The Photoelectric Effect

Photoelectric effect: experiment showing light is also a particle. Energy comes in particle-like chunks- basics of quantum physics. (energy of one chunk depends on frequency, wave-like beam of light has **MANY** chunks, energy of beam is sum)

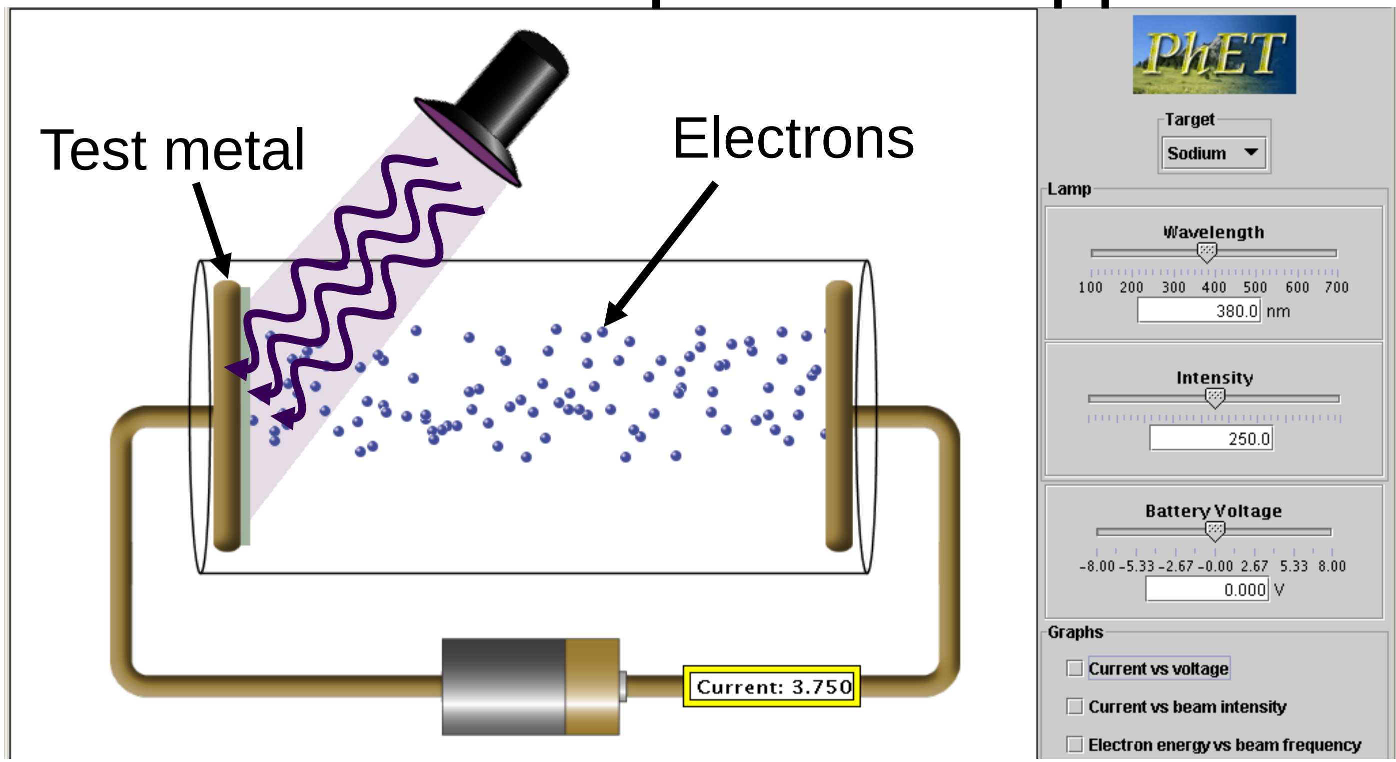
Next 2 classes:

I. Understand the P.E. experiment and what results you would expect if light were a classical wave (like physicists at the time expected the experiment should give).
II. What experimental results it actually did give.
III. The implications/interpretation of the results.

Important to take notes today

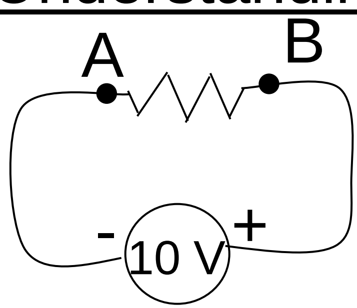
a) record predictions to compare with experiment.
b) record results of experiments.

Photoelectric effect experiment apparatus.



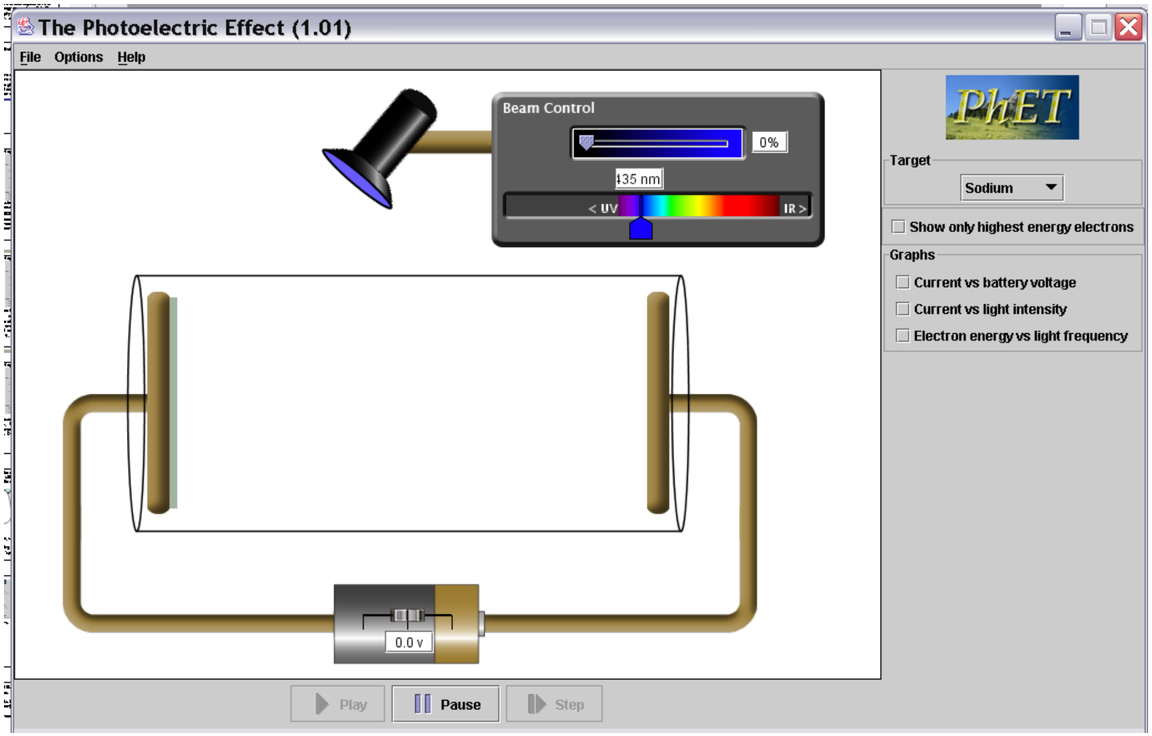
Two metal plates in vacuum, adjustable voltage between them, shine light on one plate. Measure current between plates.

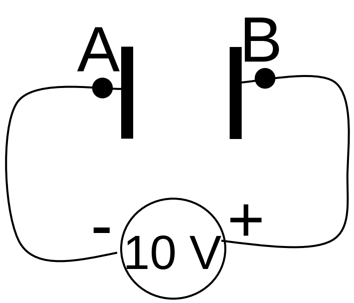
I. Understanding the apparatus and experiment.



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

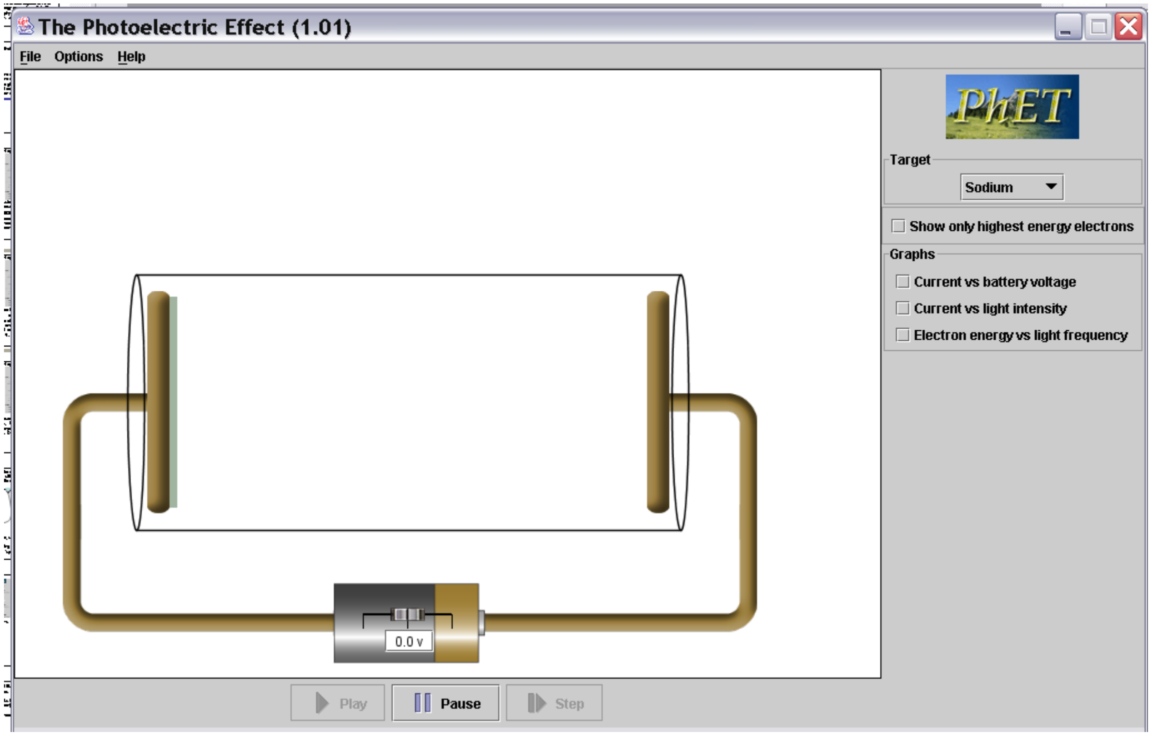
Photoelectric effect experiment apparatus.

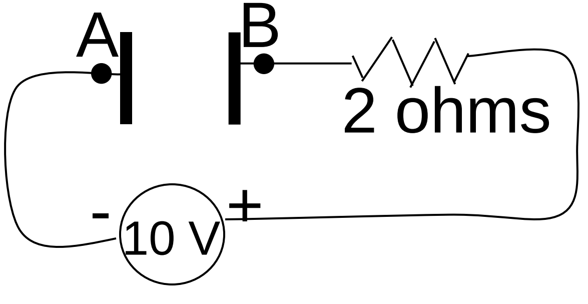




Potential difference between A and B =
a. 0 V, b. 10 V, c. infinite volts

Photoelectric effect experiment apparatus.





