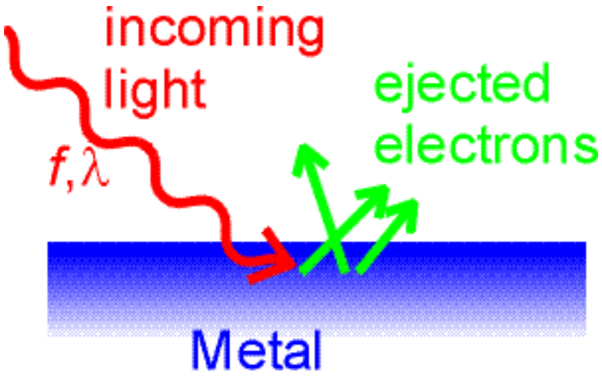
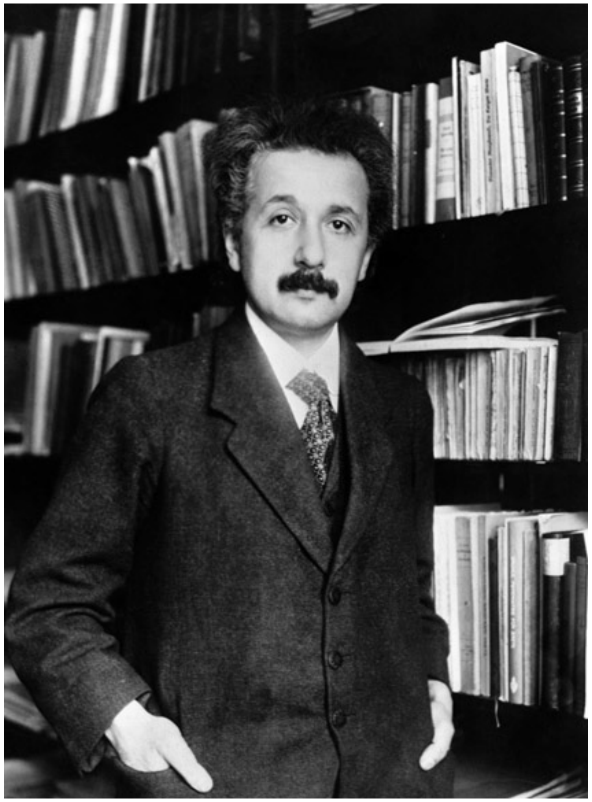
Photoelectric effect



Announcements:

- First midterm is next Thursday at 7:30pm this room – Humanities1B50.
- The exam will have a formula sheet. You will not be allowed to bring in your own formula sheet.
- Sample midterm exam.
- Exam will cover material in Chapters 1-4 + PE based on descriptions from lecture.



Understanding the blackbody spectrum

In 1900, Max Planck proposed a new theory which matched the blackbody observations perfectly.

The new theory required a minimum energy in the emitted light which was proportional to the frequency of light.

The energy coming out of the blackbody is *quantized* as a multiple of *hf*.

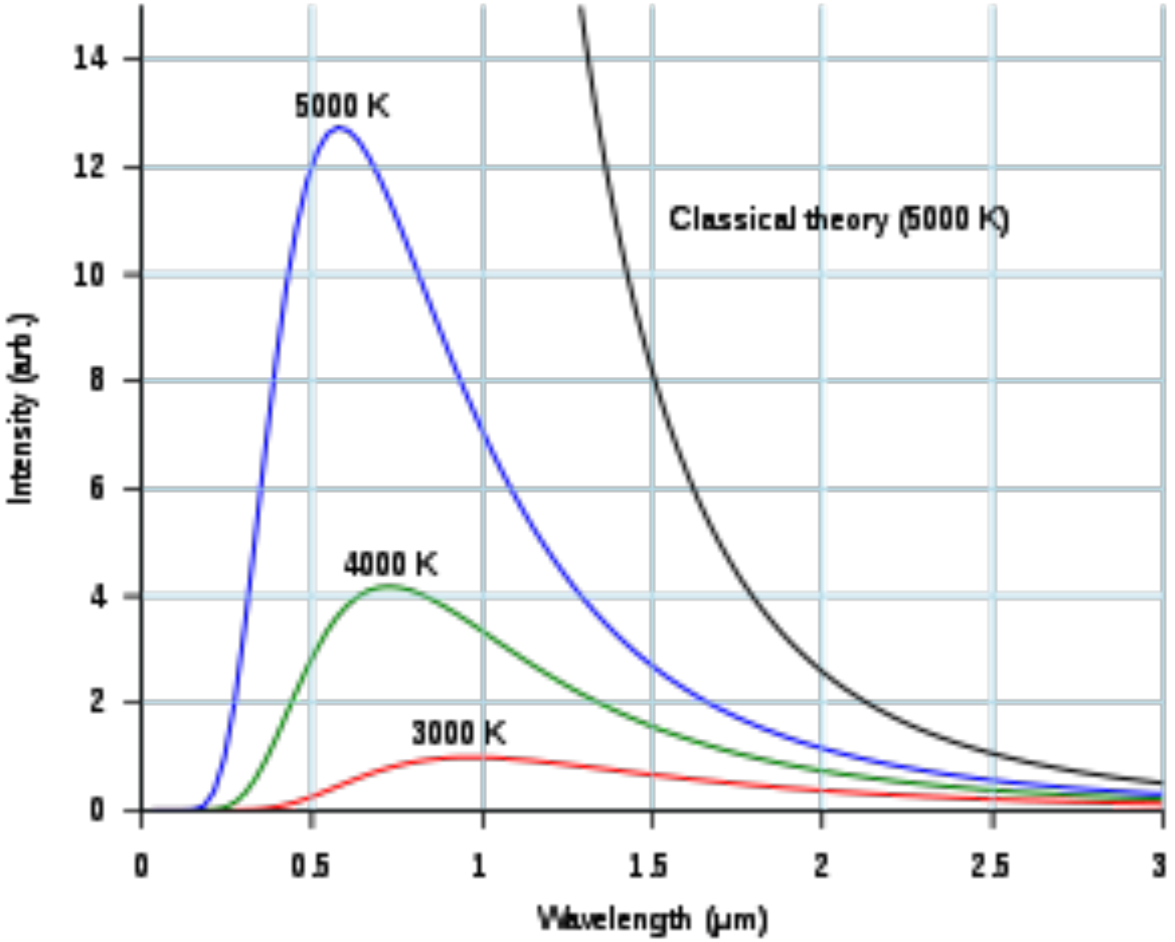
This is the first example of a quantum effect.

The proportionality constant is now called Planck's constant *h*.

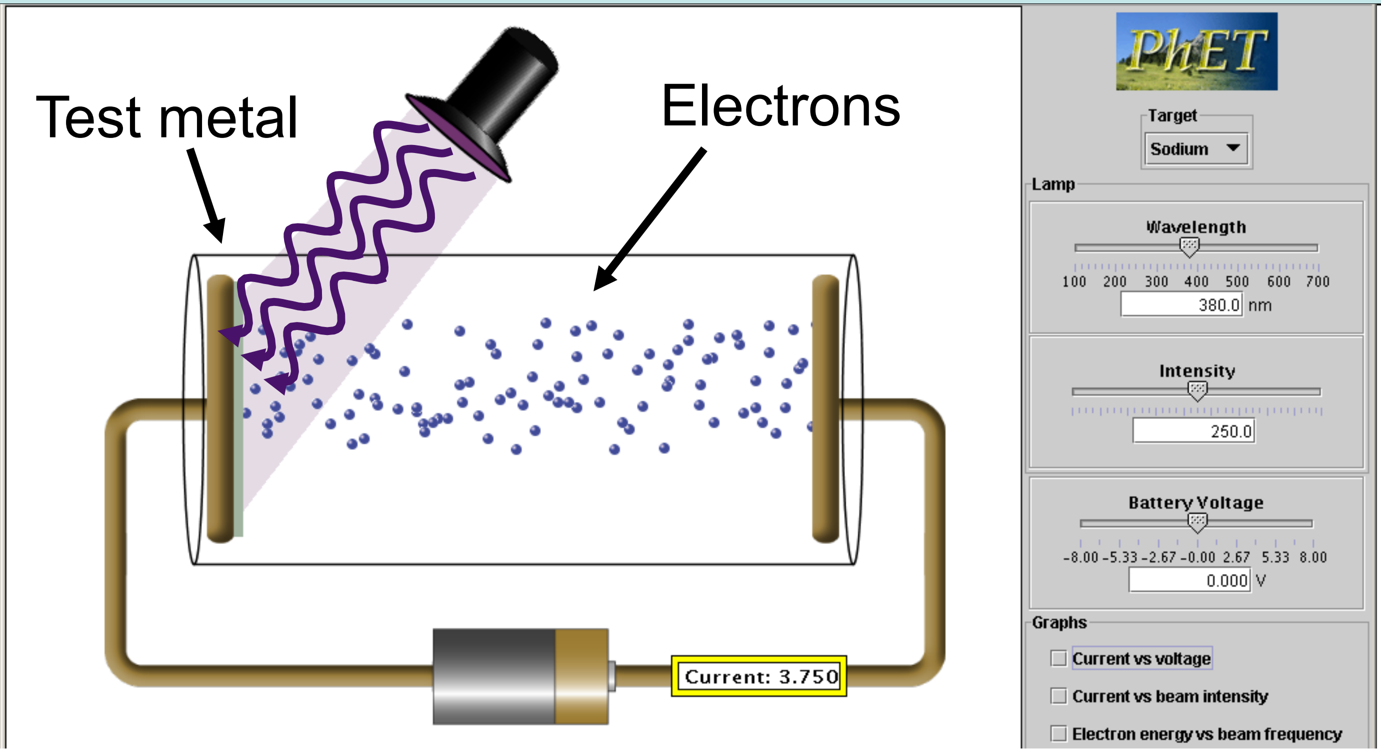
Planck did not think that light itself was quantized. He just found that when he required the atoms in the blackbody to emit quantum amounts of energy in the form of light that everything worked.

