

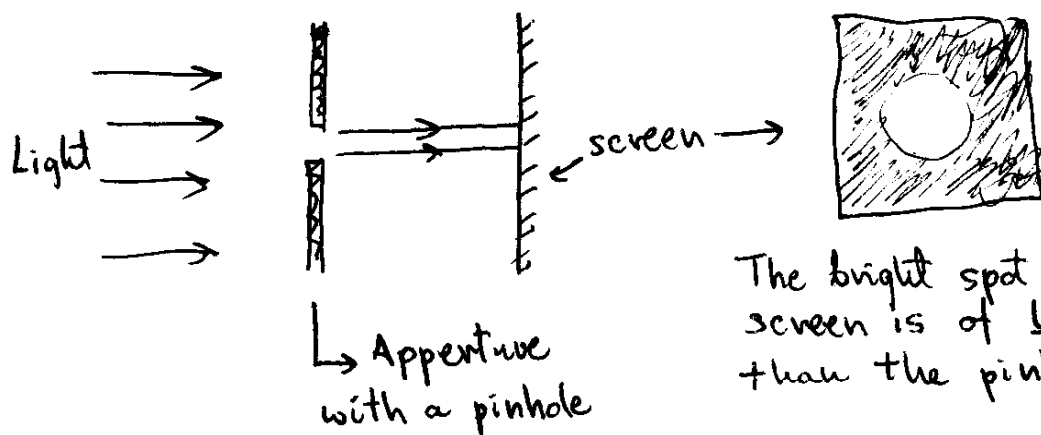
The particlelike properties of light

The nature of light has fascinated philosophers since the ancient times

But the first scientific theory of light started emerging only in the XVI century (Galileus).

In the XVII century, there were two competing theories:

- According to a Dutch scientist, ~~the~~ Christiaan HUYGENS, light consisted of waves. The main argument he used ~~was~~ for ~~the~~ supporting his theory was the effect of diffraction:

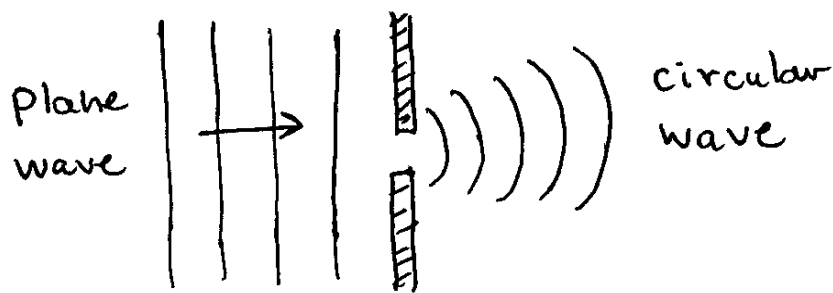


The bright spot on the screen is of larger size than the pinhole

Huyghens observed a similar behavior in the case of waves on water surface — that inspired his thinking.

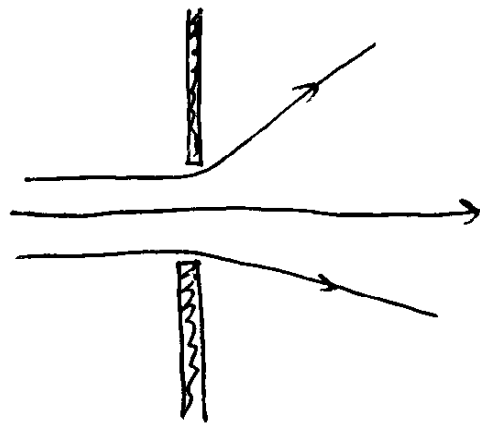
Waves on water surface, passing through a narrow opening:

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— According to NEWTON, light was a stream of tiny particles.

