- If we apply a potential $\Delta V < 0$ between the cathode and anode, the electron will be repulsed by the anode
 - remember: electrons are accelerated in the direction of **INCREASING** electric potential



$\Delta V < 0$: Biasing the anode negative repels the electrons. Only the very fastest make it to the anode.

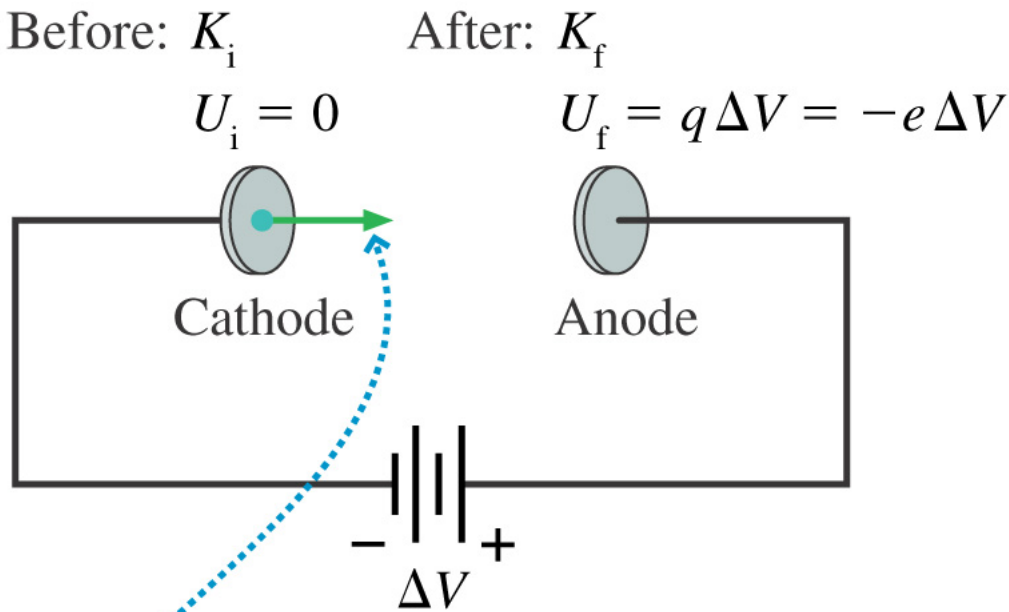
- As the electron moves through the potential, it will lose kinetic energy and gain potential energy:

$$K_i + U_i = K_f + U_f$$

$$K_i = K_f - e\Delta V$$

$$K_f = K_i + e\Delta V$$

$$\therefore \Delta V < 0 \Rightarrow K_f < K_i$$



Energy is transformed from kinetic to potential as an electron moves from cathode to anode.

- If we keep increasing the potential, eventually we will use up all the kinetic energy of the electron, so $K_f=0$ and:

$$K_f = K_i + e\Delta V$$

$$0 = K_i + e\Delta V$$

$$\Delta V = -\frac{K_i}{e}$$

- So the ΔV necessary to turn back the fastest electrons is:

$$\Delta V = -\frac{K_{\max}}{e}$$

- So the stopping potential of this metal is:

$$V_{stop} = -\Delta V = \frac{K_{max}}{e}$$

- This explains **result 5** (the existence of a stopping potential).
- We can also explain **result 1** by saying that, the more light we shine on the metal, the more energy we are providing, so the more electrons we should expect to see

- What about results 2,3,4, and 6?
 - 2: the current should not appear instantaneously – it should be possible to slowly pump electrons free
 - 3,4: why should the energy of the electron have anything to do with the frequency of the light?
 - 6: more intense light should give the electrons more kinetic energy, so the potential required to stop them should depend on the intensity of the light

Planck & Einstein to the Rescue

- Planck's little trick which Einstein took seriously: light comes in packets (photons), each of which has energy

$$E = nh\nu \text{ for } n = 0,1,2,3,\dots$$

- An electron absorbs a photon all at once, instantly, not in parts, and not over time

