The Photoelectric Effect

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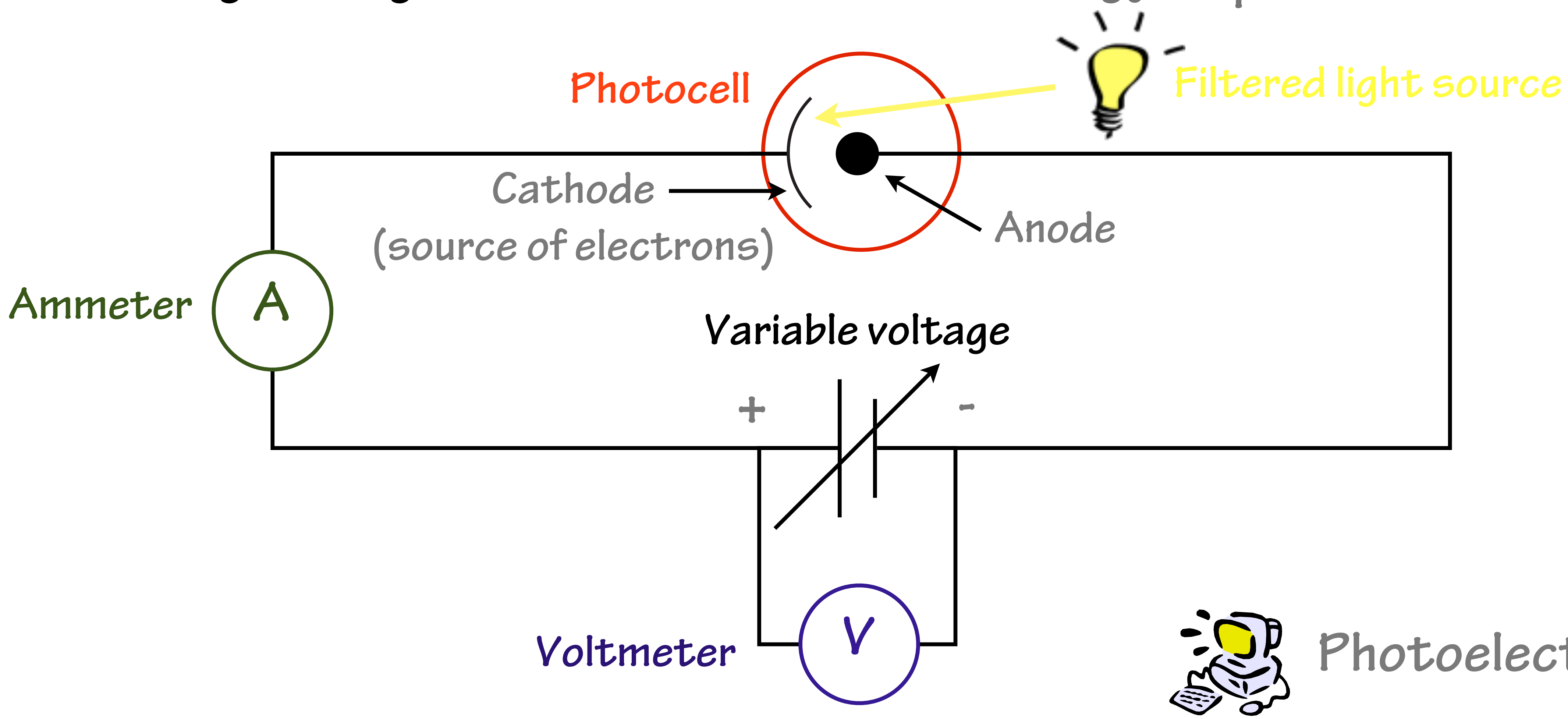
- Electron energy