He explained diffraction as the effect of attraction forces acting on the light particles passing close to the opening edges, and deflecting them:

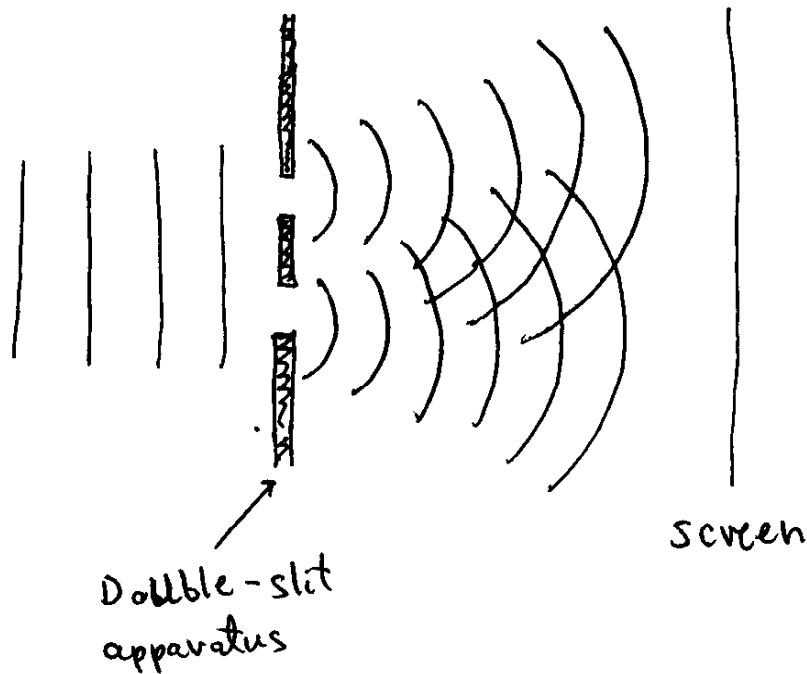


Diffraction
according
to Newton

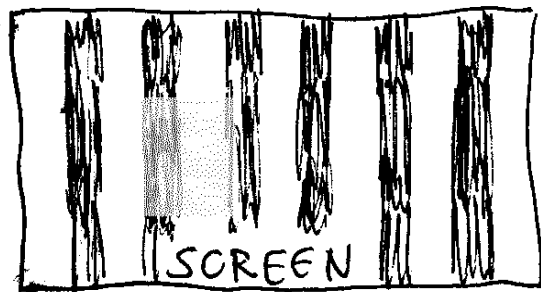
NEWTON was the TOP GURU for the XVII-th century physicists, so his theory WON.

The NEWTON'S theory (the "CORPUSCULAR THEORY OF LIGHT") became the official theory, and it was so until the year 1805, when the situation took a dramatic turn...

In 1805, Thomas YOUNG made his famous double-slit experiment - one of the most important experiments in the history of physics:



On the screen, Young observed a pattern of bright and dark stripes:



The ONLY possible explanation of YOUNG'S result was that the stripes occurred due to interference of light waves emerging from the slits

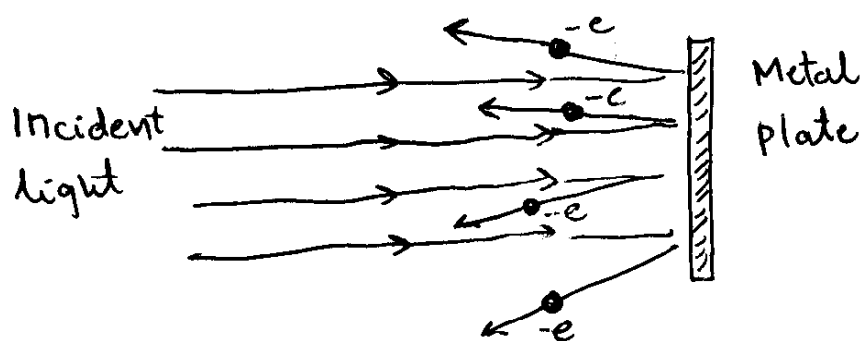
Young's experiment "killed" the Newton's theory!

Another support for the wave theory came from the famous Maxwell's Equations, which explained that light is an electromagnetic wave.

After that, the Newton's theory seemed to be completely dead...

But then another confusion happened...