Energy emitted is $E = nhf$ where *n* is an integer.

Blackbody Radiation



Photoelectric effect experiment apparatus.



Target: Sodium

Lamp

Wavelength: 380.0 nm

Intensity: 250.0

Battery Voltage: 0.000 V

Current: 3.750

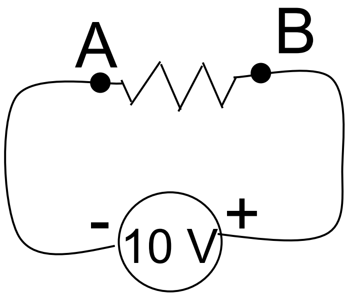
Graphs

☐ Current vs voltage

☐ Current vs beam intensity

☐ Electron energy vs beam frequency

Two metal plates in vacuum, adjustable voltage between them, shine light on one plate. Measure current between plates.



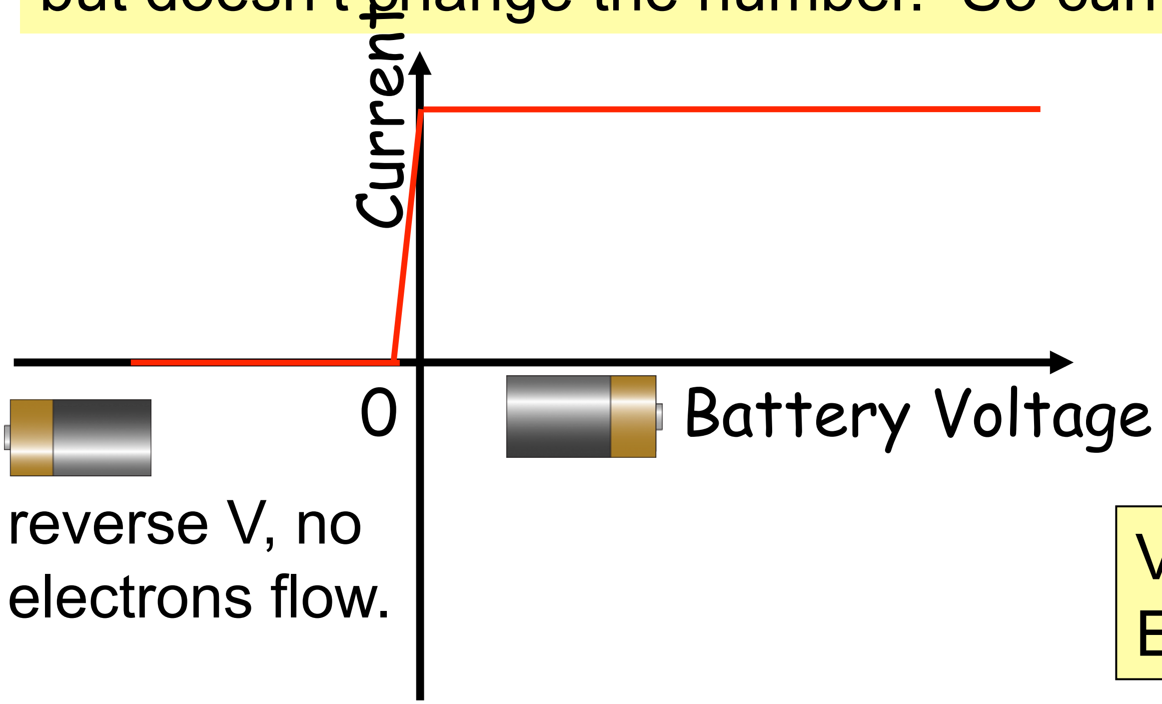
Potential difference between A and B = +10 V. Measure of energy an electron gains going from A to B.

Current versus voltage for the “hot plate” model

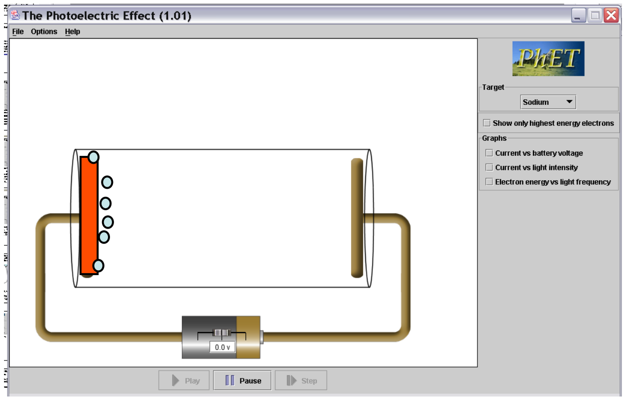
When voltage is reversed, only a few electrons that come off with relatively high KE make it to the other side. So low current. Note – electrons come off with different KE.

Once the voltage is >0, all electrons that come off are *accelerated* to the other side. So high current.

Higher voltage means higher KE when they reach other side but doesn’t change the number. So current stays constant.

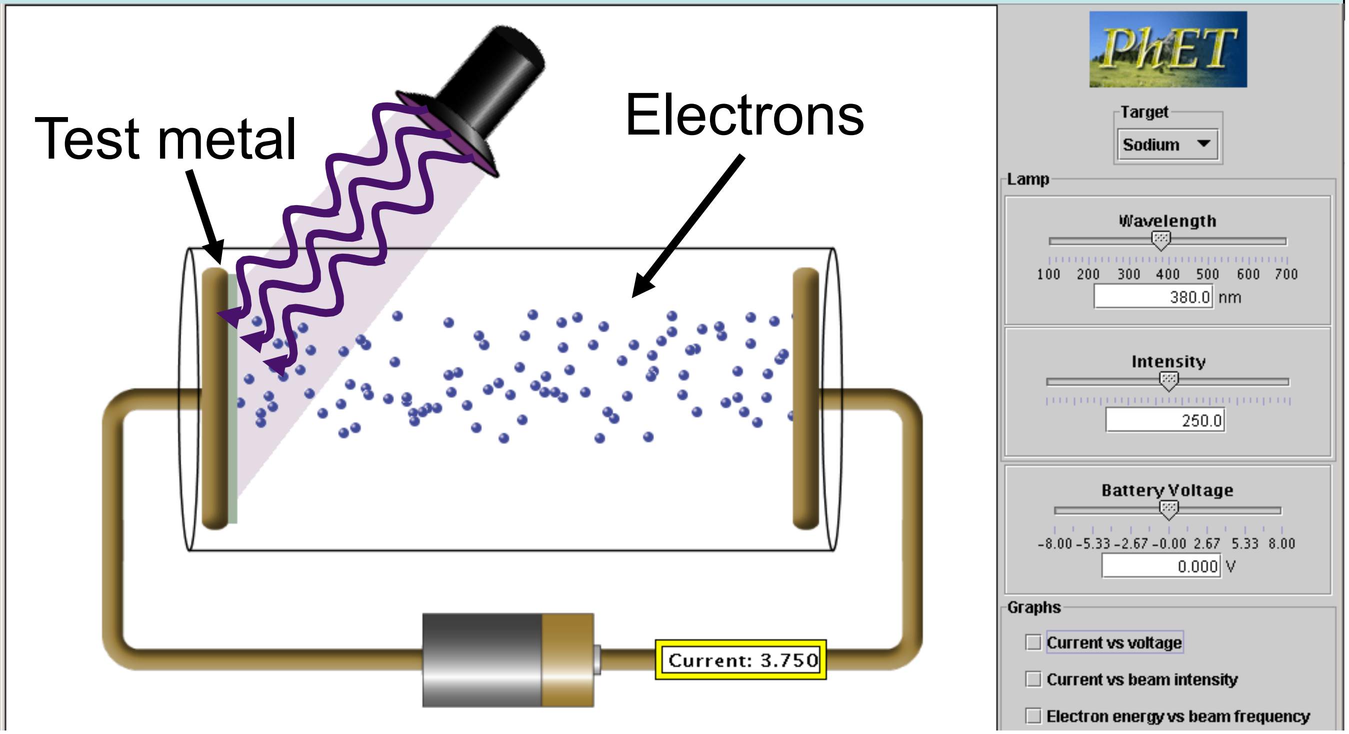


reverse V, no electrons flow.