What is current from A to B?

a. 0 amps, b. 5 amps, c. 0.2 amps

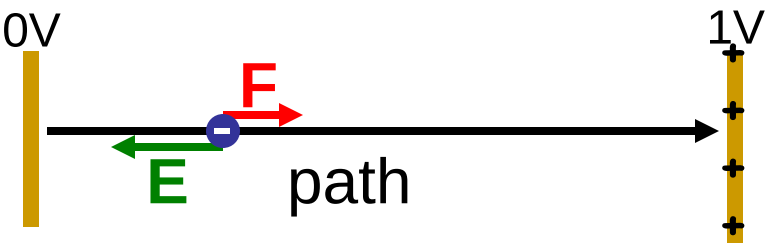
A note about units of energy

Joules: good for macroscopic energy conversions

But when talking about energy of single electrons Joules is inconvenient… (too big)

Define new energy unit (the electron-volt (eV))

= kinetic energy gained by an electron when accelerate through 1 volt of potential difference



$\Delta KE = - \Delta U$

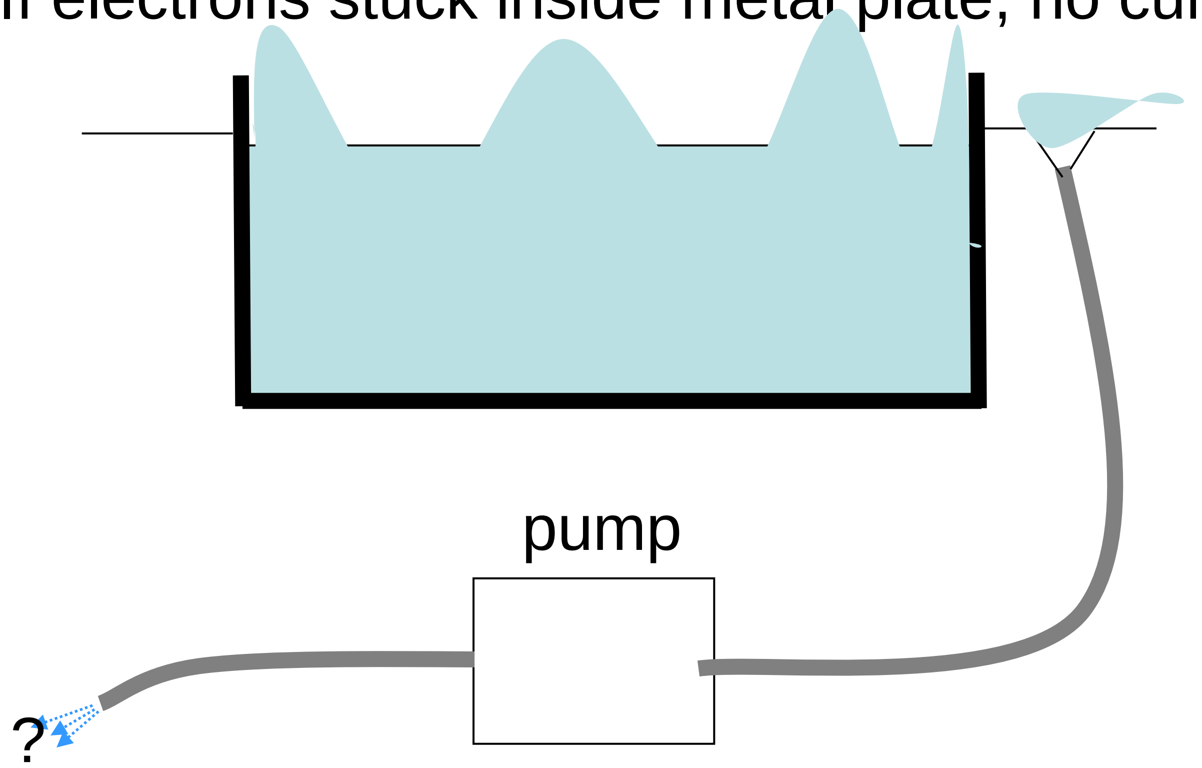
$= - q\, \Delta V$

$= - (- e)*(1V)$

$= + (e)*(1V) = 1.6 \times 10^{-19}$ J

$= 1 eV$

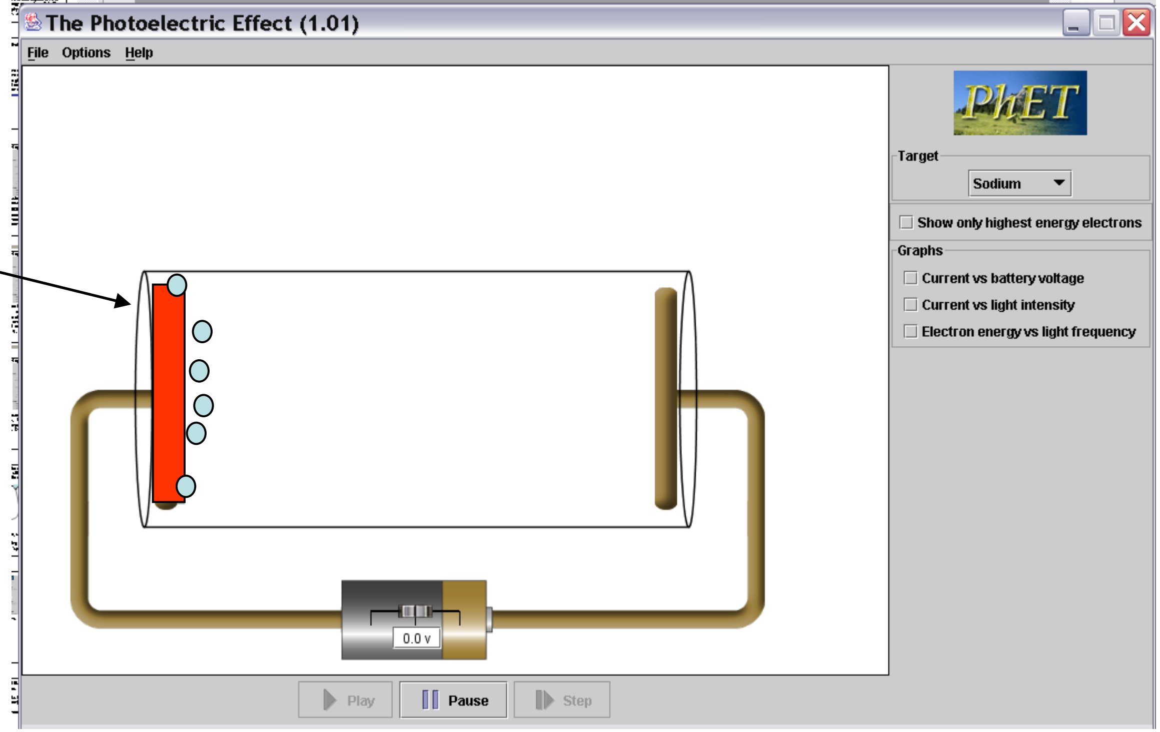
swimming pool analogy- If no water slops over side of pool, no flow. Little pump or big pump, still no water current.
If electrons stuck inside metal plate, no current for little or big V.



Put bunch of energy into water, splash some out,
get flow through pump.
Put energy into metal by heating it very hot,
gives electrons energy, some “splash” out. Gives current.

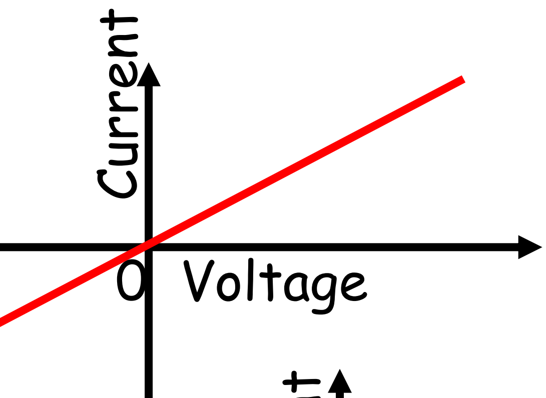
Hot plate.

A few electrons get enough energy to just barely “splash” out.

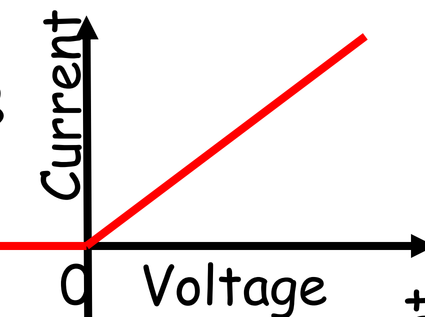


What is the current vs battery voltage?

A



B



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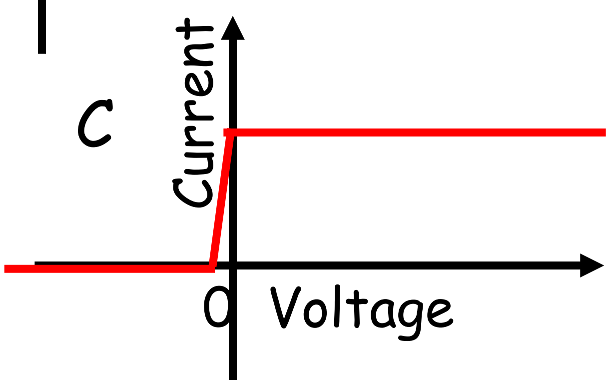
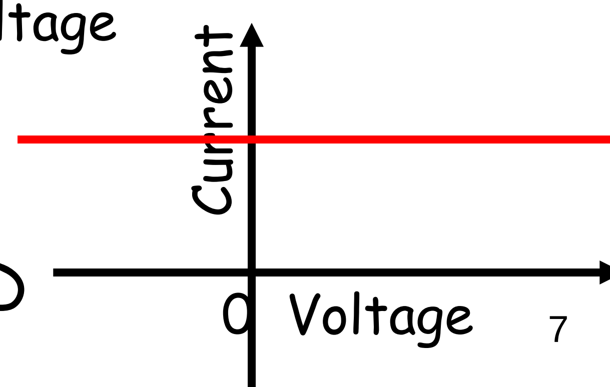