In the 1880's, German physicist, Heinrich HERTZ - the one who performed crucial experiments confirming the Maxwell's theory - discovered the PHOTOELECTRIC EFFECT:



When a beam of light is incident on a metal surface, electrons are ejected from the metal!

The discovery of PHOTOELECTRIC EFFECT again led to a highly confusing situation. It was impossible to explain the effect on the grounds of the wave theory!

Predictions of the wave theory concerning the photoelectric effect - let's quote the book text:

1. *The maximum kinetic energy should be proportional to the intensity of the radiation.* As the brightness of the light source is increased, more energy is delivered to the surface (the electric field is greater) and the electrons should be released with greater kinetic energies. Equivalently, increasing the intensity of the light source increases the electric field $\mathbf{E}$ of the wave, which also increases the force $\mathbf{F} = -e\mathbf{E}$ on the electron and its kinetic energy when it eventually leaves the surface.
2. *The photoelectric effect should occur for light of any frequency or wavelength.* According to the wave theory, as long as the light is intense enough to release electrons, the photoelectric effect should occur no matter what the frequency or wavelength.
3. *The first electrons should be emitted in a time interval of the order of seconds after the radiation first strikes the surface.* In the wave theory, the energy of the wave is uniformly distributed over the wave front. If the electron absorbs energy directly from the wave, the amount of energy delivered to any electron is determined by how much radiant energy is incident on the surface area in which the electron is confined. Assuming this area is about the size of an atom, a rough calculation leads to an estimate that the time lag between turning on the light and observing the first photoelectrons should be of the order of seconds (see Example 3.2).

Experimental facts - again, let's quote the book text:

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1. *The maximum kinetic energy (determined from the stopping potential) is totally independent of the intensity of the light source.* Figure 3.11 shows a representation of the experimental results. Doubling the intensity of the source leaves the stopping potential unchanged, indicating no change in the kinetic energy of the electrons. This experimental result disagrees with the wave theory, which predicts that the maximum kinetic energy should depend on the intensity of the light.
 2. *The photoelectric effect does not occur at all if the frequency of the light source is below a certain value.* This value, which is characteristic of the kind of metal surface used in the experiment, is called the *cutoff frequency* ν_c . Above ν_c , any light source, no matter how weak, will cause the emission of photoelectrons; below ν_c , no light source, no matter how strong, will cause the emission of photoelectrons. This experimental result also disagrees with the predictions of the wave theory.
 3. *The first photoelectrons are emitted virtually instantaneously (within 10^{-9} s) after the light source is turned on.* The wave theory predicts a measurable time delay, so this result also disagrees with the wave theory.
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The explanation of all these confusing facts and views came from Einstein's famous 1905 work (for which he was awarded a Nobel Prize).

Einstein theory, in a way, was a "revival" of the Newton's concept.

According to Einstein, the energy of a light wave is not continuously distributed over the wavefront, but is concentrated in localized "bundles". Einstein called them "light quanta".

Now, we use the term "photons", but it was created some 20 years later.

The energy of an individual photon is:

$$E = h \nu \quad \text{where } h - \text{Planck's constant} \\ \nu - \text{light frequency.}$$

In Einstein's theory, the photon transfers its entire energy to an electron, and disappears.

The photon energy (electromagnetic) is converted into electron's kinetic energy.

Does it mean that

$$K_{\text{electron}} = h\nu ?$$

Not exactly! The electron has to use some of the energy it acquires to get out of the metal.

The energy needed to get out of the metal is ~~to~~ called the work function, and is denoted as ϕ (sometimes as W).

Therefore, the equation has the form:

$$K_{\text{electron}} = h\nu - \phi$$

Why such a strange name, "work function"?

Why "function"? Well, someone used such a term first, others adopted it, and... so it stayed.

I personally think it's not the most fortunate term - for instance, "exit work" would be better, perhaps. But since everybody uses this term, we have no other choice than to use it, too.