Lenard's experiment

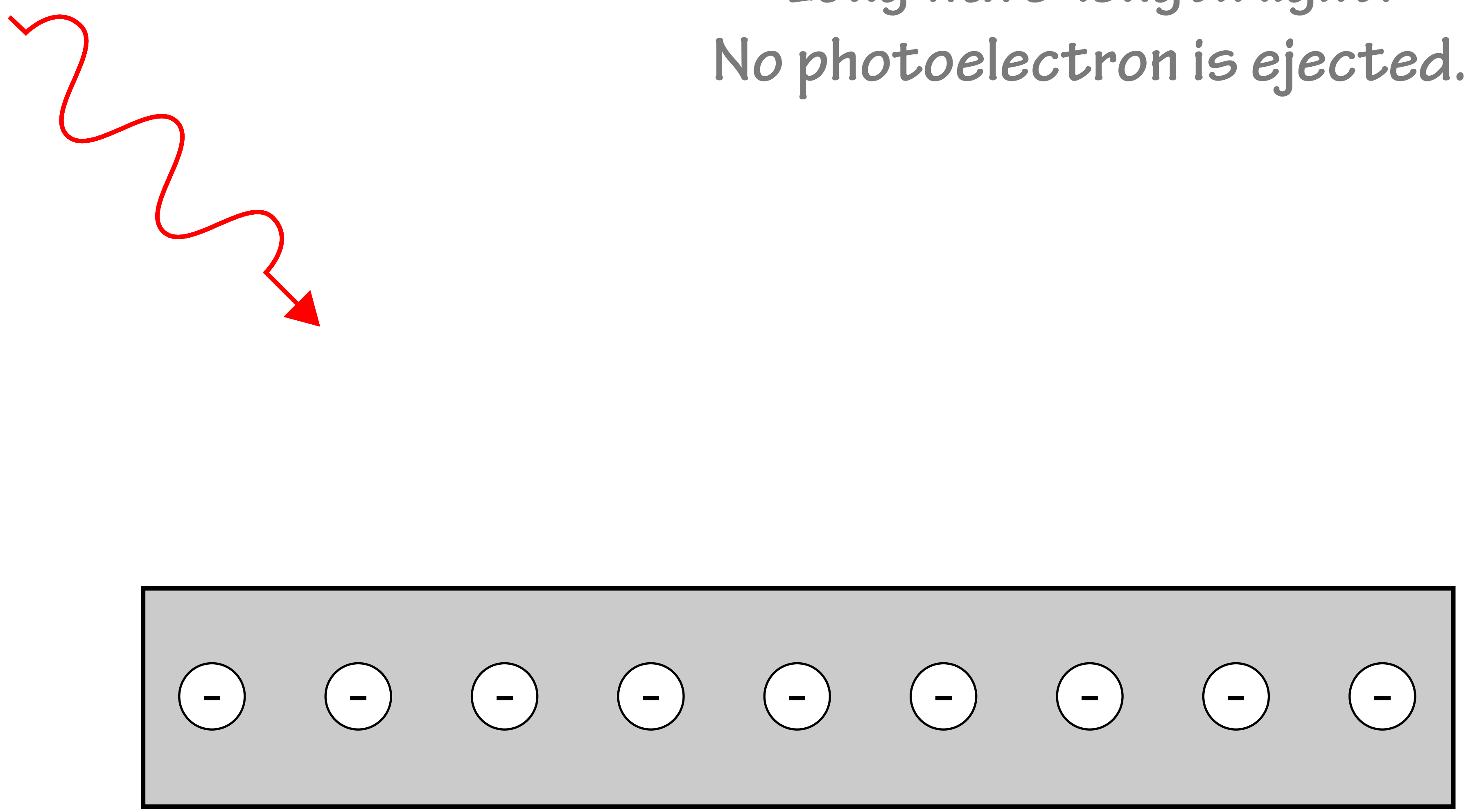
- Philipp Lenard measured the energy of photo electrons, ejected from a metal by the absorption of a photon.
- Current flow was measured, a retarding or accelerating voltage was also applied.
- **Current** is a measure of the number of photoelectrons.
- **Retarding voltage** is an indicator of the energy of photoelectrons.