D

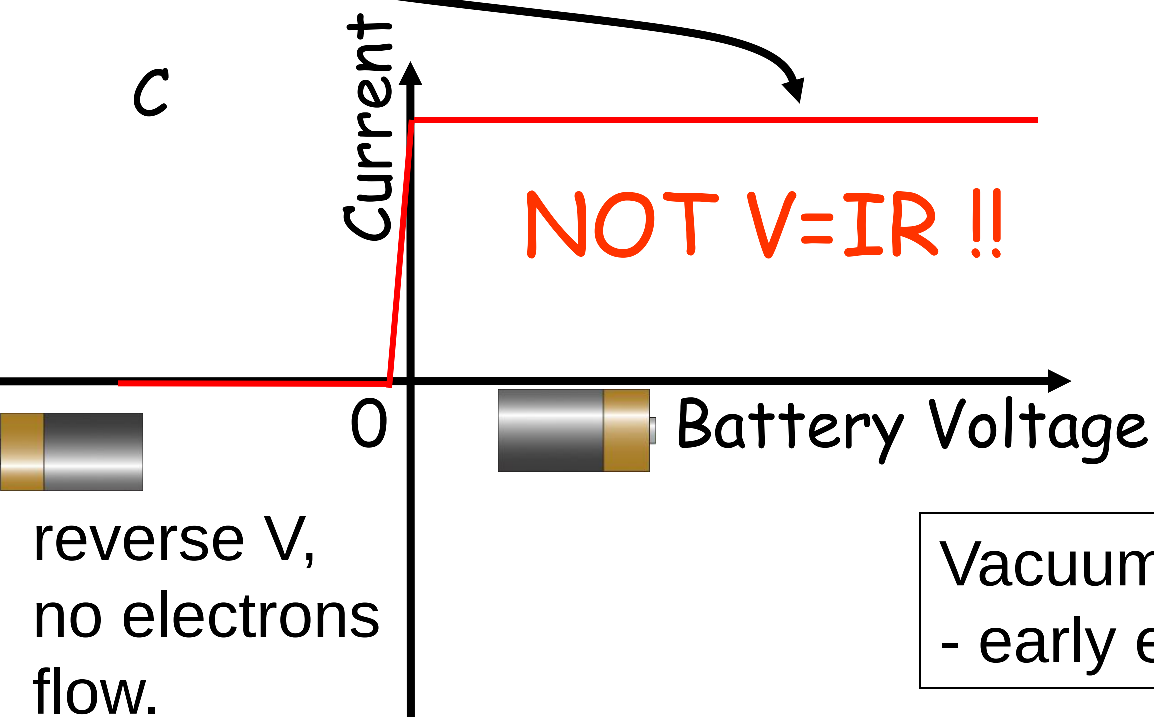


What's happening here?

Each electron that pops out is accelerated more so hits far plate with higher velocity,

BUT $\boxed{\dfrac{\#\text{ of electrons}}{\text{sec}} = \text{constant}}$

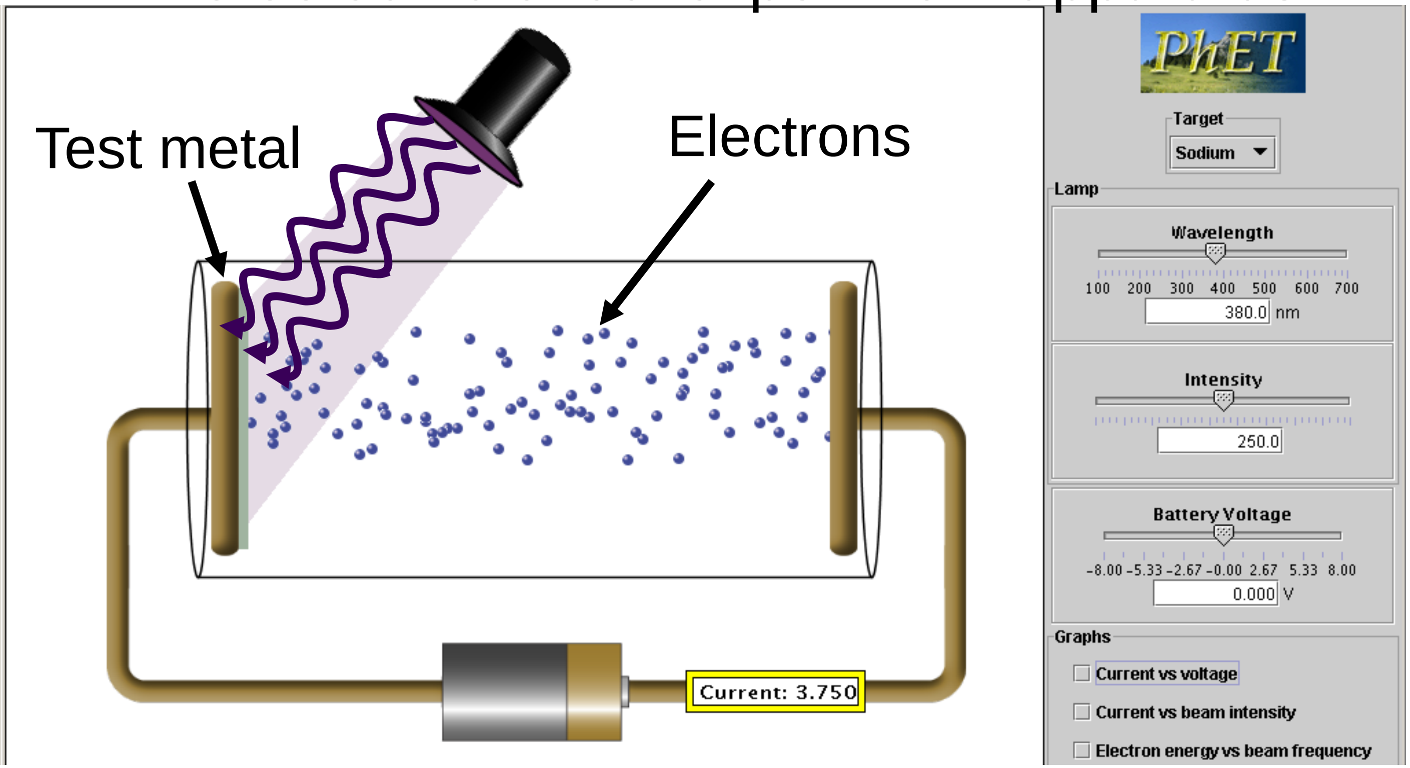
So current is constant!



reverse V, no electrons flow.

Vacuum tube diode. Works. - early electronic device.

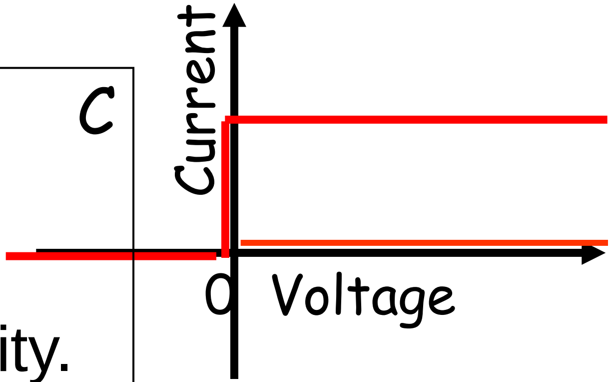
Photoelectric effect experiment apparatus.

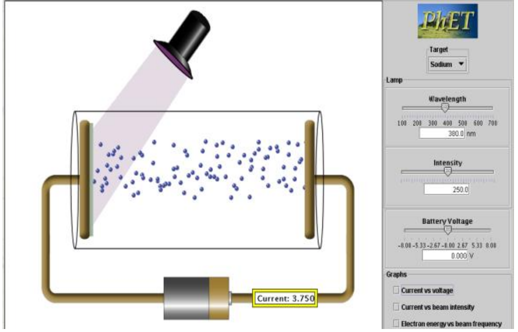


So if light is classical wave, predict that just puts energy into plate, heats up, get diode current voltage curve.

Also takes time to heat up.
- Light on longer, heat more, e's out faster = more current.
- Color light does not matter, only intensity.

C

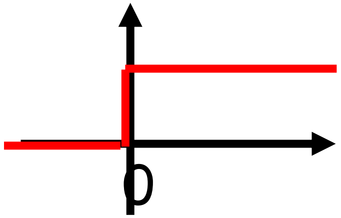




<u>Have now covered.</u>

I. How apparatus works.

II. What would expect to see if light classical wave as previous experiments like double slit interference, heating barrels, etc. had shown.



•Current vs voltage step at zero then flat.

•Color light does not matter, only intensity.

•Takes time to heat up ⇒ current low and increases with time.

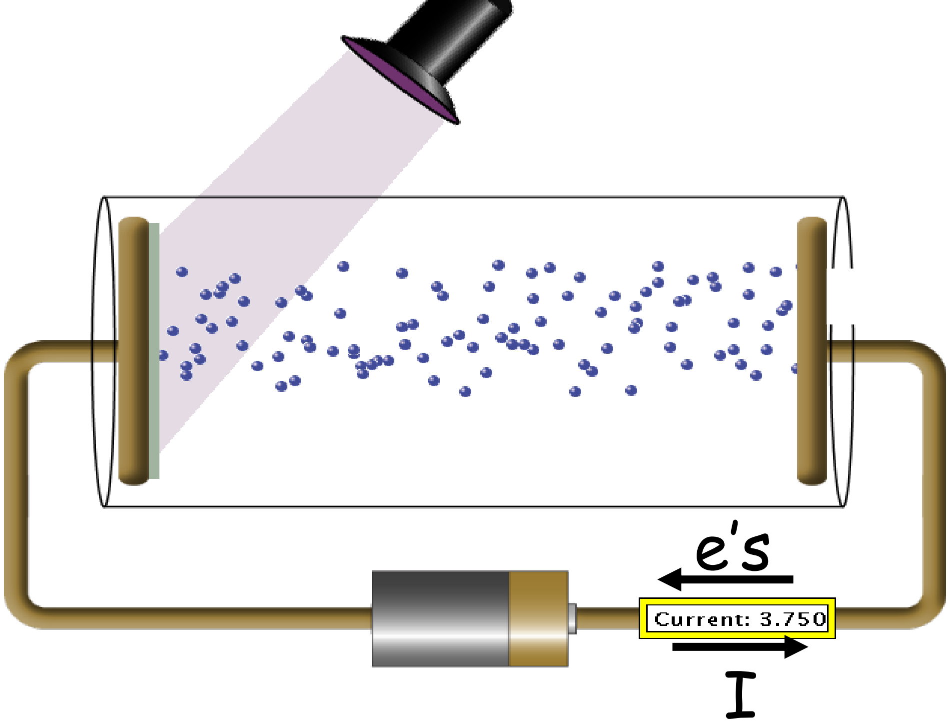
•Increase intensity, increase current.

questions?

III. Do actual experiment, see if agrees with prediction.

Current I vs V. How depends on intensity and color of light?