Why is energy needed to pull out an electron from a metal? ~~Well~~, Well, it's a longer story, and we will skip it. (66)

All I want you to know is:

- (a) A photon carries an energy $E_{\text{photon}} = h\nu$
(red light has lower frequency than blue light, therefore a photon of blue light carries more energy than a red light photon).
- (b) in photoelectric effect, all the energy carried by the photon is passed to an electron;
- (c) the electron has to use some part of the acquired energy to get out of the metal, and this energy is called the "work function" ϕ .
- (d) The remainder is the electron kinetic energy, so after leaving the metal, the electron has a kinetic energy equal:

$$K = h\nu - \phi$$

Here, we will show an animation

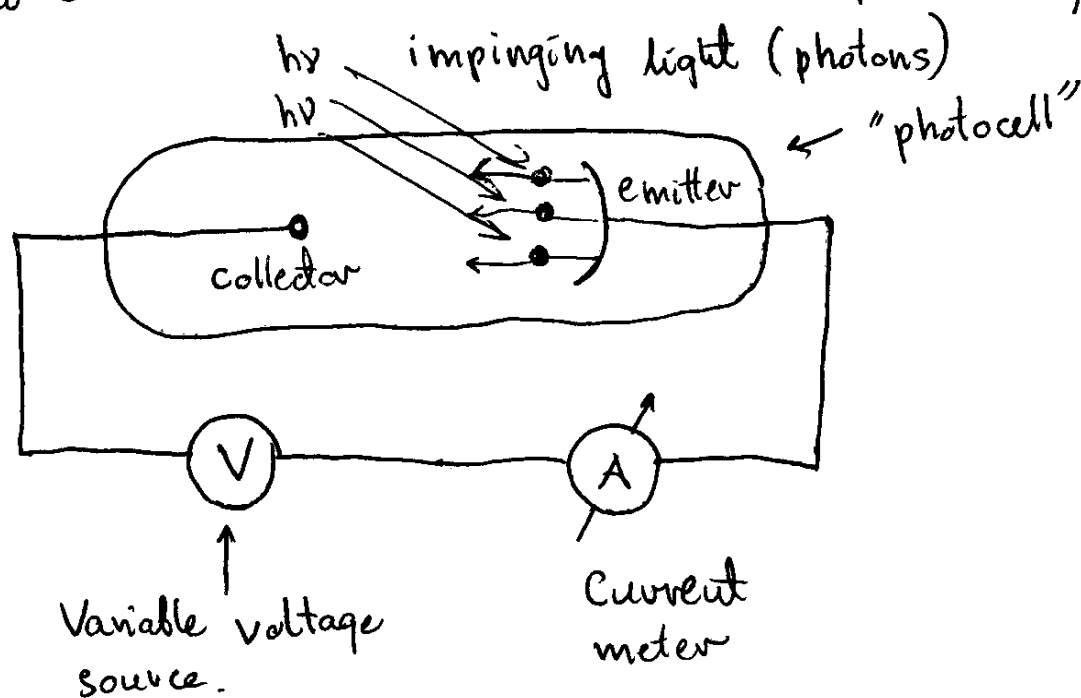
(67)

The work function is a material property its value is different for different metals.

But if we measure ϕ for different samples of the same metal, we always obtain the same value.

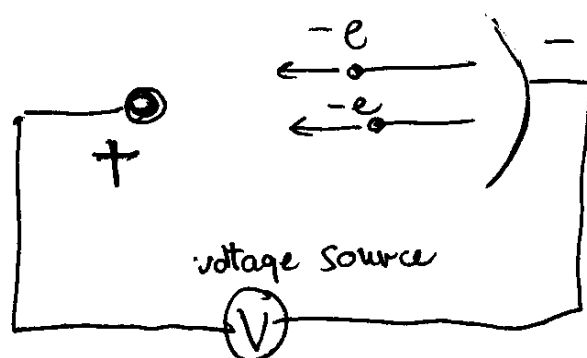
Investigating the photoelectric effect

How can we measure the work function ϕ ?