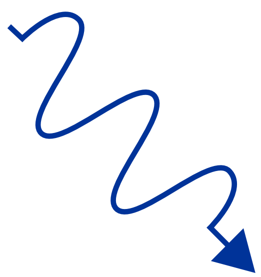
Photoelectric effect

Lenard's experiment

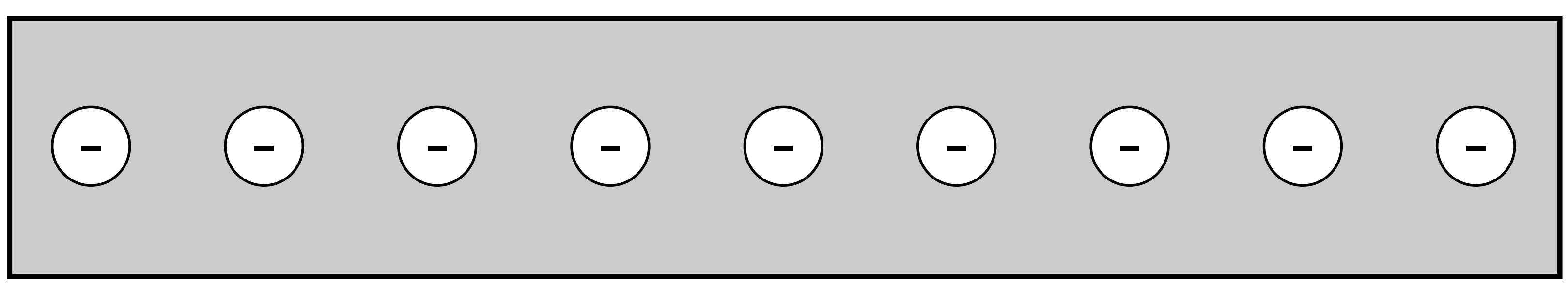
Long wave-length light.
No photoelectron is ejected.