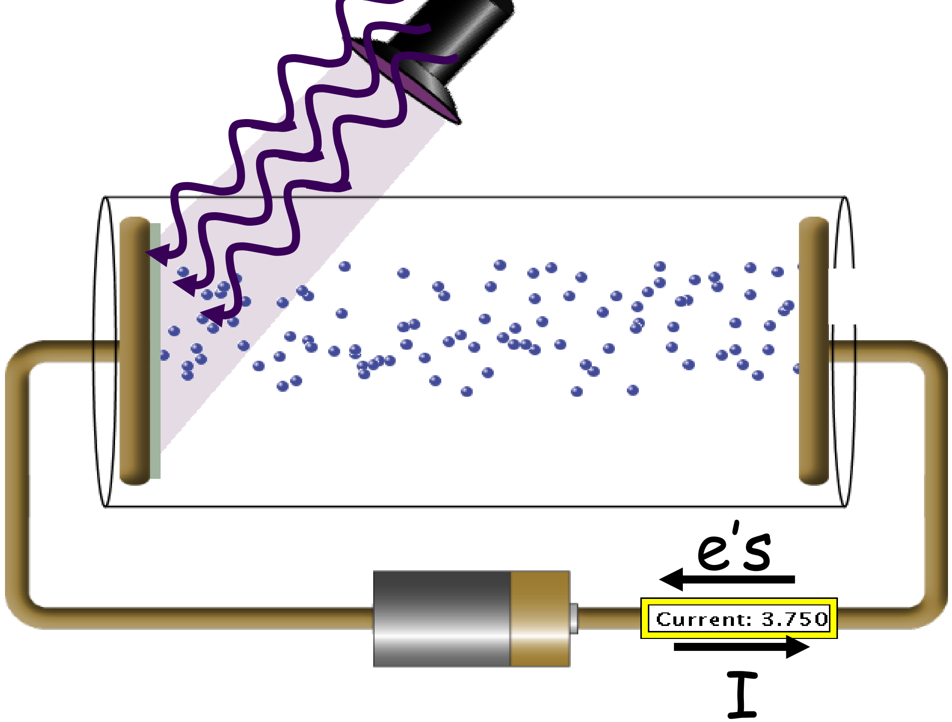
http://phet.colorado.edu/new/simulations/sims.php?sim=Photoelectric_Effect



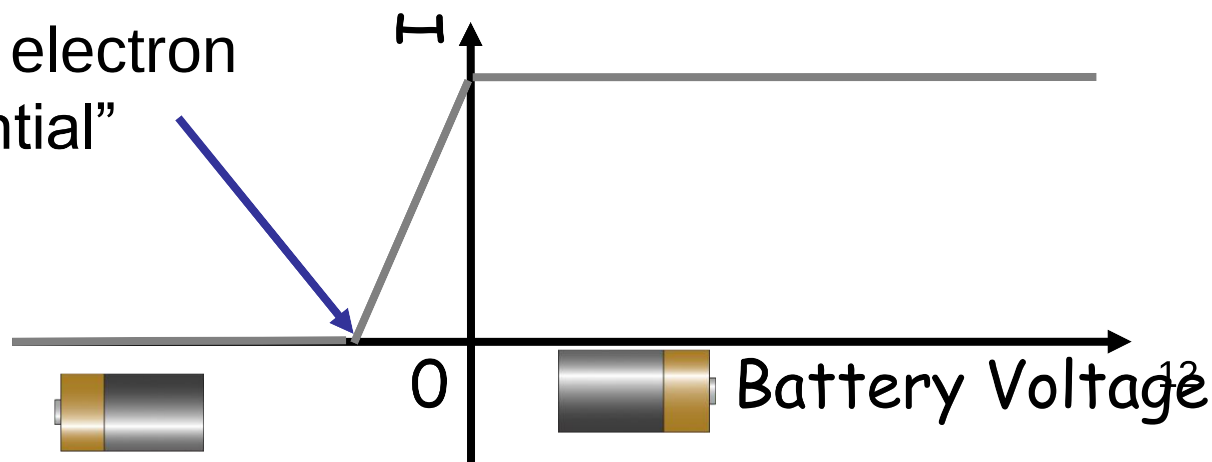
First experiment- I vs. V high intensity, low intensity

I vs. V two different colors

write down what happens

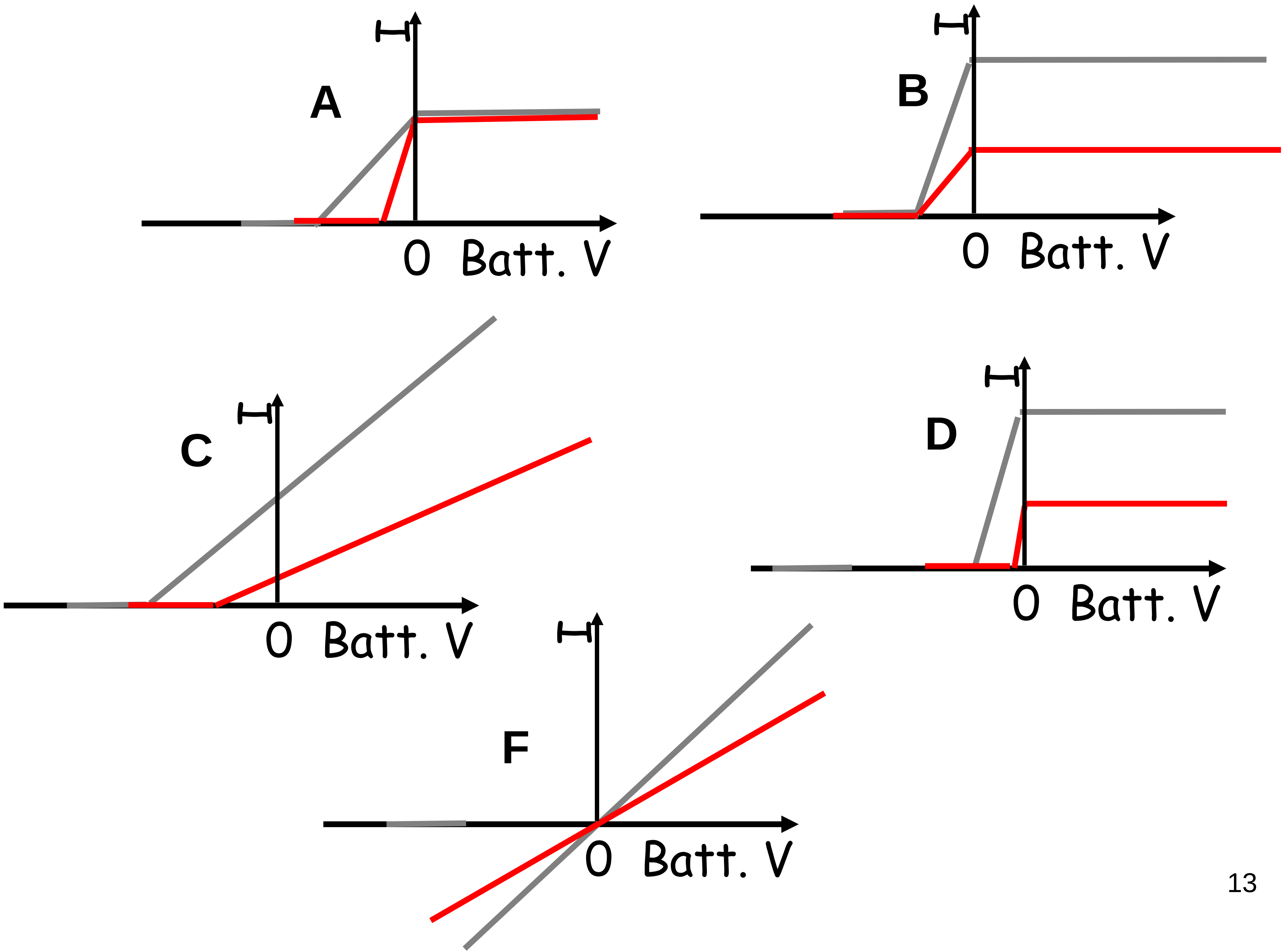


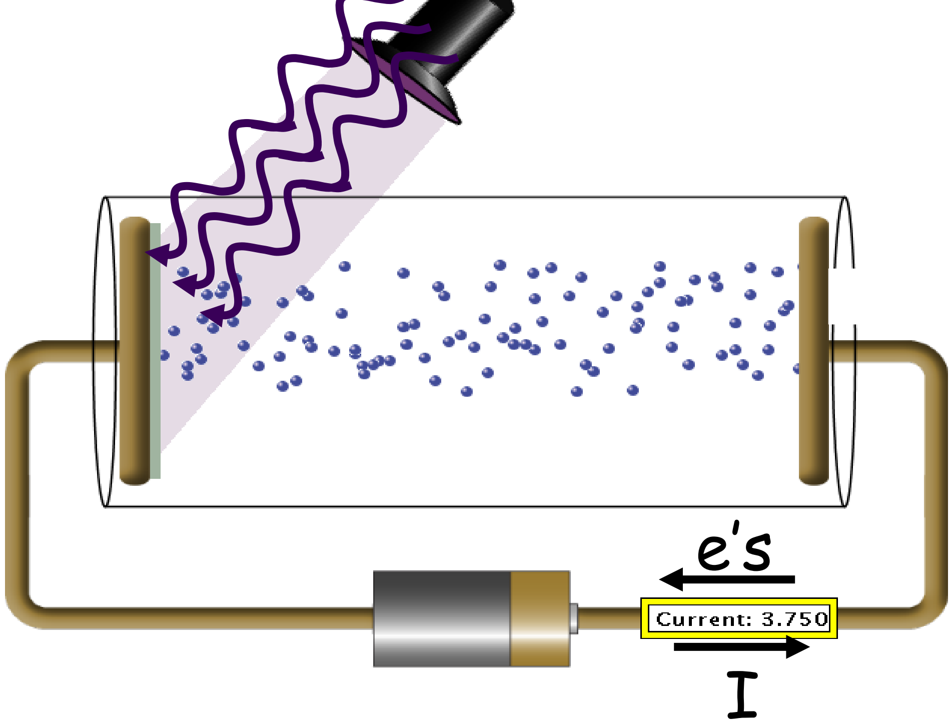
voltage to turn around
most energetic electron
"stopping potential"

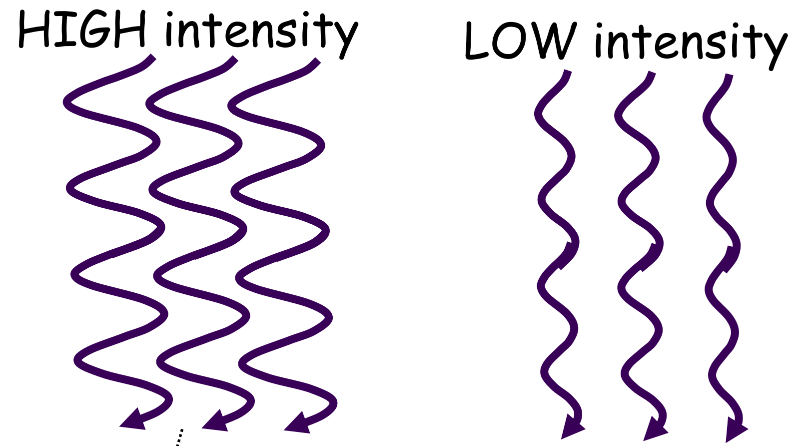


do low I exper.