Vacuum tube diode.
Early electronic device.

Classical solution to photoelectric effect



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Graphs

☐ Current vs voltage

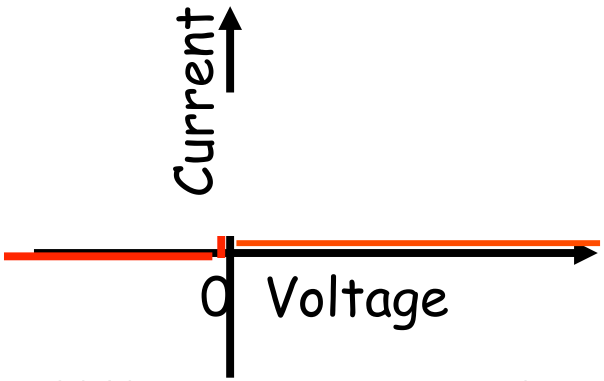
☐ Current vs beam intensity

☐ Electron energy vs beam frequency

If light is a classical wave, one predicts that it just puts energy into plate, heats up, get diode current voltage curve.

Also takes time to heat up.

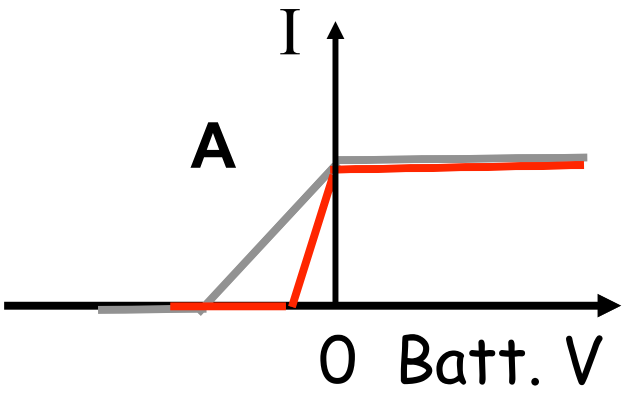
- Light on longer, heat more, more electrons and electrons have higher KE.
- Color light does not matter, only intensity.

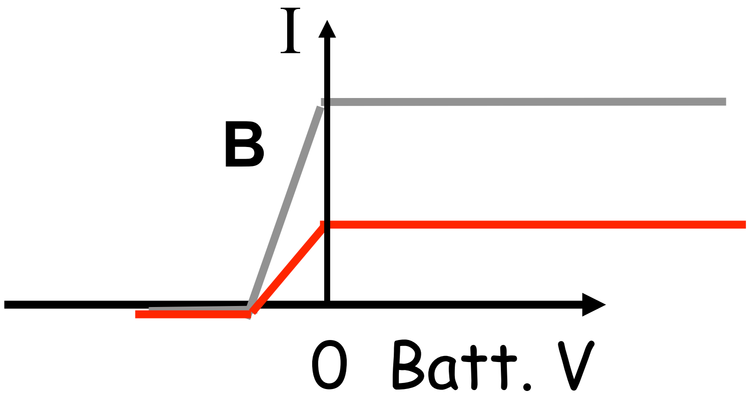


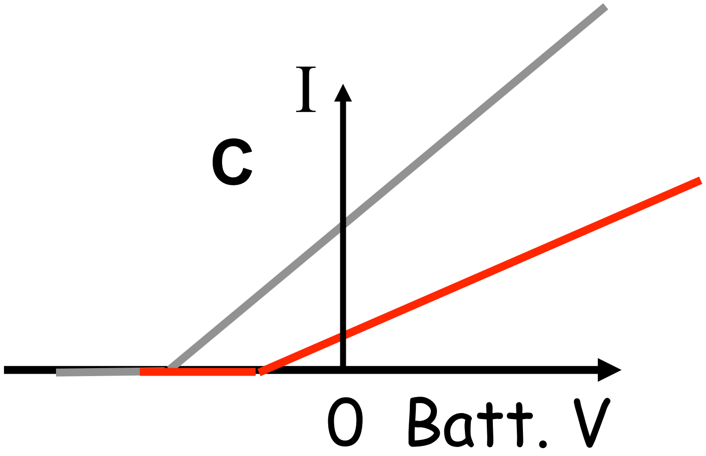
Clicker question 1

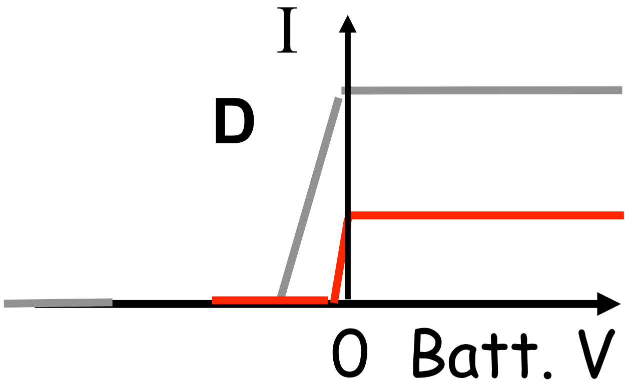
Set frequency to AD

Which graph represents **low** and **high** intensity curves?







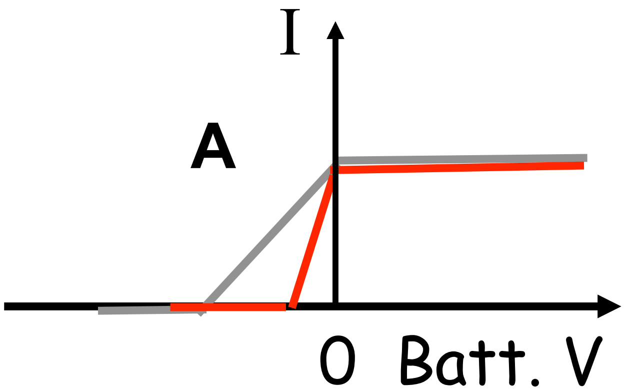


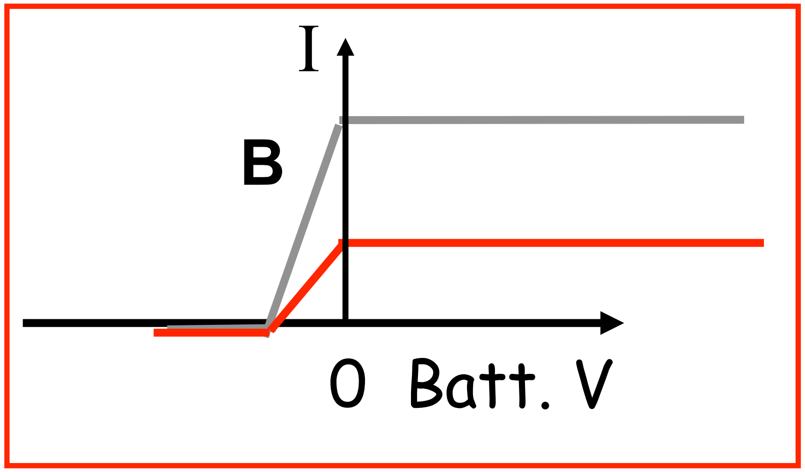
E. None of them

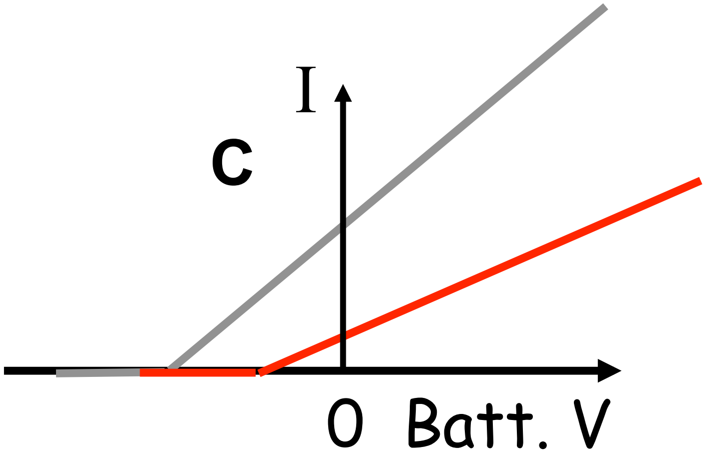
Clicker question 1

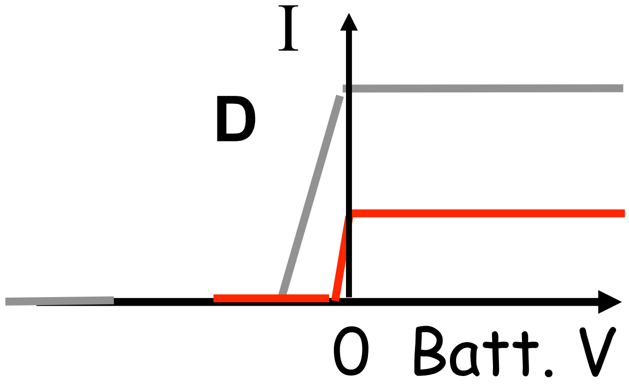
Set frequency to AD

Which graph represents **low** and **high** intensity curves?