Lenard's experiment

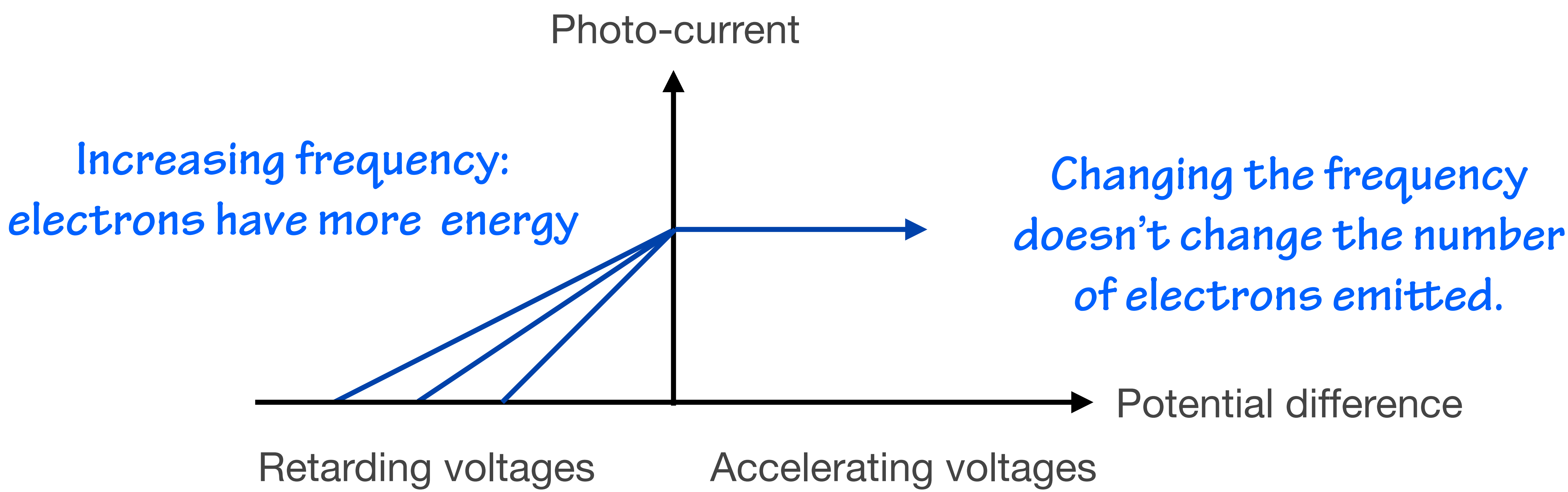


Short wave-length light.
A photoelectron is ejected.



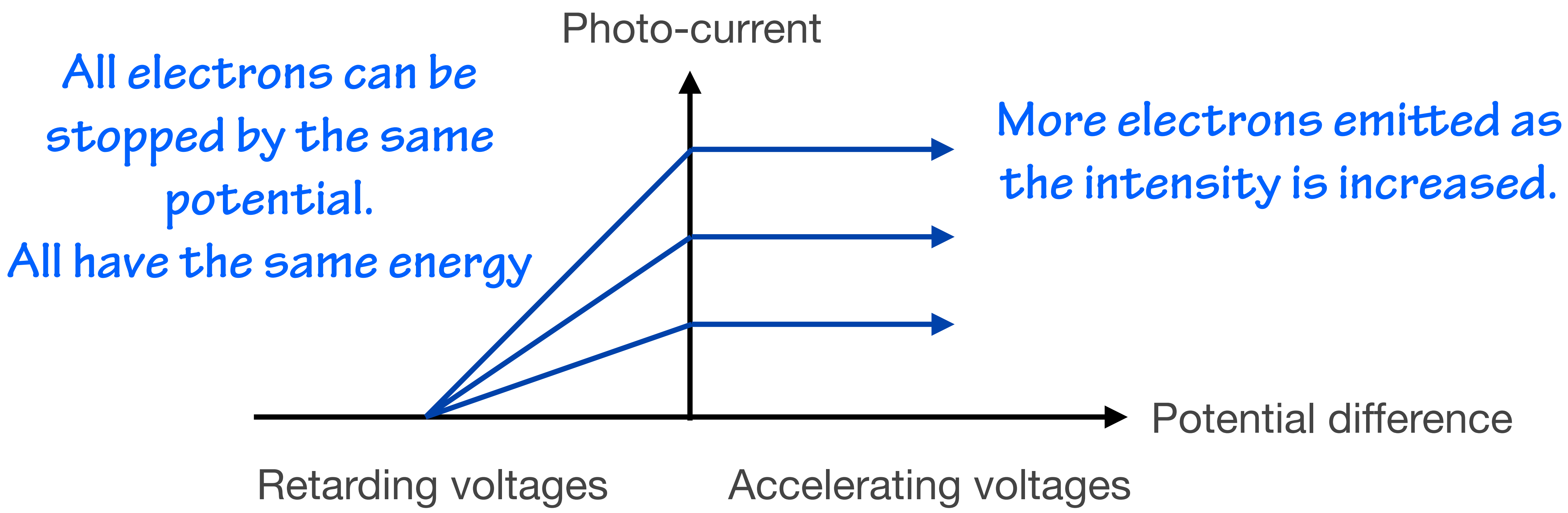
Lenard's experiment

- Changing frequency, intensity of light kept constant
- Increased frequency required a higher retarding voltage to stop photocurrent, but the current was the same.



Lenard's experiment

- Changing intensity, frequency of light kept constant.
- Increased intensity resulted in an increased photocurrent, but the same retarding voltage was required.



- Lenard's experiment caused problems for the wave model of light.
- Wave energy varies with intensity.
- So increased intensity (not wavelength) should have caused an increase in photon energy.