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

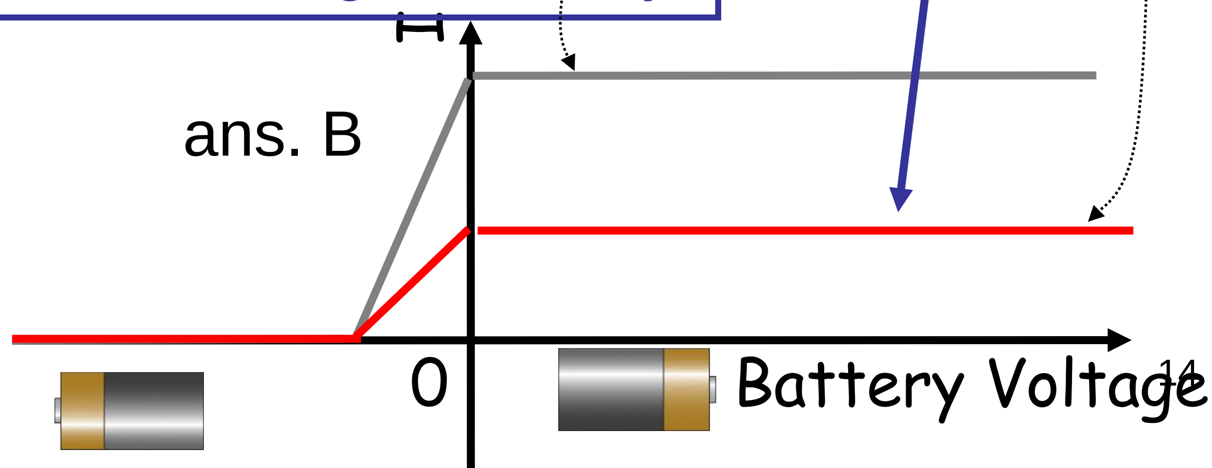


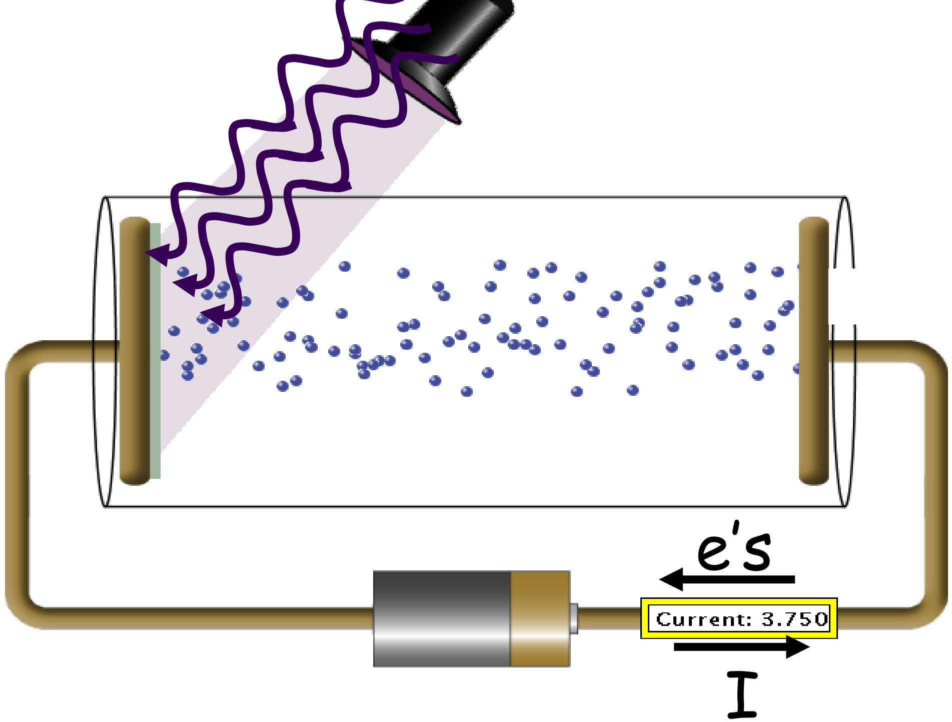


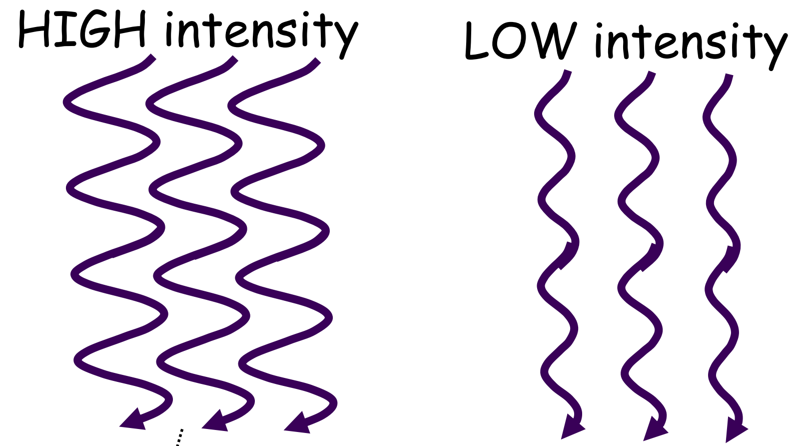


Fewer electrons pop off metal
Current decreases.
Current proportional to light intensity.

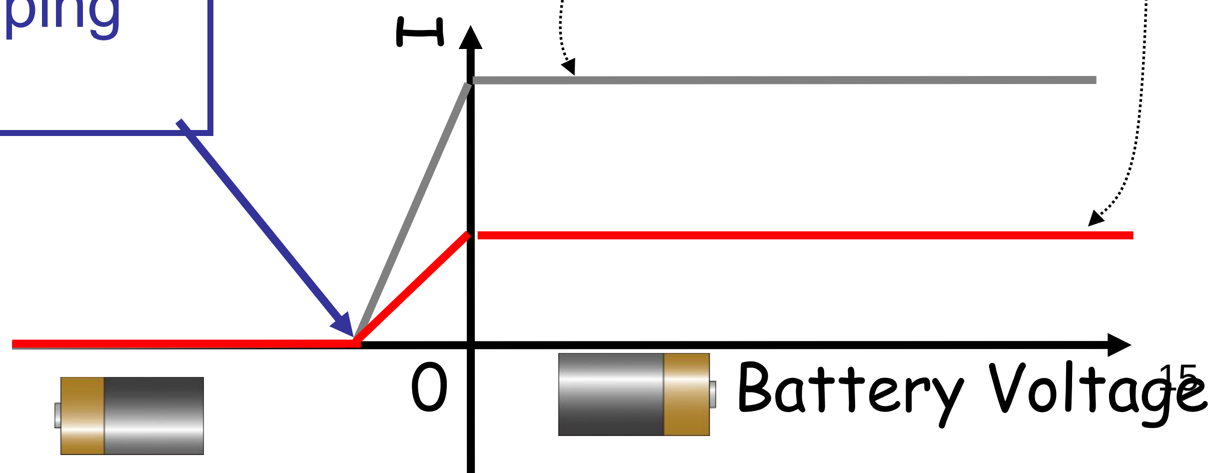
ans. B





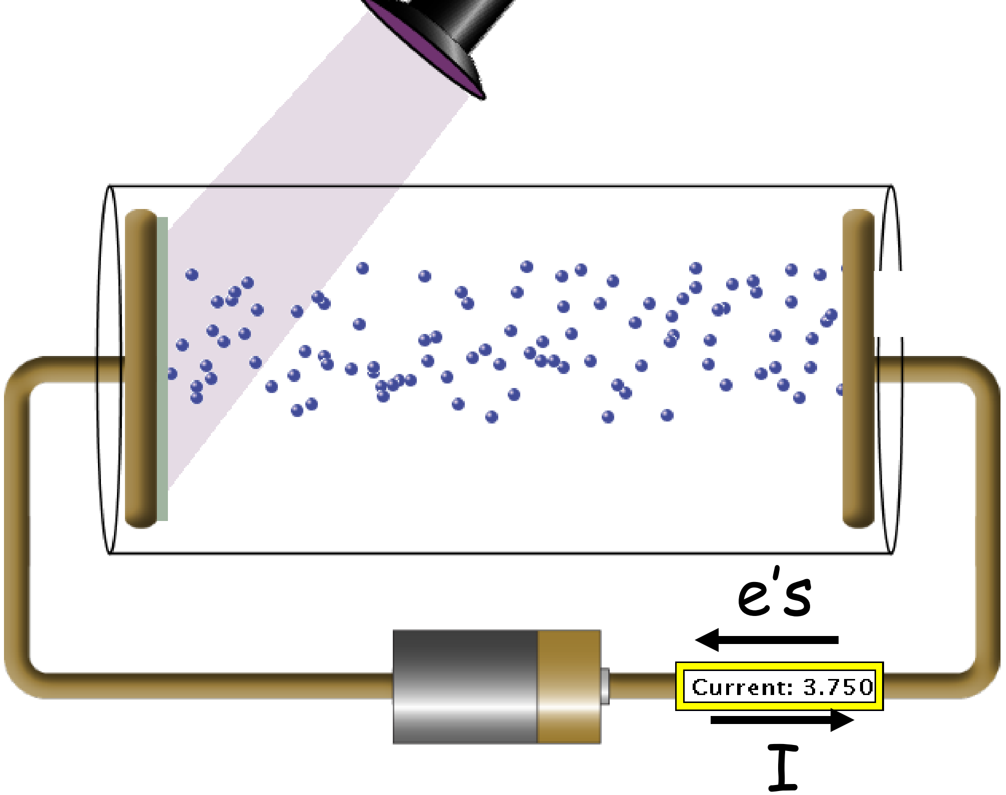


Same KE electrons popping off metal. So same "stopping potential".