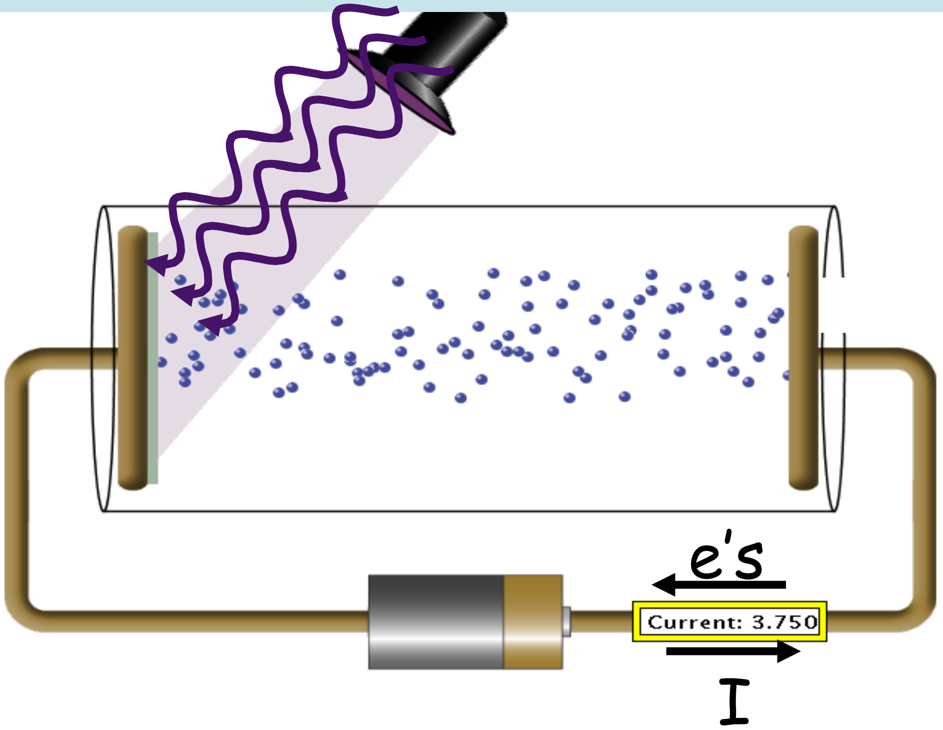


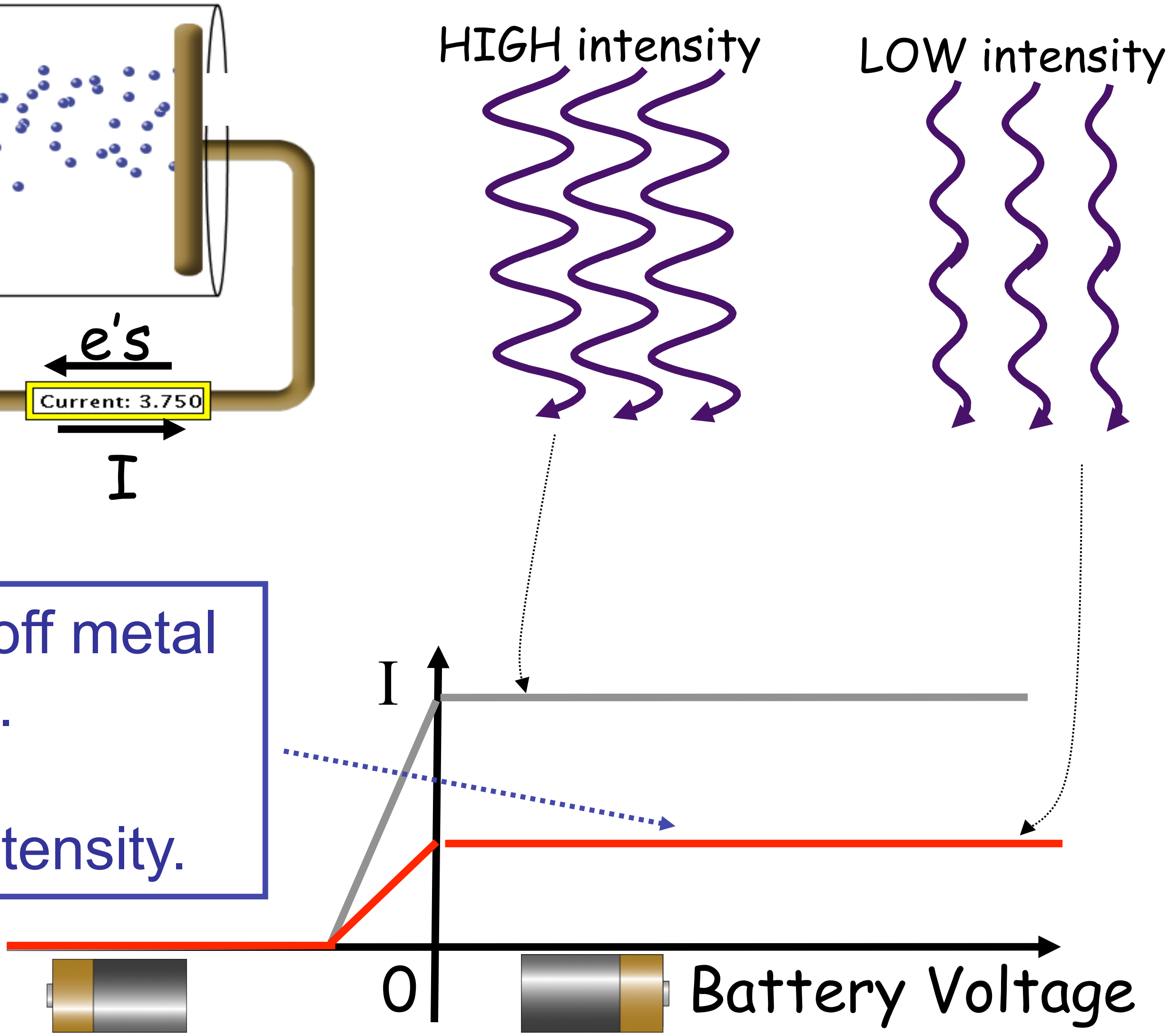






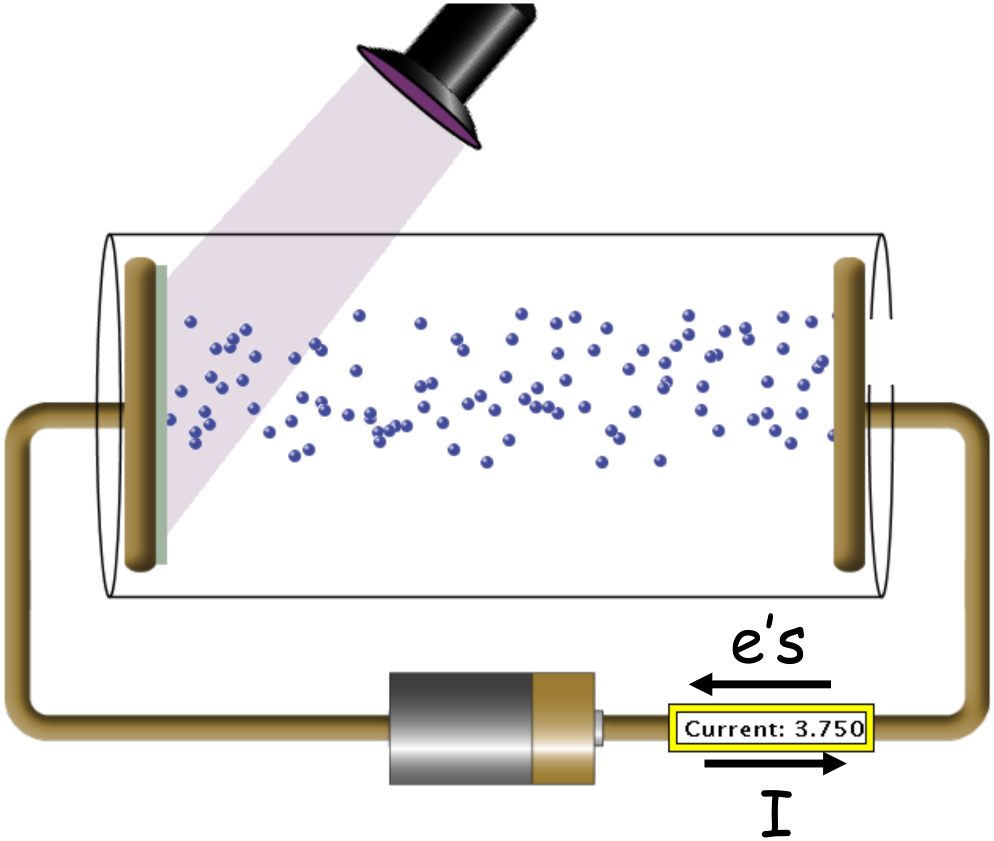
E. None of them



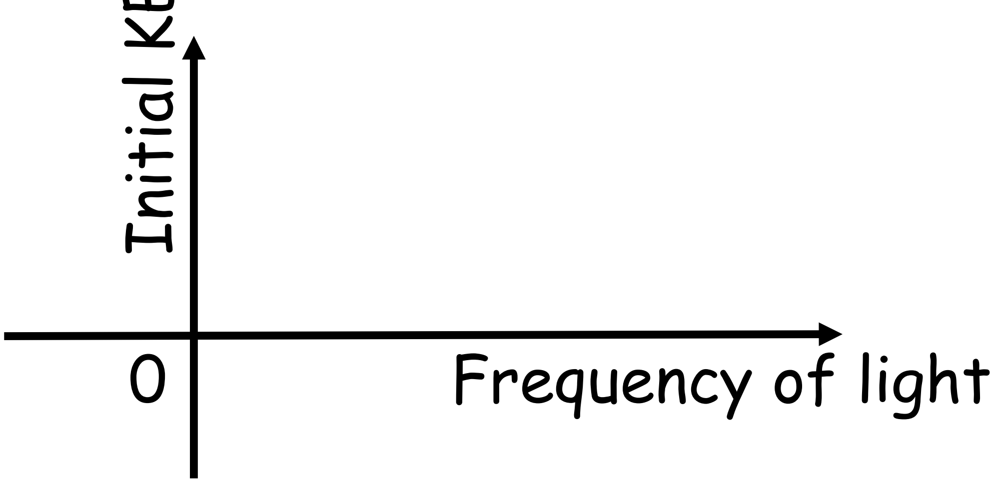


Fewer electrons pop off metal
So current decreases.
Find that current is
proportional to light intensity.