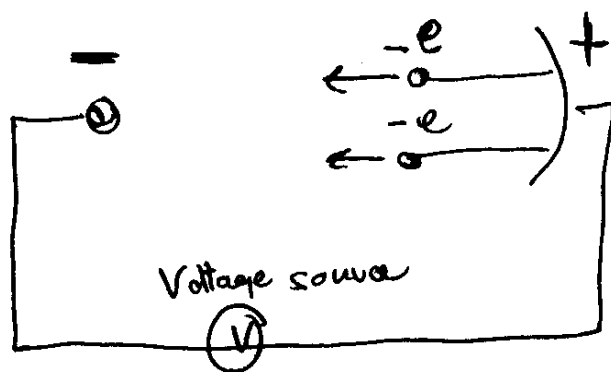


We bombard the emitter (metal) with photons of known frequency ν .

The ejected electrons fly toward the collector



If the collector is ~~is~~ positively polarized then the electrons are attracted, they will even gain energy - all electrons will be "collected"



If the ~~at~~ collector polarization is negative the electrons are repelled...

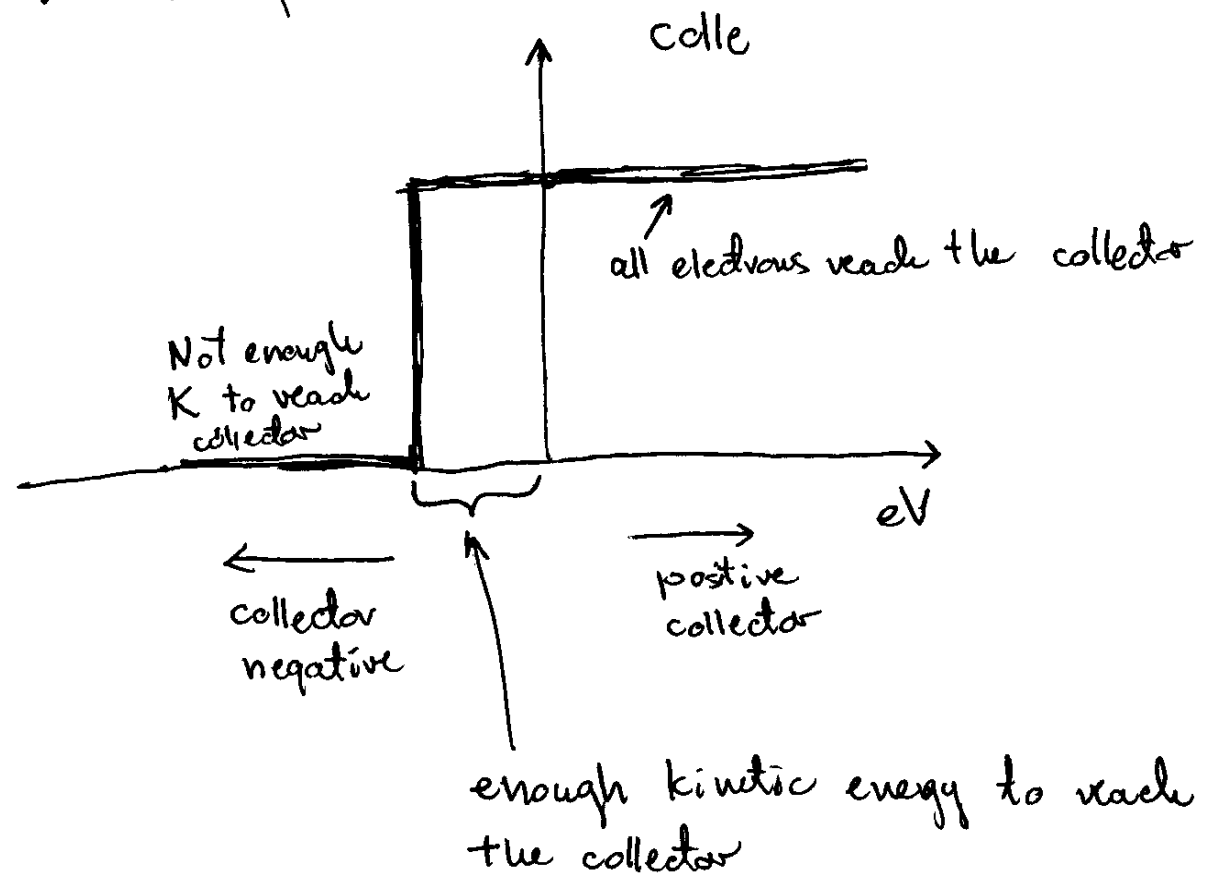
On the way from photocathode they lose energy $-e \cdot V$