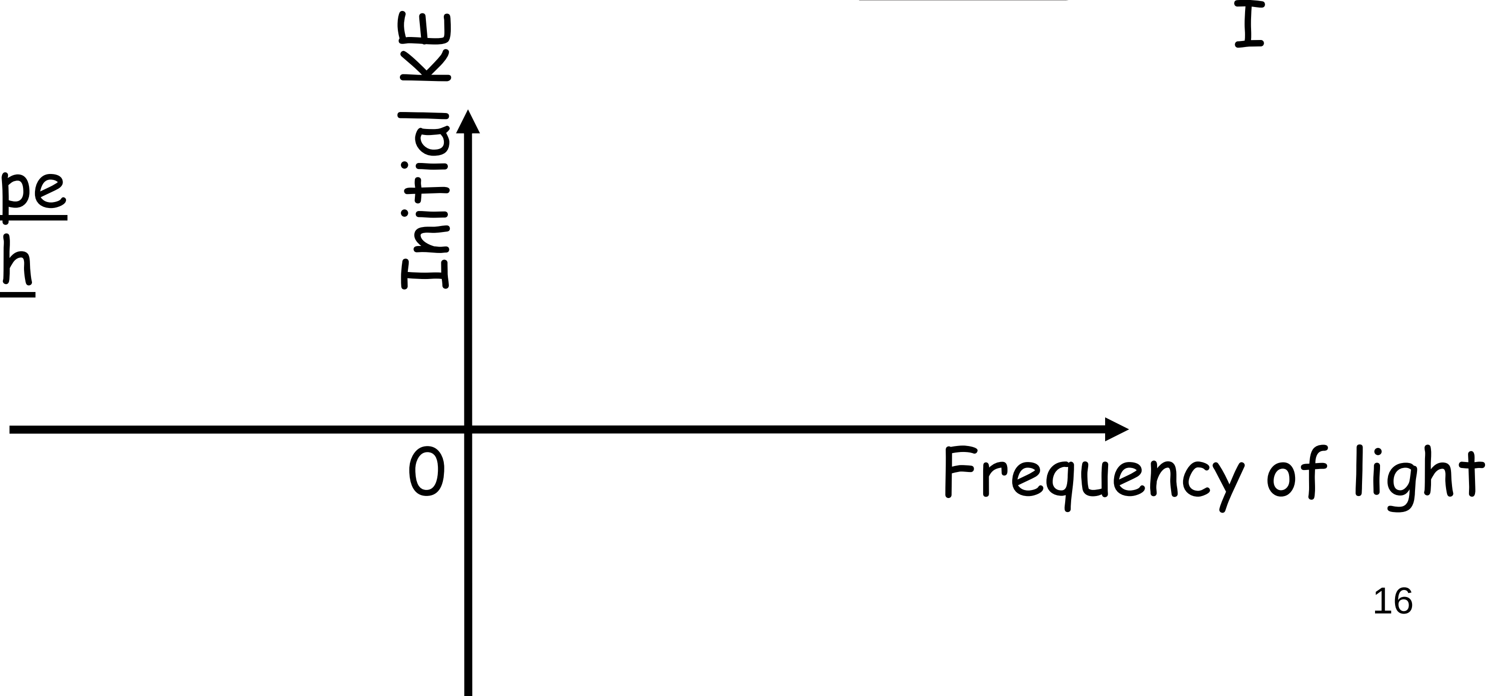


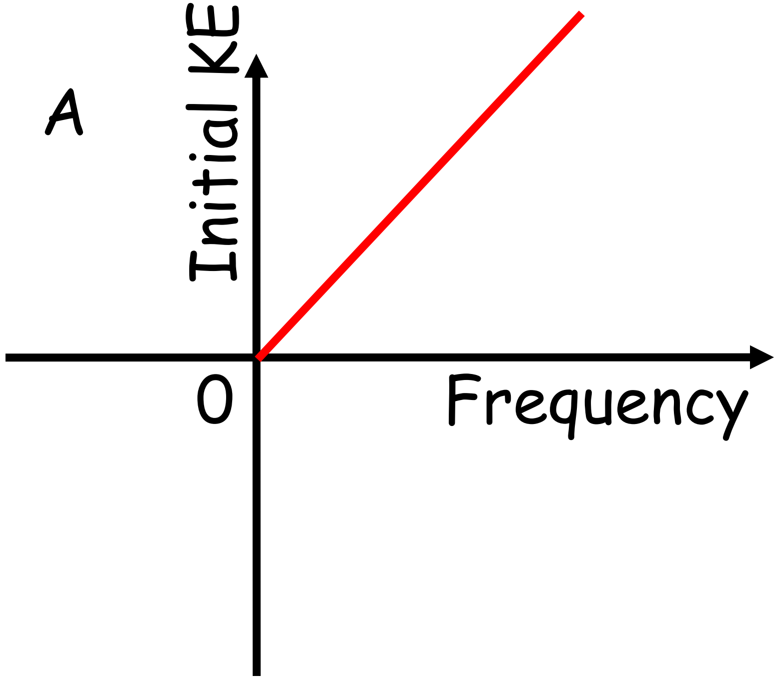
look at sim for few different colors, small forward V

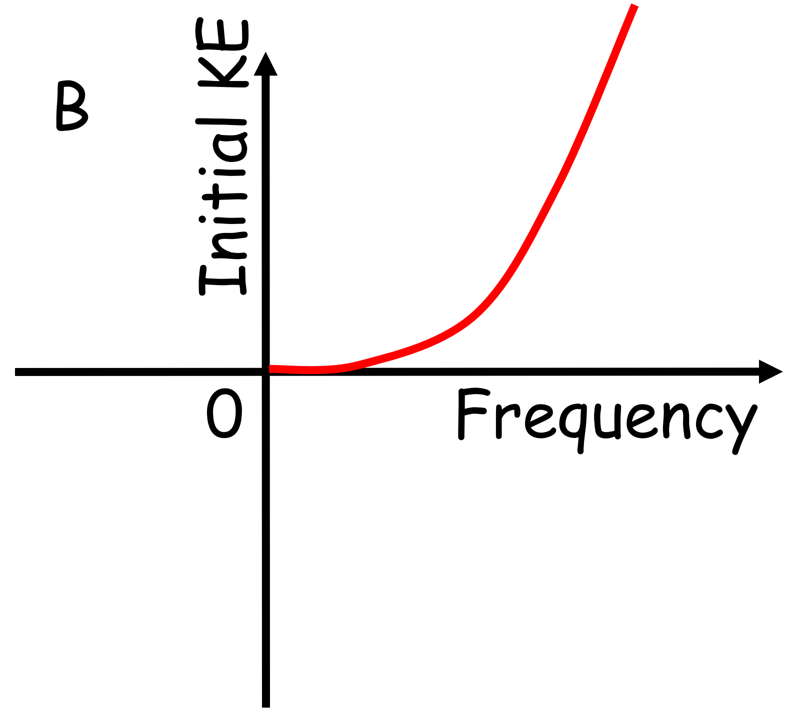
Predict what happens to the initial KE of the electrons as the *frequency* of light changes? (Light intensity is constant)

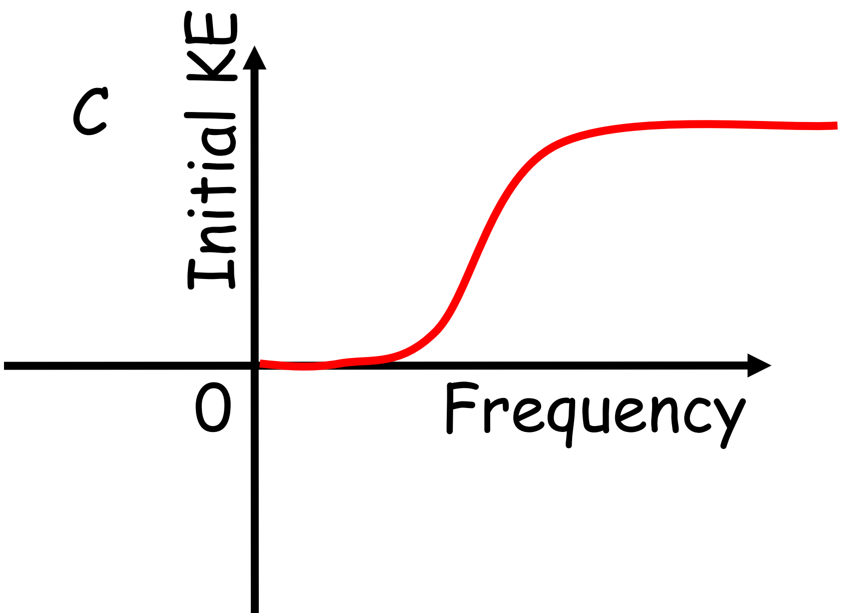


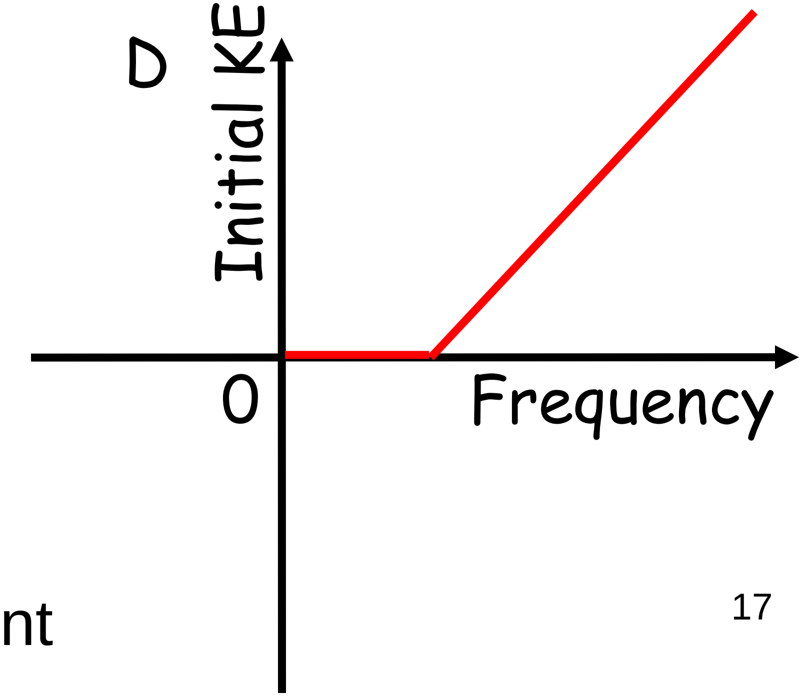
Predict shape of the graph







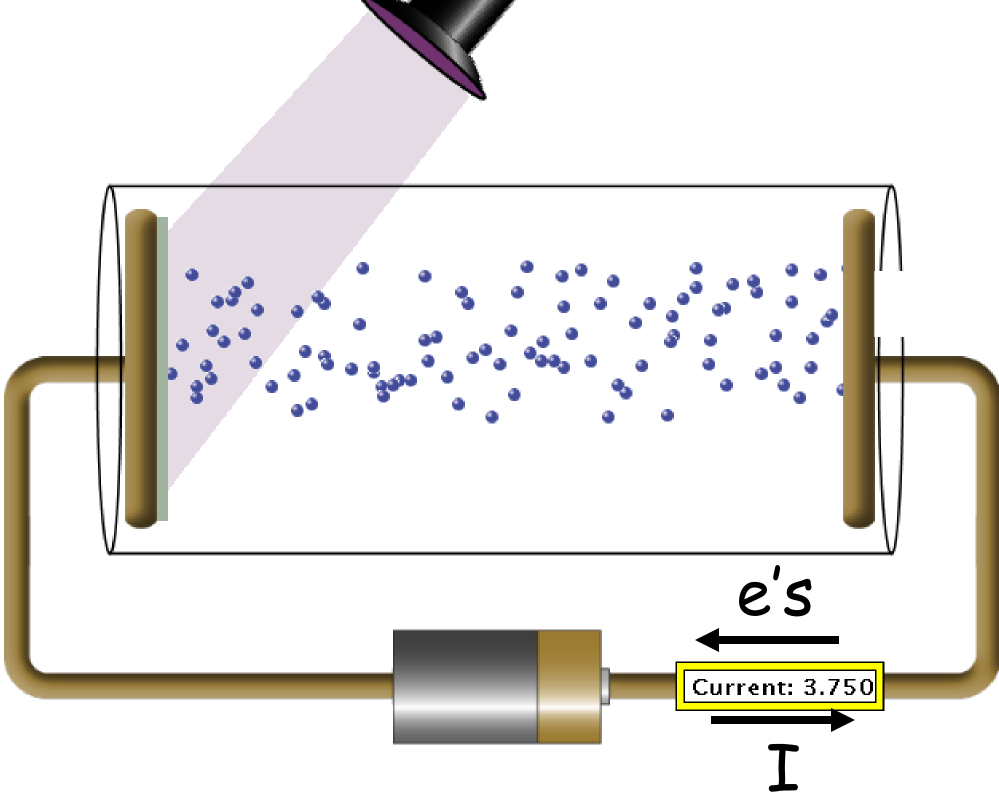




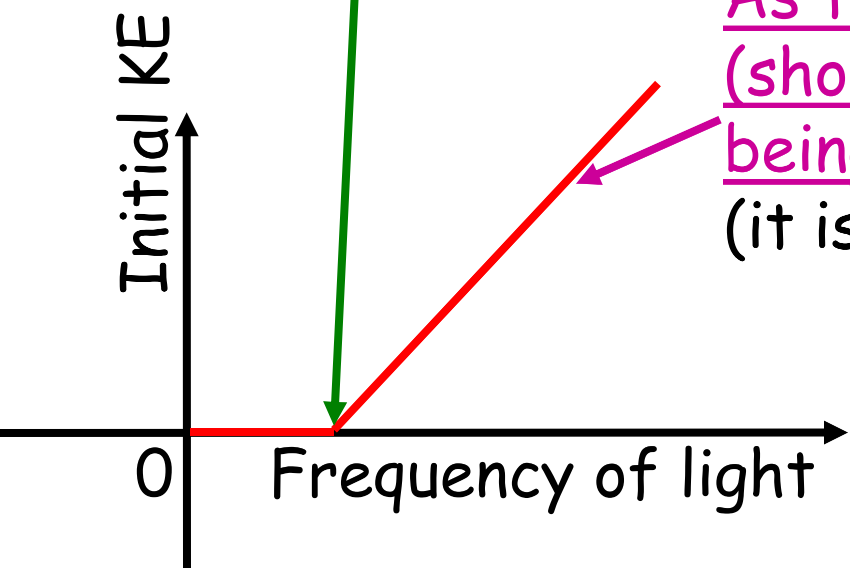
E. something different

Correct answer is D.