Predict what happens to the initial KE of the electrons as the *frequency* of light changes? (Light intensity is constant)



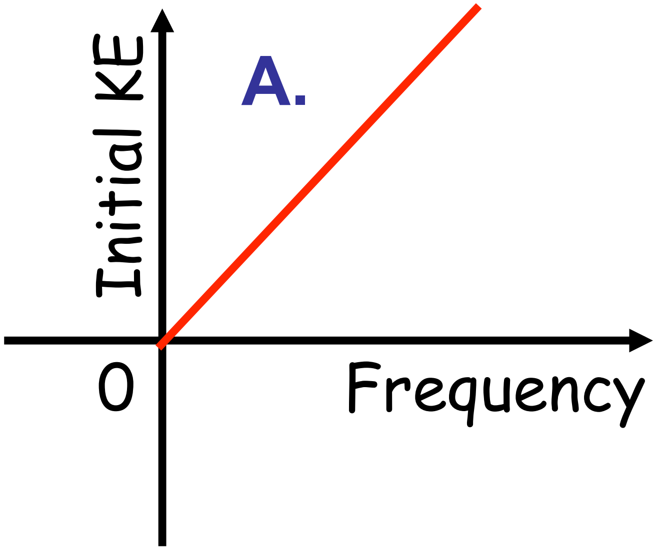
Predict shape of the graph

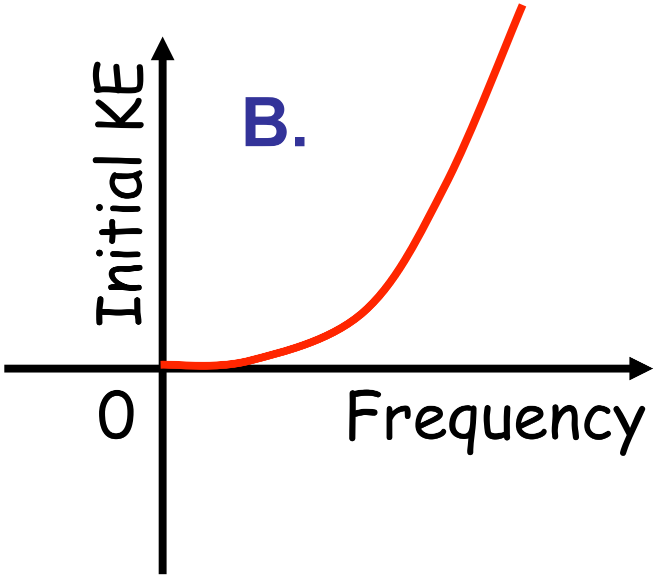


Clicker question 2

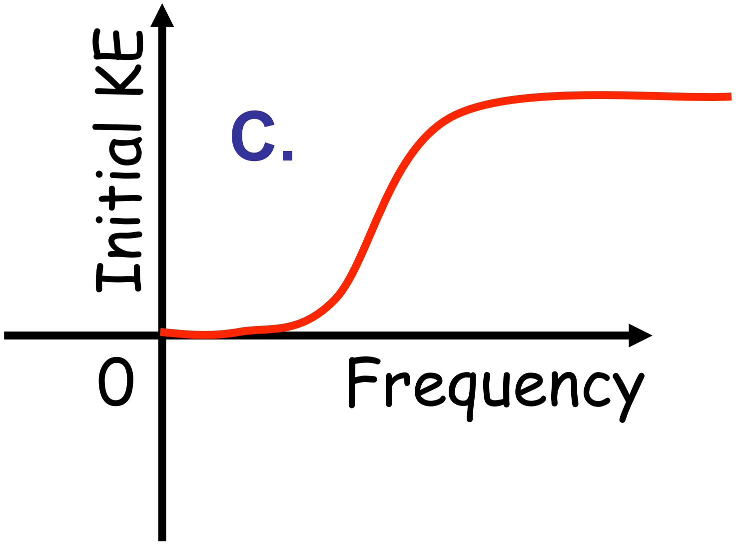
Set frequency to AD

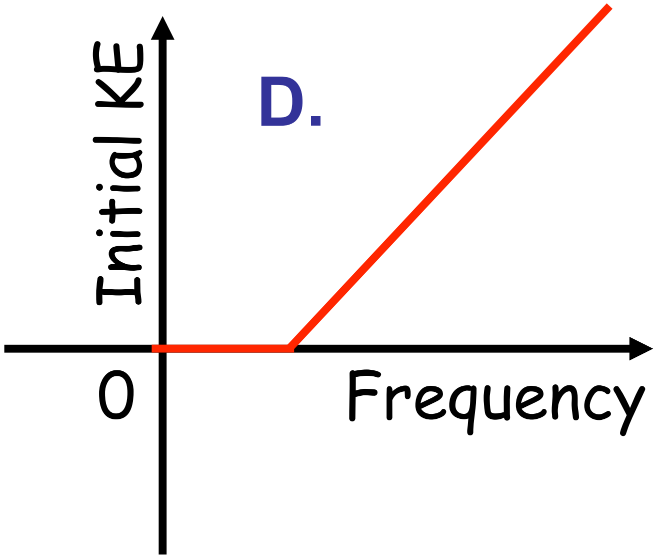
Which graph is correct?