The photon model

- Electromagnetic radiation is a stream of particles (photons) that travel as a wave.
- Each photon carries a defined amount of energy ($E = hf$)
- h is Planck's constant $h = 6.63 \times 10^{-34}$ J s
- *eg.* violet light 400nm, each photon carries:

$$E = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34} Js)(3 \times 10^{8} m/s)}{400 \times 10^{-9} m}$$

$$= 5 \times 10^{-19} J$$

Light as photons

- A higher intensity of energy means that more particles are being transmitted in a time period.
- If the energy intensity is known, then the photon intensity can be calculated.
- eg. a 1mW laser of 400nm light:

$$P = \frac{E}{t} = \frac{n_{photons} \times E_{photons}}{t}$$

$$n = \frac{1 \times 10^{-3} J/s}{5 \times 10^{-19} J/photon}$$

$$= 2 \times 10^{15} \, photons/second$$

Einstein's explanation of the photoelectric effect

- Electrons can be ejected from a solid by electromagnetic radiation.
- Photoelectrons carry an amount of **energy** dependent on the **frequency** of photons; not intensity.
- No intensity of too long wavelengths of radiation will cause an ejection.
- The radiation must carry sufficient **photon energy** to cause an ejection (eg throwing tennis balls to move a heavy object!)
- The kinetic energy of the ejected electron is the difference of photon energy & energy to remove electron.

Photon energy

Maximum kinetic energy of ejected electron

Work Function: minimum energy to remove an electron from the material

$$E_k(\text{max}) = hf - W$$

Planck's constant
$= 6.63 \times 10^{-34}$ Js
$= 4.14 \times 10^{-15}$ eVs

Threshold frequency:

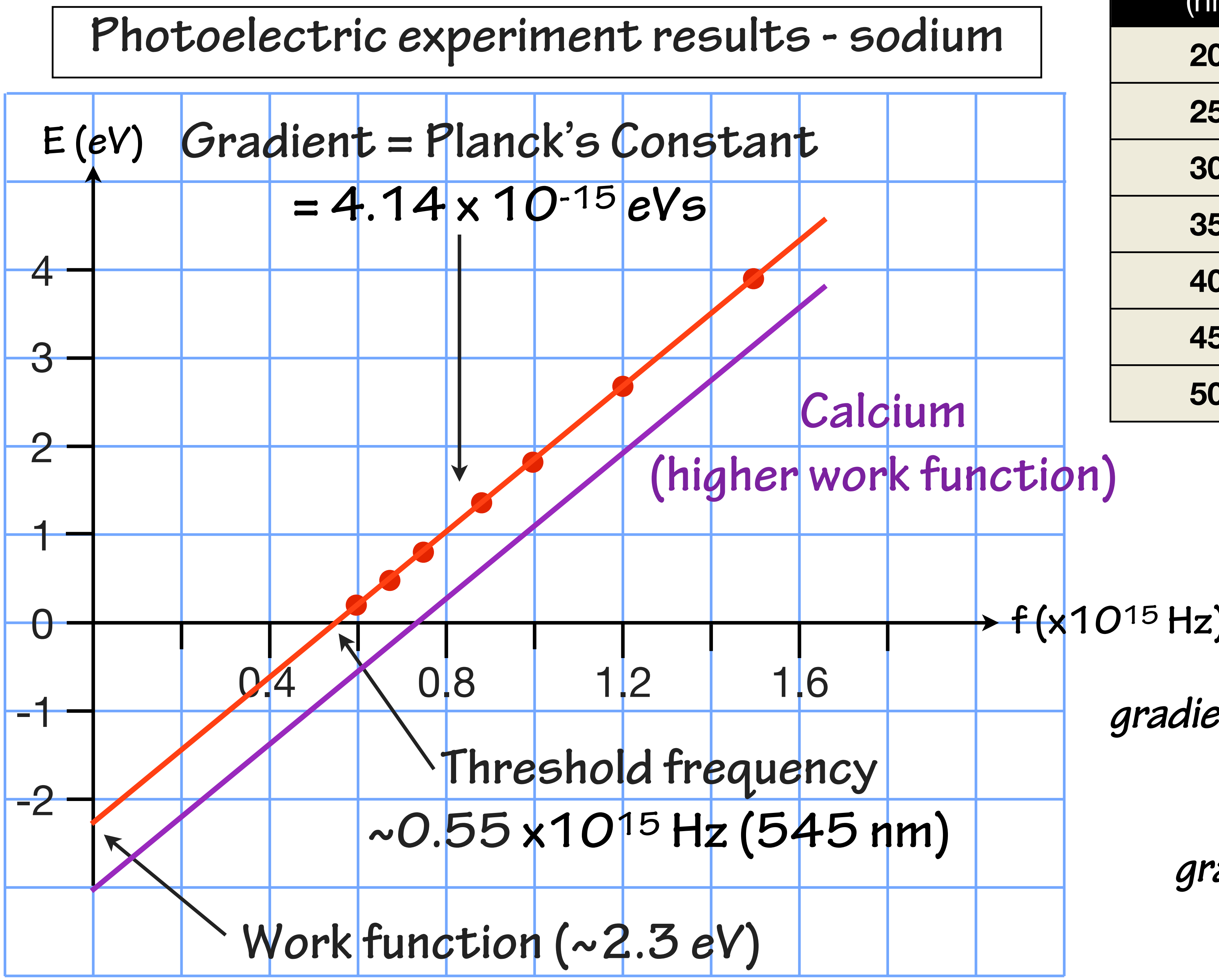
$$0 = hf - W$$

$$f_0 = \frac{W}{h}$$

Electron volts

- Recall that 1 *eV* is the amount of potential energy given to an electron ($Q=1.6\times10^{-19}$C) when moving through a potential difference of 1 volt (*V* = 1 J/C)
- **1 *eV* = 1.6×10^{-19} J**
- This is a more convenient unit of energy to describe photon energy.
- h = 6.63×10^{-34} J s = 4.13×10^{-15} *eVs*
- Work function for most metals is in the region of 2 - 6 *eV*.

Photon energy



Wavelength (nm)	Frequency ($\times 10^{15}$ Hz)	Stopping potential (V)
200	1.50	3.90
250	1.20	2.60
300	1.00	1.80
350	0.86	1.23
400	0.75	0.77
450	0.67	0.45
500	0.60	0.18

$$gradient = \frac{(3.90-0.18)\ eV}{(1.50-0.60) \times 10^{-15} Hz}$$

$$gradient \approx 4.1 \times 10^{-15} eVs$$

Photon energy

- eg. Calcium has a photoelectric work function of $W = 4.64 \times 10^{-19}$ J (2.9 eV) for an electron to be ejected.
- This corresponds to a minimum frequency and wavelength of:

$$f_0 = \frac{W}{h} = \frac{4.64 \times 10^{-19} J}{6.63 \times 10^{-34} Js} = 7.00 \times 10^{14} Hz$$

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^{8} m/s}{7.00 \times 10^{14} Hz} = 4.28 \times 10^{-7} m = 426 nm$$

Electron energy

- A photons of UV light (λ = 350 nm) are shone onto a calcium cathode with a work function of 2.9 eV
- The maximum kinetic energy (& speed) of the electrons can be found from the difference between photon energy & work function.

Photon energy:

$$E = \frac{hc}{\lambda} = \frac{(4.14\times10^{-15} Js)(3\times10^{8} m/s)}{350\times10^{-9} m} = 3.55\ eV$$

Electron energy:

$$\text{Maximum } E_k = (3.55 - 2.90)\ eV = 0.65\ eV$$

$$(0.65\ eV) \times (1.60\times10^{-19}\ J/eV) = 1.04\times10^{-19} J$$

Electron speed:

$$E_k = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2E_k}{m}}$$

$$v = \sqrt{\frac{2 \times 1.04\times10^{-19} J}{9.11\times10^{-31} kg}} = 4.78\times10^{5} m/s$$