Hence, in order to reach the photocathode, when the collector is negative, the kinetic energy of the electrons has to be larger than:

$$K_{\text{elect.}} > -eV$$

or $h\nu - \phi > -eV$

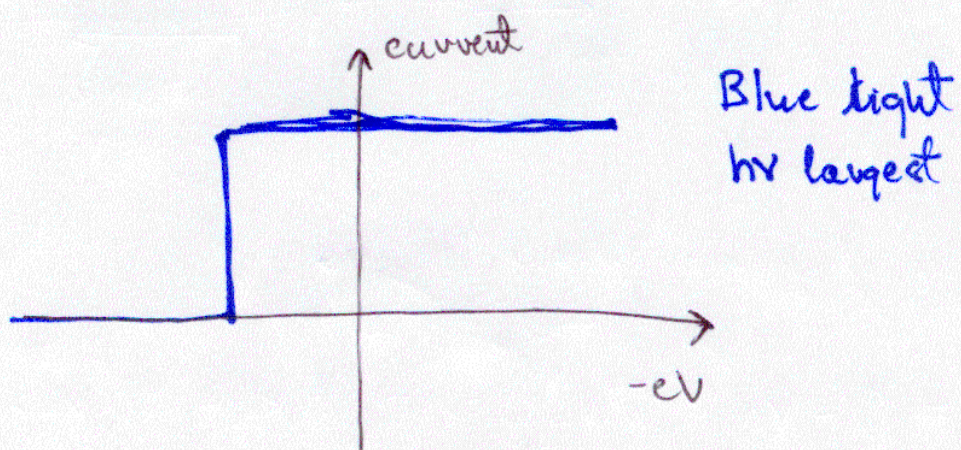
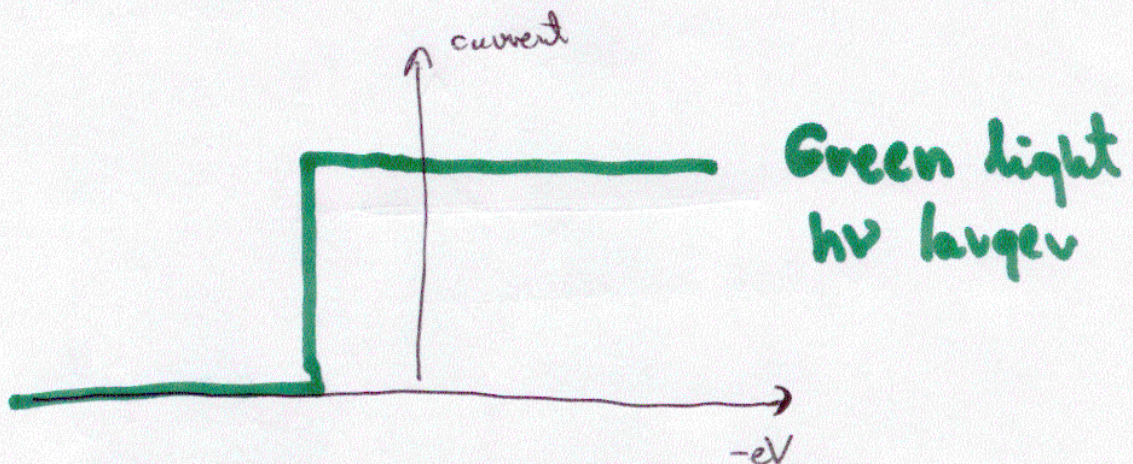
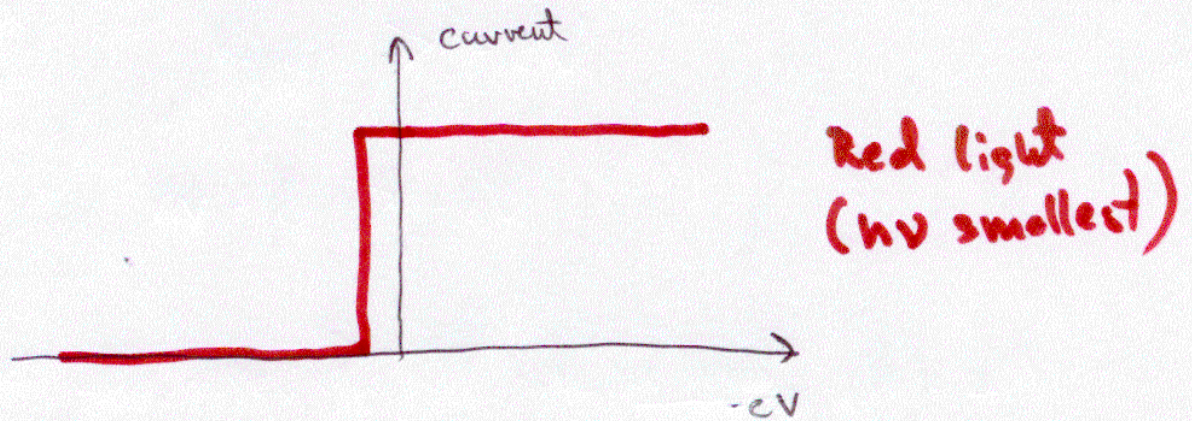
The characteristic of an ideal photocell is therefore:



The current falls to zero when $h\nu - \phi = -eV$

Note that: if $h\nu - \phi < 0$, or $h\nu < \phi$, (70)
the electrons cannot leave the metal.

if $h\nu > \phi$, the ideal characteristics look like:



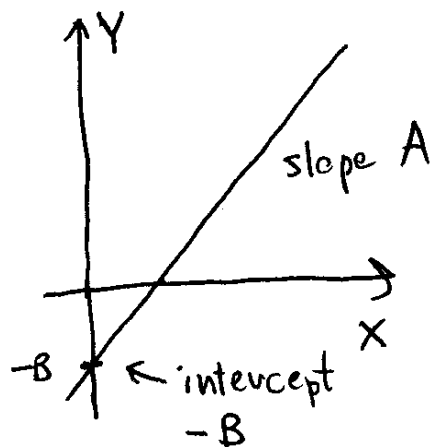
The "cut-off" voltage is: (or "stopping voltage")

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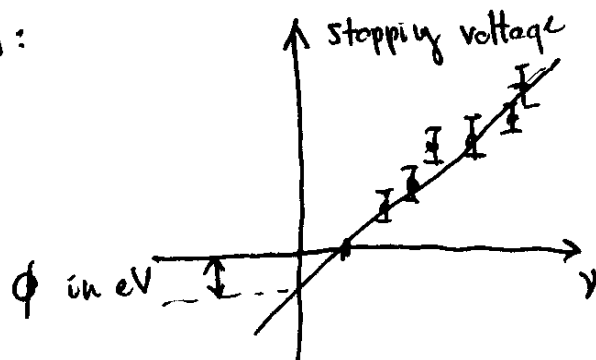
$$-eV = h\nu - \phi \quad \text{or} \quad |V| = \frac{h}{|e|} \nu - \frac{\phi}{|e|}$$

The frequency of lights of different colours is known from other measurements (λ is known from diffraction measurements, and $\nu = \frac{c}{\lambda}$).