E. something different





Clicker question 2

Set frequency to AD

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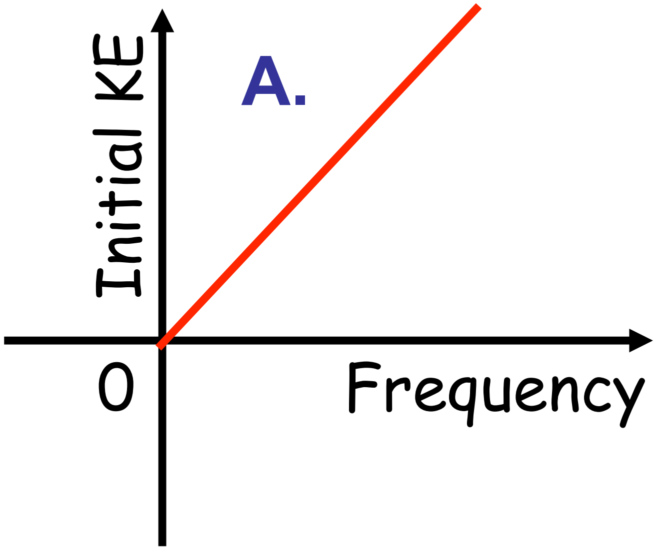
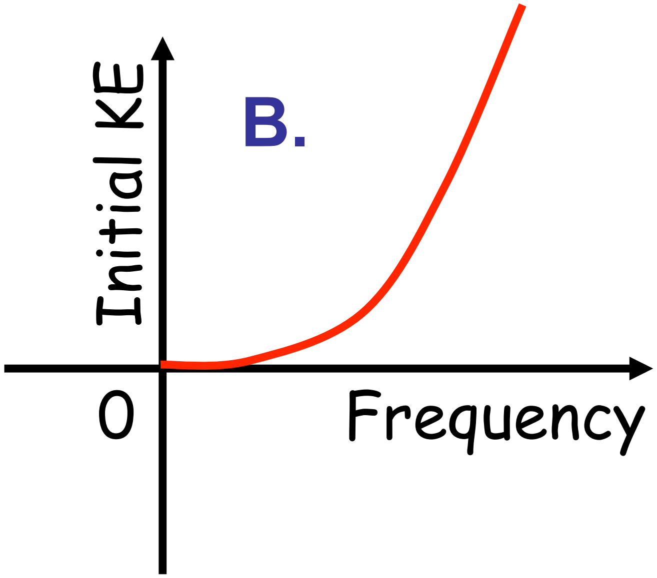
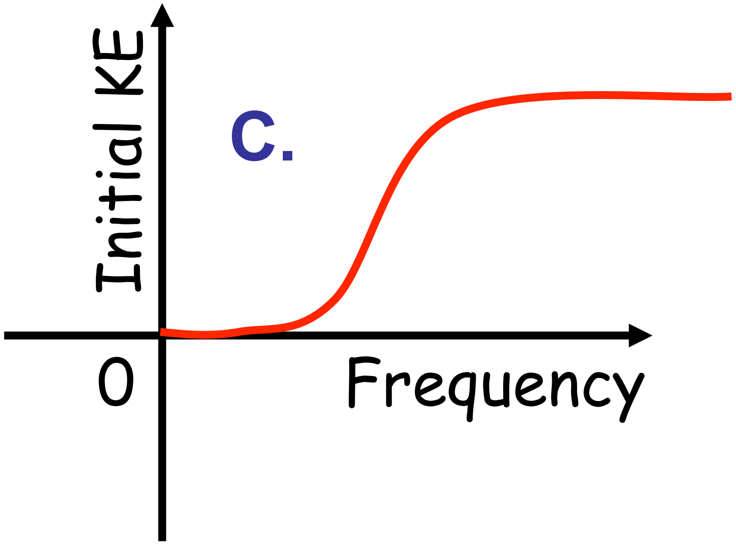
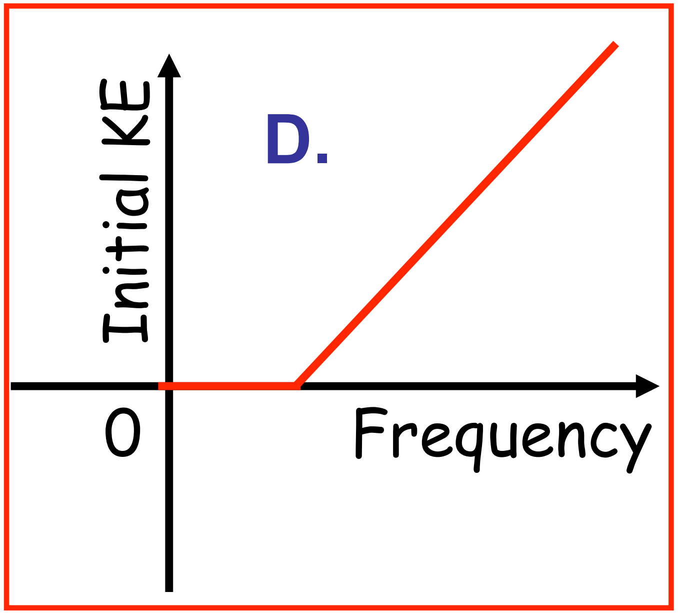
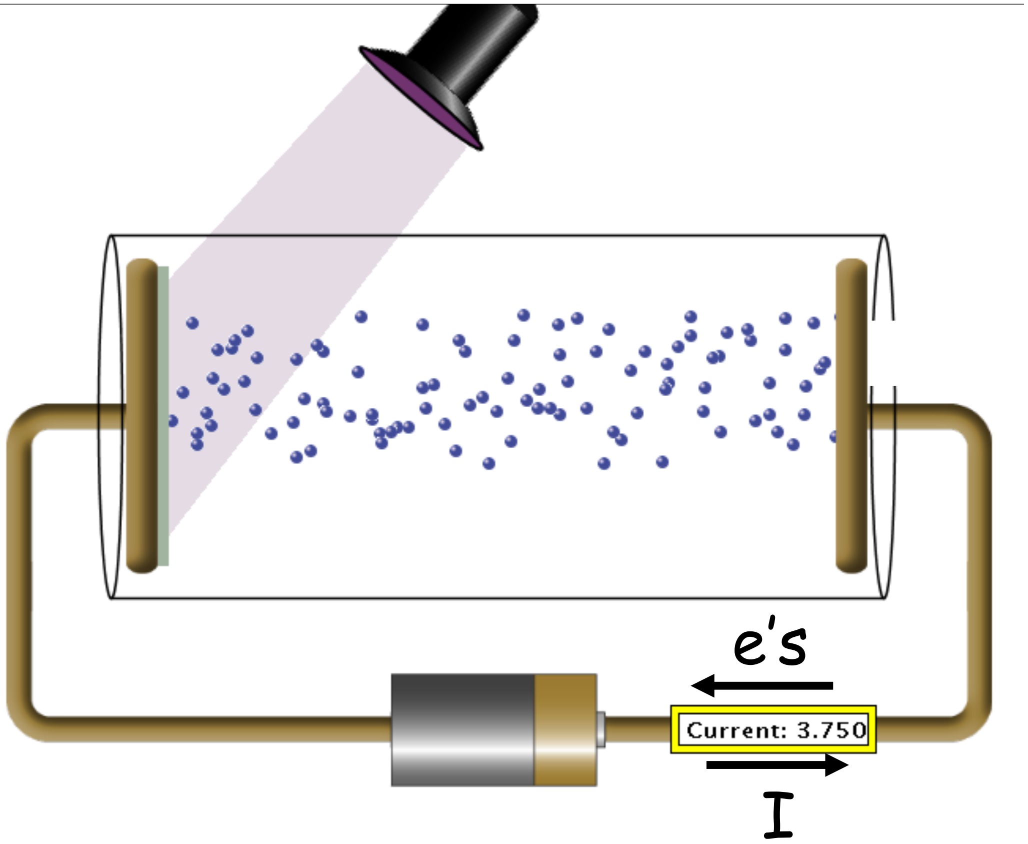




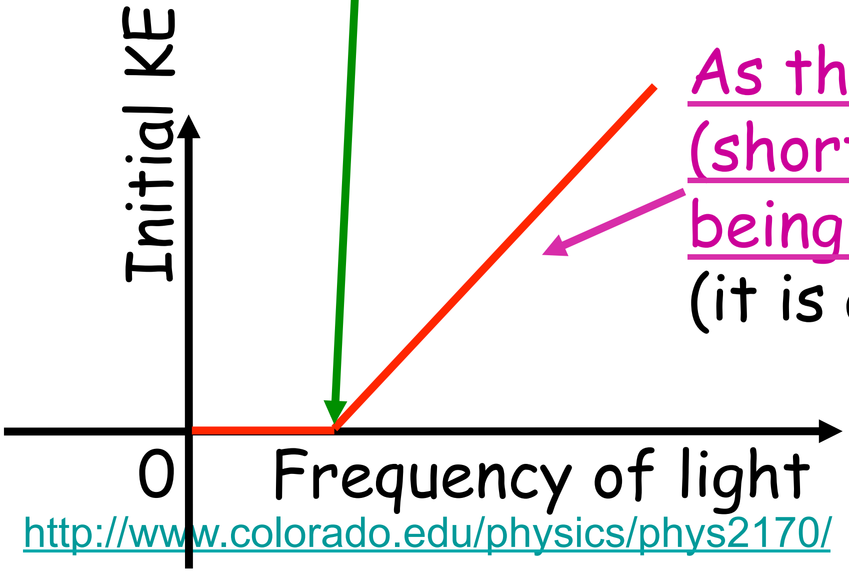




E. something different



There is a minimum frequency below which the light cannot kick out electrons…
no matter what intensity!



<u>As the *frequency* of light increases (shorter λ!), the KE of electrons being popped off increases.</u>
(it is a linear relationship)

Summary of photoelectric effect results

http://phet.colorado.edu

1. The current is linearly proportional to the light intensity.
2. Current appears with no delay.
3. Electrons only emitted if frequency of light exceeds a threshold. (same as "if wavelength short enough").
4. Maximum energy that electrons come off with increases linearly with frequency (=c/wavelength).
(Max. energy = stopping potential)
5. Threshold frequency depends on type of metal.

How do these compare with classical wave predictions?

Classical wave predictions versus experimental results

- Increasing intensity will increase the current.
experiment matches

- Current vs voltage step at zero then flat.
(flat part matches, but experiment has tail of energetic electrons, *energy of which depends on color*)

- Color of light does not matter, only intensity.
experiment shows strong dependence on color

- Takes time to heat up ⇒ current low and increases with time.
experiment: electrons come out immediately, no time delay to heat up and no increase in current with time.

Summary of what we know so far

1. If light can kick out electron, then even the tiniest intensities will do so. Electron kinetic energy does **not** depend on intensity.
   (Light energy must be getting concentrated/focused somehow)
2. Electron initial kinetic energy increases linearly with frequency.
   (This concentrated energy is linearly related to frequency)
3. There exists a minimum frequency below which light won't kick out electrons.
   (Need a certain amount of energy to free electron from metal)

(Einstein) Need "photon" picture of light to explain observations:
- Light comes in chunks ("particle-like") of energy ("photon").
- A photon interacts with a single electron.
- Photon energy depends on frequency of light; low frequency photons don't have enough energy to free an electron.