do sim showing graph



There is a minimum frequency below which the light cannot kick out electrons…
even if wait a long time



As the ***frequency*** *of light increases (shorter λ!), the KE of electrons being popped off increases.*

(it is a linear relationship)

what happens if change metal?

do experiment

Summary of Photoelectric experiment results.

(play with sim to check and thoroughly understand)

http://phet.colorado.edu/new/simulations/sims.php?sim=Photoelectric_Effect

1. Current linearly proportional to 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 (=1/wavelength). (Max. energy = -stopping potential)

5. Threshold frequency depends on type of metal.

how do these compare with classical wave predictions?

Classical wave predictions vs. experimental observations

•Increase intensity, increase 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 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

Summary of what we know so far:

1. If light can kick out electron, then even smallest intensities of that light will continue to kick out electrons. KE of electrons does not depend on intensity.
   (Light energy must be getting concentrated/focused somehow)

2. At lower frequencies, initial KE decreases & KE changes linearly with frequency.
   (This concentrated energy is linearly related to frequency)

3. Is 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 only with single electron
- Photon energy depends on frequency of light, …
for lower frequencies, photon energy not enough to free an electron

questions?, more sim experiments?

show photon view

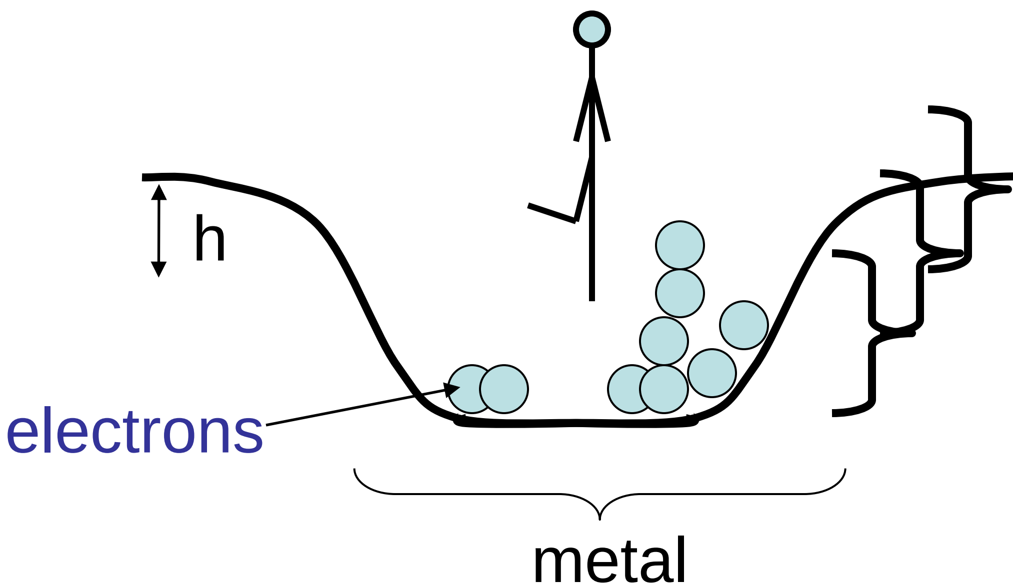
An analogy with a ball and a pit

Light 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:

$\boxed{\text{KE = kick energy - mgh}}$

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



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

show photon view

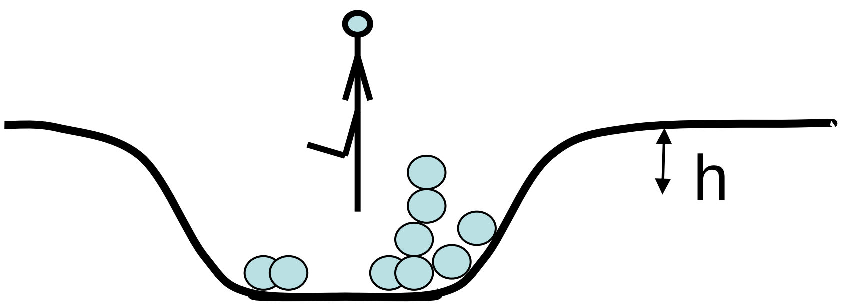
An analogy with a ball and a pit

Light 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:

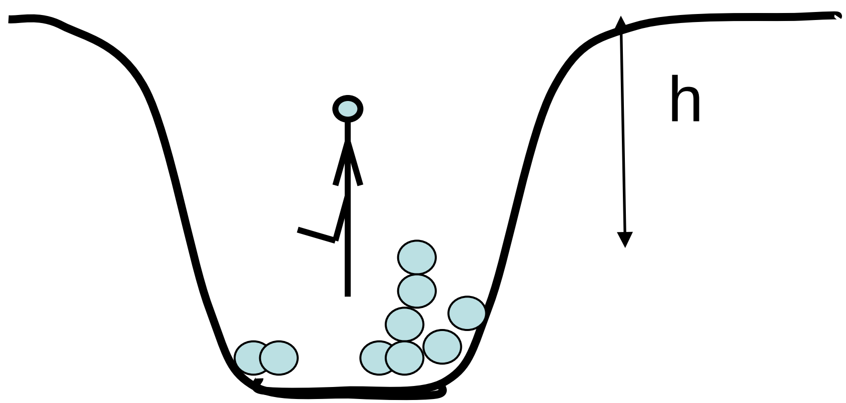
$$\boxed{KE = \text{kick energy} - mgh}$$

energy needed to get most energetic electron out of pit ("work function")



sodium- easy to kick out

small work function ⇔ shallow pit



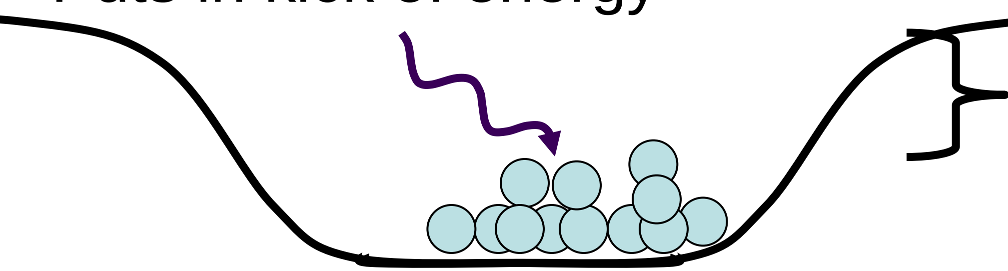
platinum, hard to kick out

large work function ⇔ deep pit

If photon has enough energy,
electron emerges with: $\boxed{\text{KE = photon energy – work function}}$

Photon…

Puts in kick of energy



energy needed to kick highest electron out of metal.
"WORK FUNCTION" (ϕ)

Each photon has: Energy = Planks constant * Frequency

(Energy in Joules)	(Energy in eV)
$E=hf=(6.626*10^{-34}\ \text{J-s})*(f\ s^{-1})$	$E=hf=(4.14*10^{-15}\ \text{eV-s})*(f\ s^{-1})$
$E=hc/\lambda = (1.99*10^{-25}\ \text{J-m})/(\lambda\ \text{m})$	$E=hc/\lambda = (1240\ \text{eV-nm})/(\lambda\ \text{nm})$

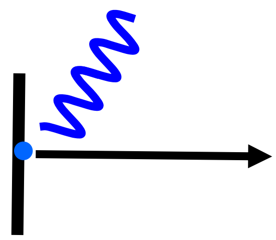
Initial KE of electron as it comes out of metal $= E_{photon}$ - energy needed to kick electron out of metal

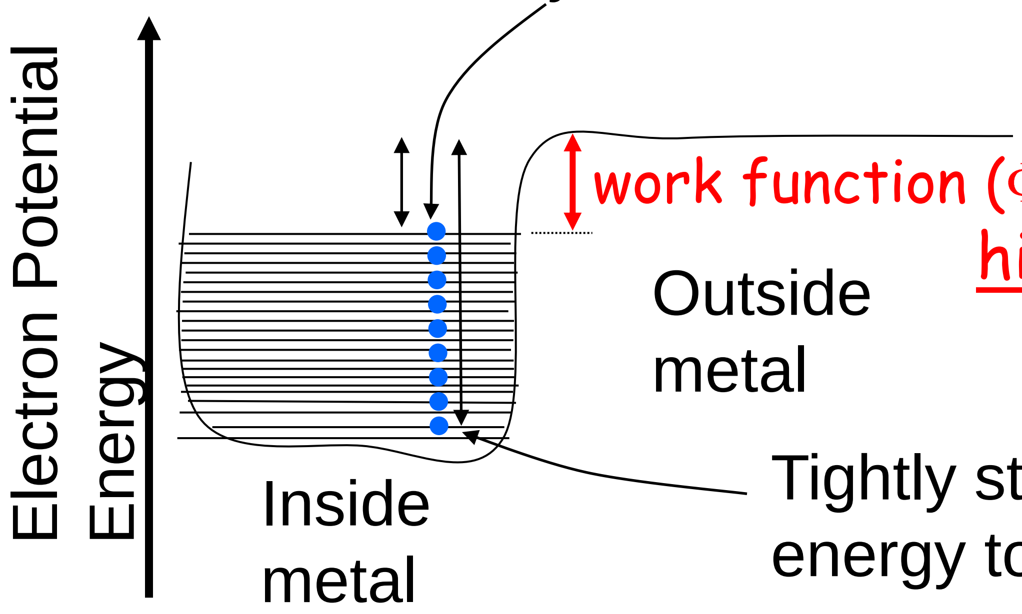
Depends on type of metal.