So, the voltage versus ν is a function of the type: $Y = Ax - B$:



So, plotting the "stopping voltage" ~~for different frequencies~~ as a function of light frequency, we can find ϕ and h :



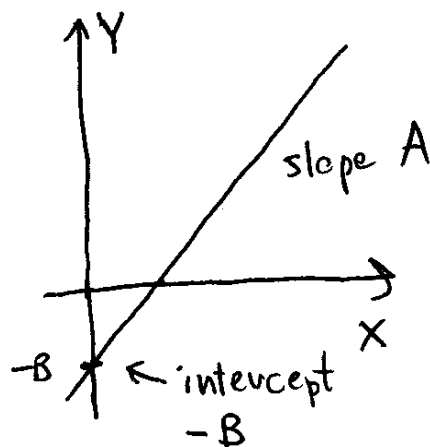
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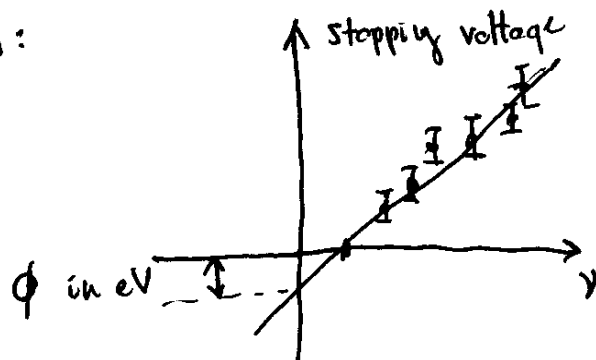
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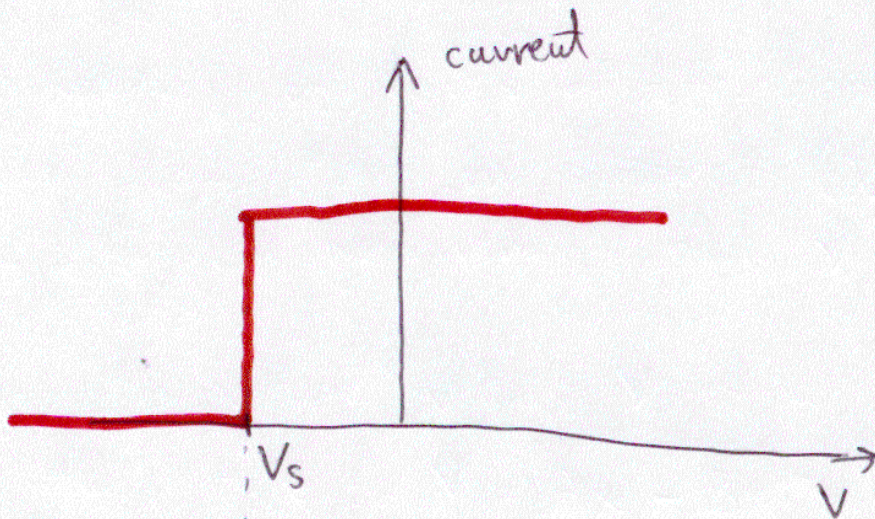
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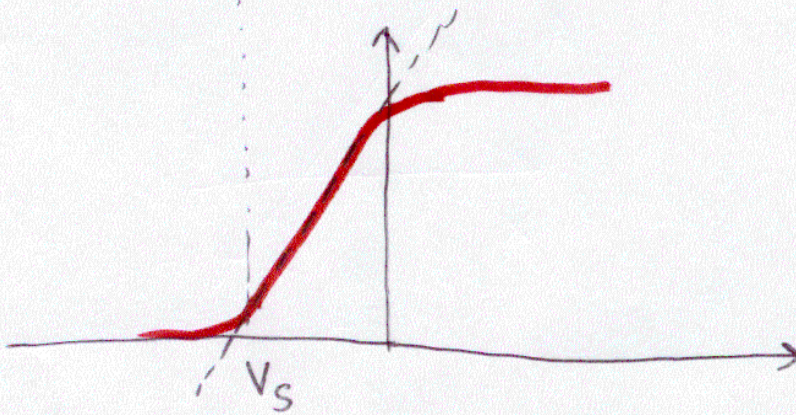
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However...

The real photocell characteristic is not step-like:



But:



Due to some additional processes inside the metal, there is a distribution of exit kinetic energies

V_s is rather the maximum kinetic energy observed.