Analogous to a kicker in a pit

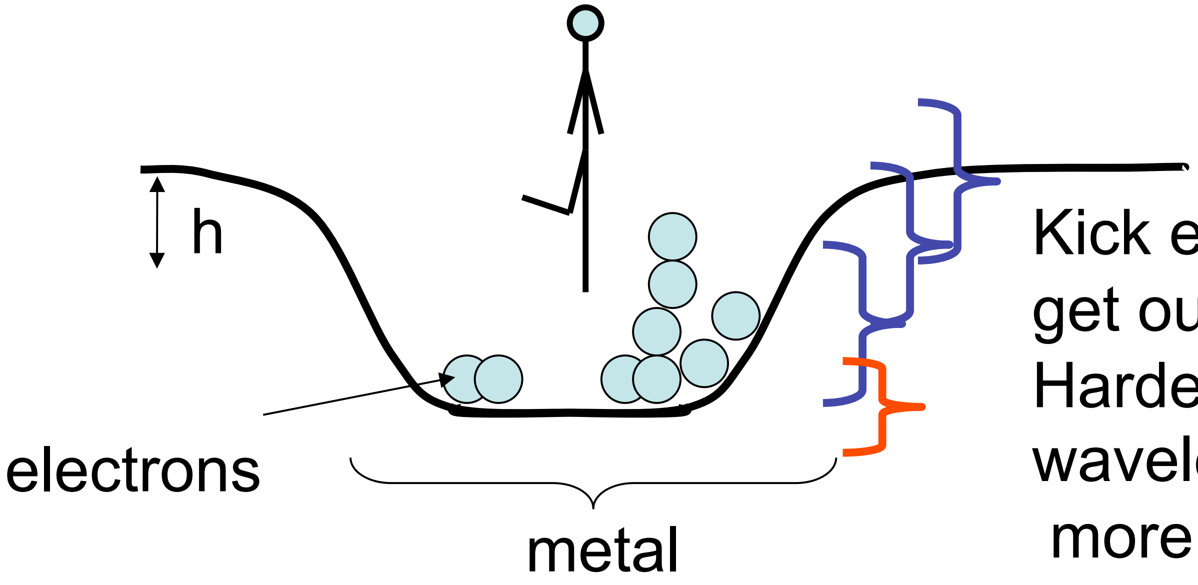
Light is like a kicker…
Puts in energy. All concentrated on one ball/electron.
Blue kicker always kicks the same,

and harder than red kicker always kicks.

Ball emerges with:

KE = kick energy - mgh

mgh = energy needed to make it up hill and out.
mgh for highest electron is analogous to work function.



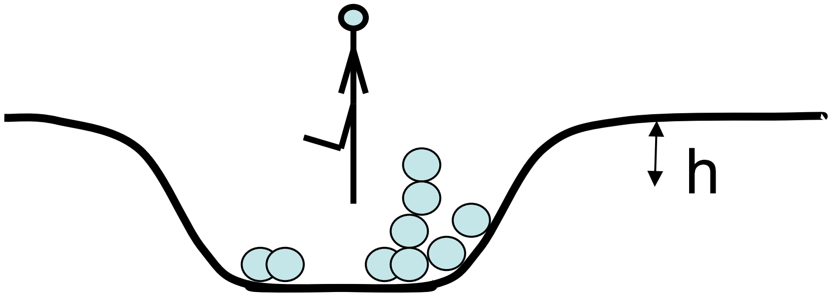
Kick energy. Top ones get out, bottom don't. Harder kick (shorter wavelength light), more get out.

Analogous to a kicker in a pit

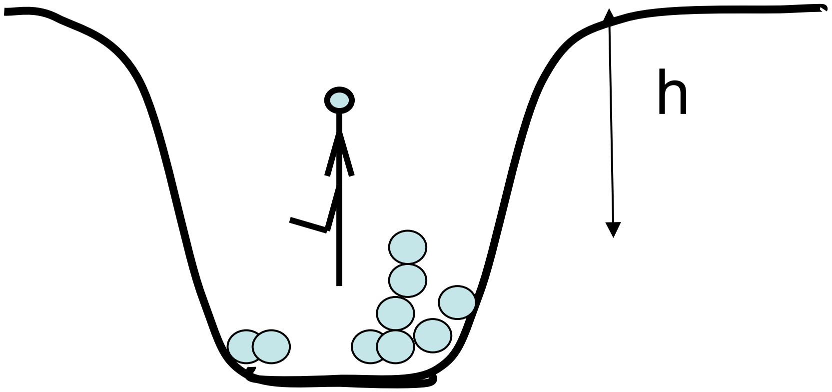
Light is like a kicker…
Puts in energy. All concentrated on one ball/electron.
Blue kicker always kicks the same, and harder than red kicker always kicks.

Ball emerges with:
KE = kick energy - mgh

energy needed to get most energetic (highest) electron out of pit (“work function”)



sodium- easy to kick out
small work function ⇔ shallow pit

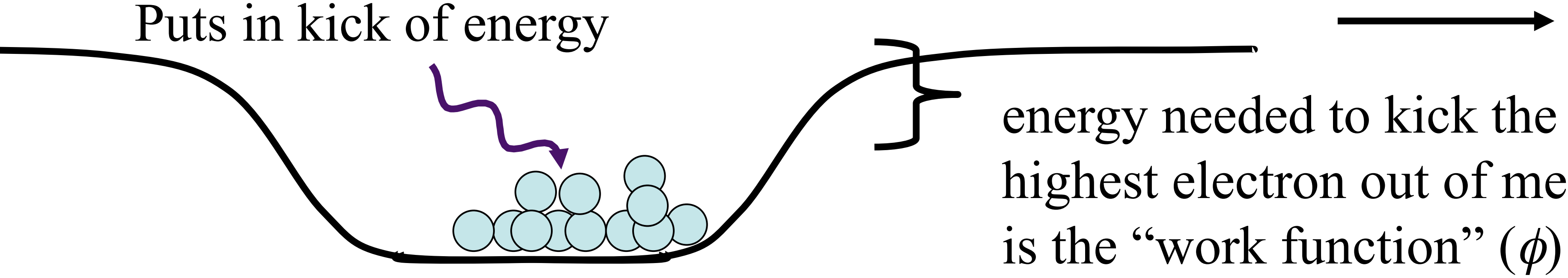


platinum, hard to kick out
large work function ⇔ deep pit

Einstein's Explanation of the Photoelectric Effect

KE = photon energy – work function

Photon…
Puts in kick of energy



energy needed to kick the highest electron out of metal is the "work function" (ϕ)

Each photon has: $E = hf$ = Planck's constant * Frequency

(Energy in Joules)	(Energy in eV)
$E = hf = 6.626 \times 10^{-34}\ \text{J·s} \bullet f$	$E = hf = 4.14 \times 10^{-15}\ \text{eV·s} \bullet f$
$E = hc/\lambda = 1.99 \times 10^{-25}\ \text{J·m} / \lambda$	$E = hc/\lambda = 1240\ \text{eV·nm} / \lambda$

$$KE_{\max} = hf - \phi$$

Depends on the type of metal.

Clicker question 3

Set frequency to AD

A photon with a wavelength of 300 nm kicks out an electron with kinetic energy KE_{300}. A photon with half this wavelength hits the same electron in the same metal. This kinetic energy will be:

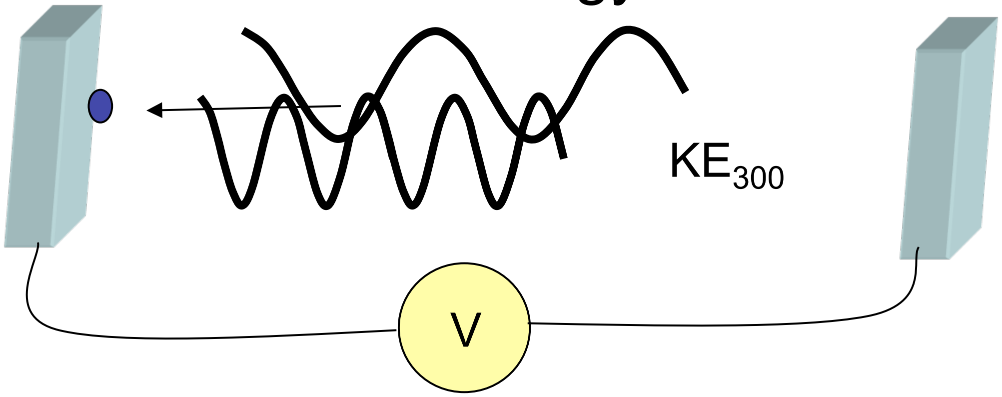
A) less than ½KE_{300}

B) ½KE_{300}

C) KE_{300}

D) 2KE_{300}

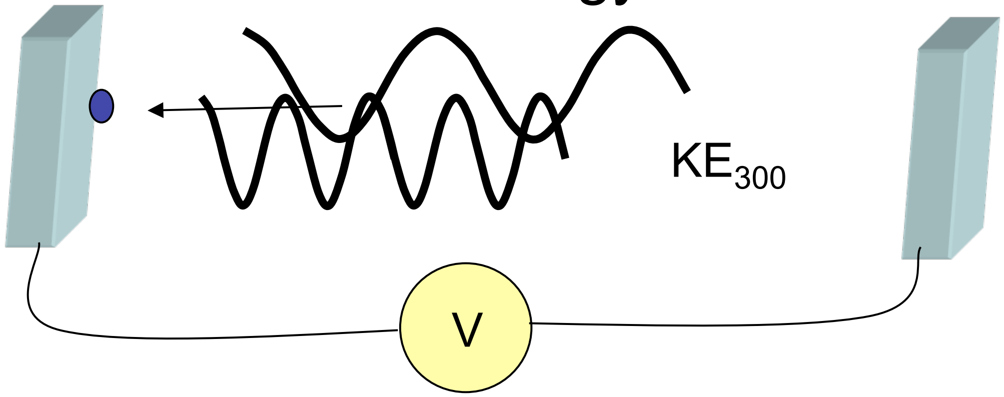
E) more than 2KE_{300}



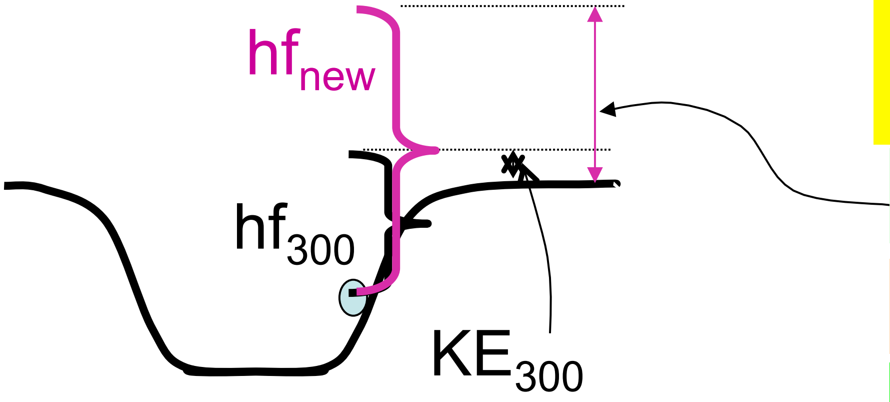
Clicker question 3 | Set frequency to AD

A photon with a wavelength of 300 nm kicks out an electron with kinetic energy KE_{300}. A photon with half this wavelength hits the same electron in the same metal. This kinetic energy will be:

A) less than $\frac{1}{2}KE_{300}$
B) $\frac{1}{2}KE_{300}$
C) KE_{300}
D) $2KE_{300}$
E) more than $2KE_{300}$



KE = photon energy − work function = hf − ϕ



½ wavelength = 2 x frequency so $E_{\gamma,new} = 2hf_{300}$

$KE_{new} = 2hf_{300} - \phi$, compared with

$KE_{300} = hf_{300} - \phi$

KE_{new} is more than $2KE_{300}$

The simulation might prompt the following question:

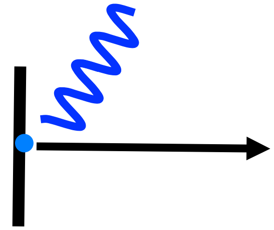
Why do the electrons in the simulation come out with different energies if all the incoming photons have the same energy?

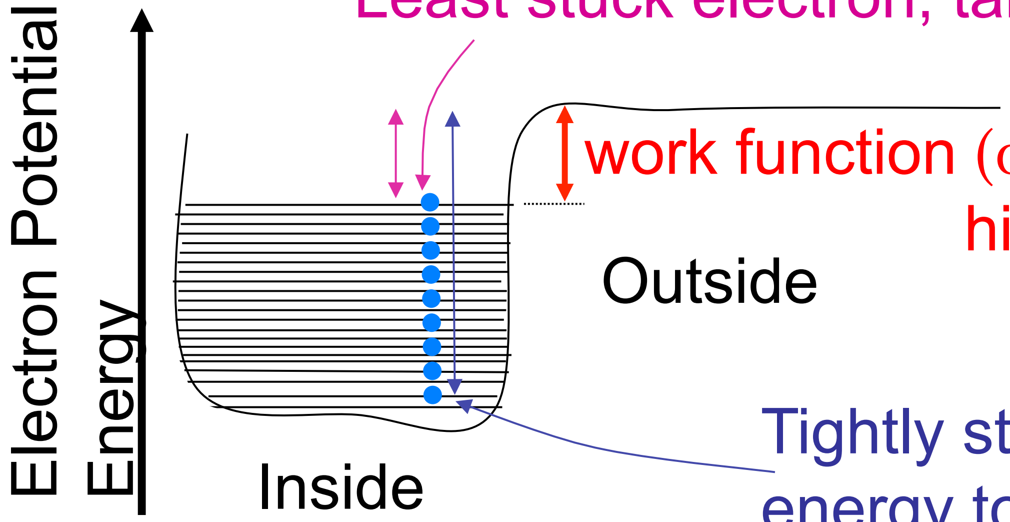
Conservation of energy still works!

Energy in = Energy out

Photon energy = Work function + Initial KE of electron

(gets electron out) (left-over energy)





Least stuck electron, takes least energy to kick out

work function (ϕ) = energy needed to kick highest electron out of metal

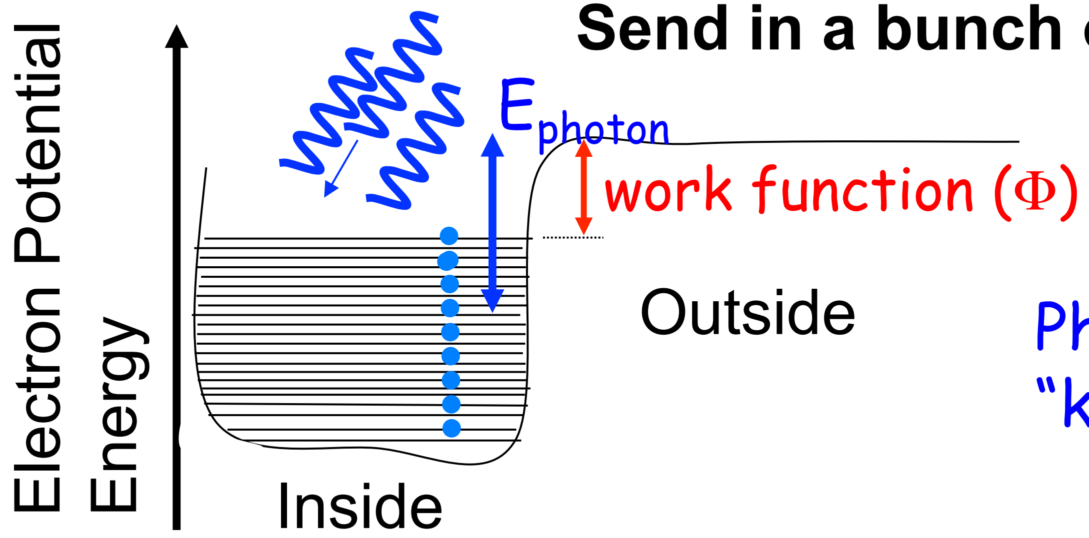
Tightly stuck, needs more energy to escape

Apply Conservation of Energy with Photons.

Energy in = Energy out

Photon energy = energy to get electron out + KE of liberated electron

Send in a bunch of blue photons…



Photon gives electron "kick of energy".

Electrons have equal chance of absorbing photon:

→ KE_{max} = photon energy − ϕ (least bound electrons)

→ Min KE = 0 (electrons just barely released)

→ Too tightly bound to get free, energy goes into heat or light.

Will learn more about electron energy levels over next 2 months.

Typical energies for photoelectric problems

Photon Energies:

Each photon has: $E = hf$ = Planck's constant * Frequency

(Energy in Joules)

$E = hf = 6.626 \times 10^{-34}\ \mathrm{J \cdot s} \bullet f$

$E = hc/\lambda = 1.99 \times 10^{-25}\ \mathrm{J \cdot m} / \lambda$

(Energy in eV)

$E = hf = 4.14 \times 10^{-15}\ \mathrm{eV \cdot s} \bullet f$

$E = hc/\lambda = 1240\ \mathrm{eV \cdot nm} / \lambda$

Red Photon: 650 nm

$$E_\gamma = \frac{1240\ \mathrm{eV \cdot nm}}{650\ \mathrm{nm}} = 1.91\ \mathrm{eV}$$

Work functions of some metals (in eV):

Aluminum	4.1 eV	Cesium	2.1	Lead	4.14	Potassium	2.3
Beryllium	5.0 eV	Cobalt	5.0	Magnesium	3.7	Platinum	6.3
Cadmium	4.1 eV	Copper	4.7	Mercury	4.5	Selenium	5.1
Calcium	2.9	Gold	5.1	Nickel	5.0	Silver	4.7
Carbon	4.81	Iron	4.5	Niobium	4.3	Sodium	2.3