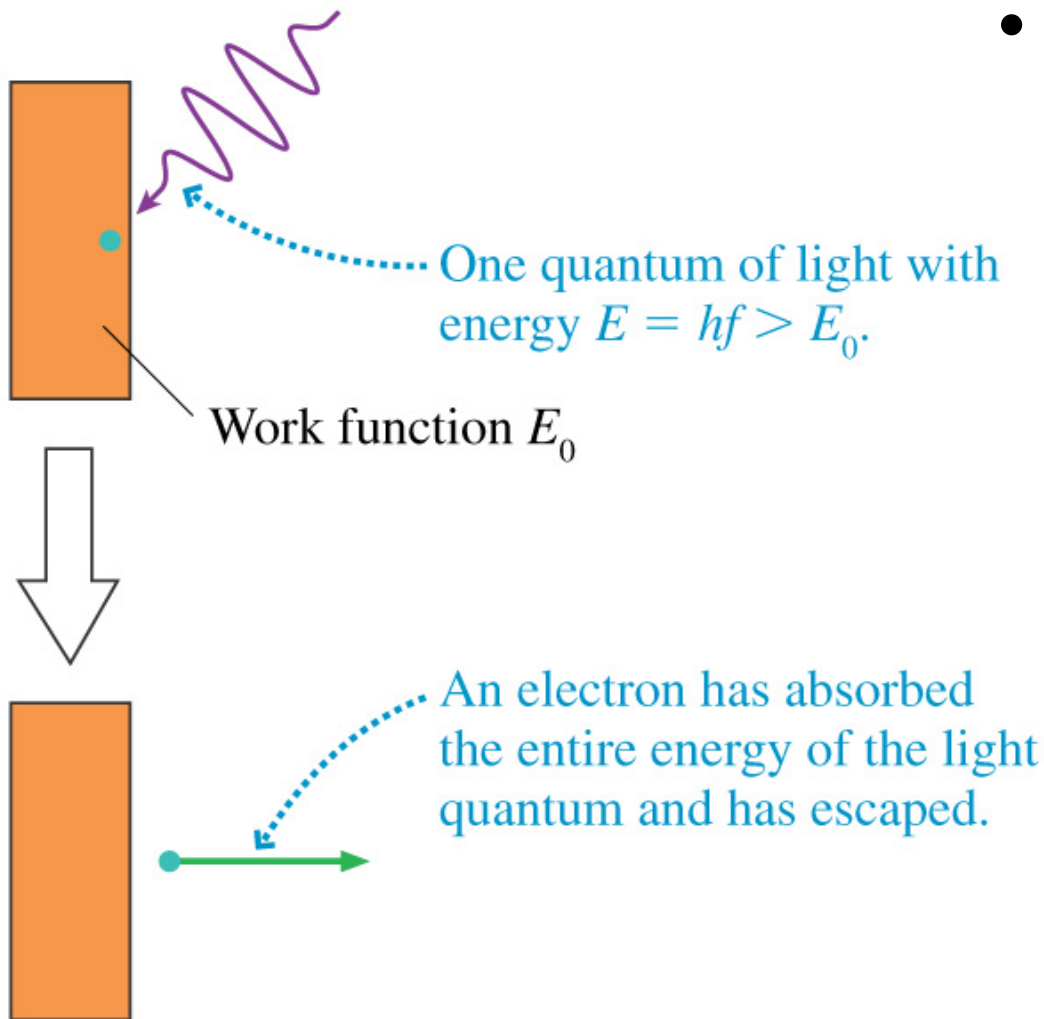
- This explains the existence of a threshold frequency (**result 3**): only photons with energy $>$ the work function will be able to eject electrons

$$h\nu_o = E_o$$

$$\nu_o = E_o / h$$

$\nu < \nu_o \Rightarrow$ no electrons ejected

$\nu > \nu_o \Rightarrow$ electrons must be ejected



- We can also explain **result 2**: any electron hit by a photon with frequency $\nu \geq \nu_0$ is immediately ejected, so the current starts flowing **as soon as the light hits the metal**

- If an electron absorbs a photon with $\nu < \nu_0$, it re-emits it without escaping from the metal (this happens very quickly)
- **Result 4:** The value of ν_0 depends on what material the cathode is made of because different materials will have different work functions

$$\nu_{o,steel} = E_{o,steel} / h$$

$$\nu_{o,gold} = E_{o,gold} / h$$

- In the photon model, more intense light simply contains more photons
- You can have intense light with a low frequency (e.g. intense radio waves), but it won't eject any electrons
- As long as the photons have enough energy (i.e. a high enough frequency), they will eject electrons, even if there are very few photons

- Light of a single frequency, ν , will produce a maximum kinetic energy of:

$$K_{\max} = E_{elec} - E_o$$

$$K_{\max} = h\nu - E_o$$

- This is ***independent*** of the intensity of the light, so the stopping potential is also independent of the intensity of the light (**result 6**)
- More intense light won't make the electrons faster, it will just eject more of them

Photoelectric Effect: Conclusions

- The photoelectric effect cannot be explained by purely classical physics
- The photon theory of light satisfactorily explains the effect

Quick Quiz 83

- Three metals, X, Y, and Z, have work functions E_X , E_Y , and E_Z , respectively. ***If all three metals are illuminated by light of the same frequency*** and if $E_X > E_Y > E_Z$, which metal has the largest stopping voltage?
 - A. X
 - B. Y
 - C. Z
 - D. need more information

Quick Quiz 84

- Two different monochromatic light sources, a yellow (580 nm) and a violet (425 nm), are used in a photoelectric experiment. If the work function of the metal is 4.11×10^{-19} J, which light source ejects electrons from the metal?
 - A. yellow
 - B. violet
 - C. neither
 - D. both