Photoelectric effect experiment: Apply Conservation of Energy

Energy in = Energy out

Energy of photon = energy needed to kick electron out of metal + Initial KE of electron as exits metal



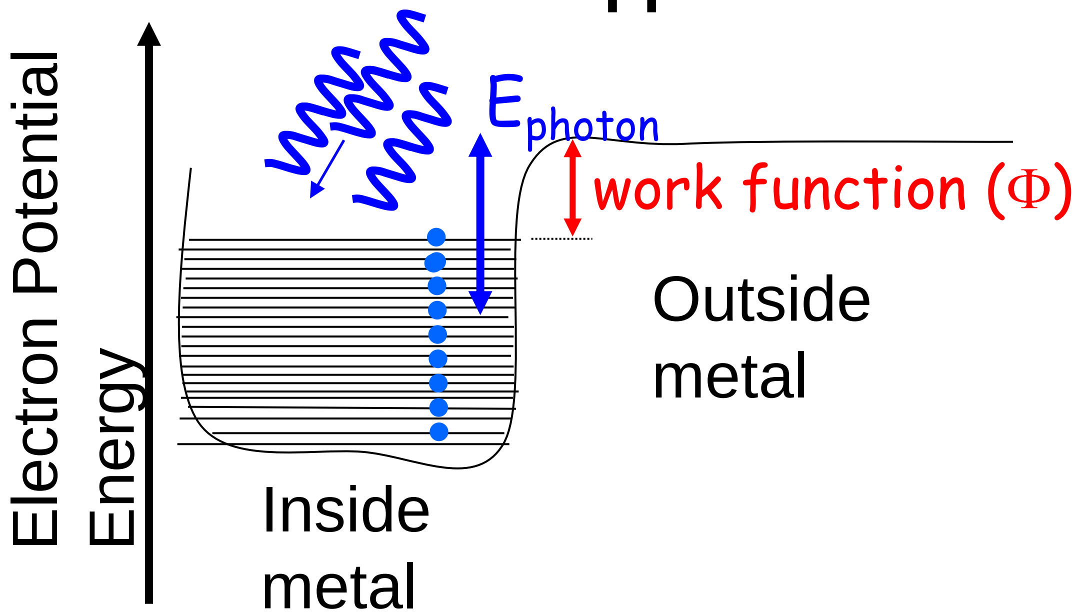


Apply Conservation of Energy.

Energy in = Energy out

Energy of photon = energy needed to kick electron out of metal + Initial KE of electron as exits metal

What happens if send in bunch of blue photons?



Photon gives electron "kick of energy".

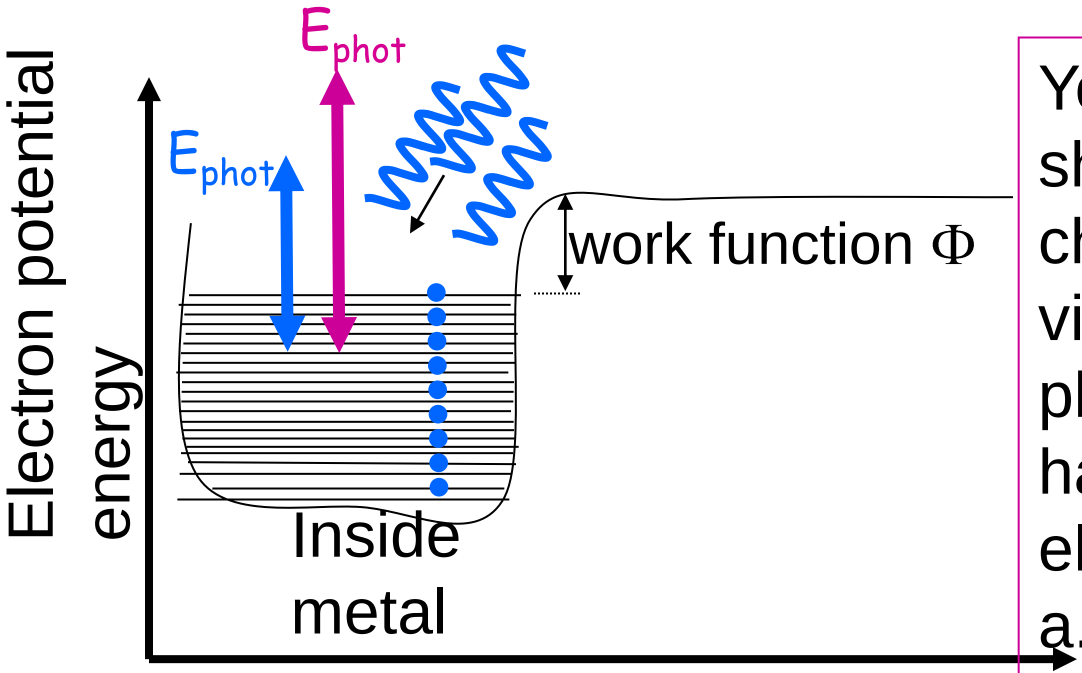
Electrons have equal chance of absorbing photon:

→ Max KE of electrons = photon energy - Φ

→ Min KE = 0

→ Some electrons, not enough energy to pop-out, energy into heat

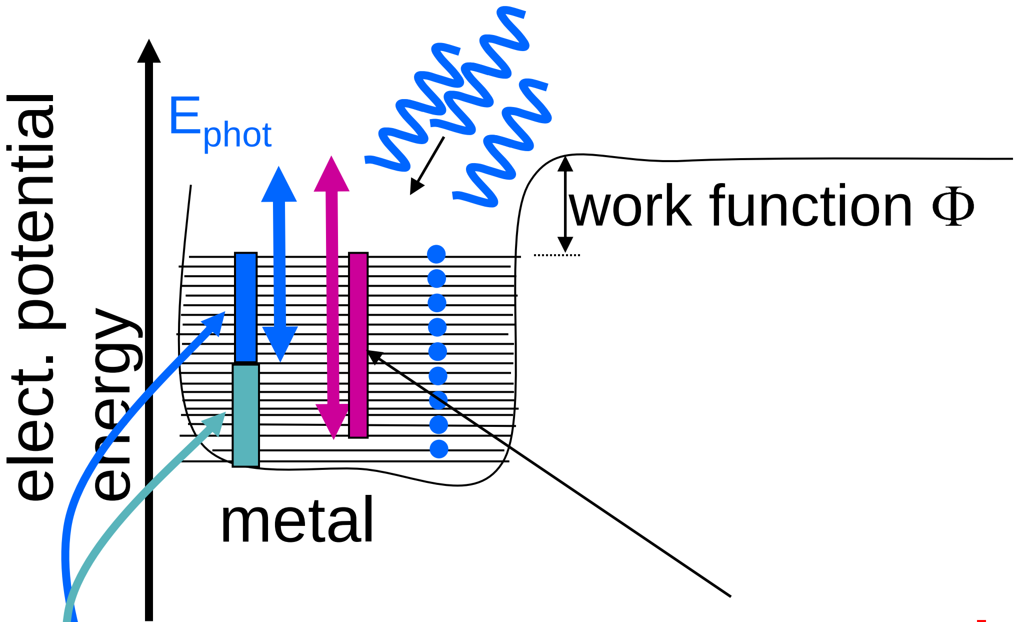
Electrons over large range of energy have equal chance of absorbing photons.



You initially have blue light shining on metal. If you change the frequency to violet light (at same # of photons per second), what happens to the number of electrons coming out?

a. fewer electrons kicked out
b. same # of electrons
c. more electrons kicked out
d. not enough information

Electrons over large range of energy have equal chance of absorbing photons.



c. more electrons come out with violet

absorb blue light and have enough energy to leave

absorb blue light, but don't come out

so the more energy the light has, the more electrons that come out, until so much energy that every electron comes out.

(violet and ultraviolet would not be very different in this case)

Typical energies

Photon Energies:

Each photon has: Energy = Planks constant * Frequency

(Energy in Joules)

$E=hf=(6.626*10^{-34}\text{ J-s})*(f\text{ s}^{-1})$

$E=hc/\lambda = (1.99*10^{-25}\text{ J-m})/(\lambda\text{ m})$

(Energy in eV)

$E=hf= (4.14*10^{-15}\text{ eV-s})*(f\text{ s}^{-1})$

$E= hc/\lambda = (1240\text{ eV-nm})/(\lambda\text{ nm})$

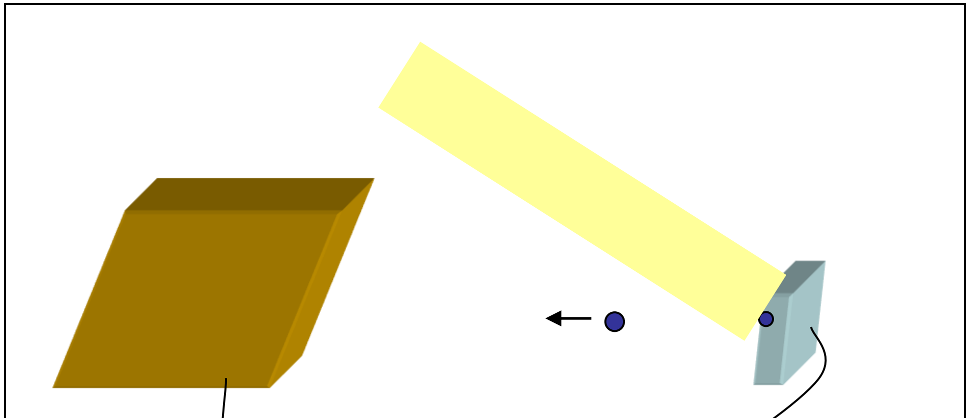
Red Photon: 650 nm

$$E_{photon} = \frac{1240\text{ eV-nm}}{650\text{ nm}} = 1.91\text{ eV}$$

Work functions of metals (in eV):

Aluminum	4.08 eV	Cesium	2.1	Lead	4.14	Potassium	2.3
Beryllium	5.0 eV	Cobalt	5.0	Magnesium	3.68	Platinum	6.35
Cadmium	4.07 eV	Copper	4.7	Mercury	4.5	Selenium	5.11
Calcium	2.9	Gold	5.1	Nickel	5.01	Silver	4.73
Carbon	4.81	Iron	4.5	Niobium	4.3	Sodium	2.28
						Uranium	3.6
						Zinc	4.3

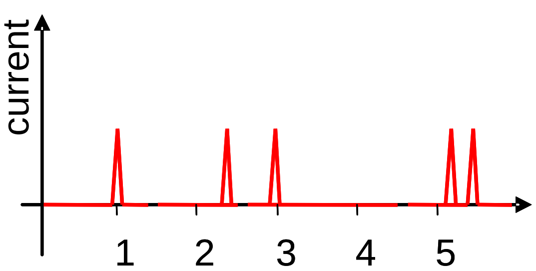
Photomultiplier tubes- application of photoelectric effect
most sensitive way to detect visible light, see single photons
(eye is incredibly good, can see a few photons)



glass vacuum enclosure

big voltage

electron amplifier, gives pulse of current for each photoelectron



cq2. what would be the best choice of these materials to make this out of?

a. Platinum $\Phi = 6.35$ eV
b. Magnesium $= 3.68$ eV
c. Nickel $= 5.01$ eV
d. lead $= 4.14$ eV
e. Sodium $= 2.28$ eV

Clicker question discussion

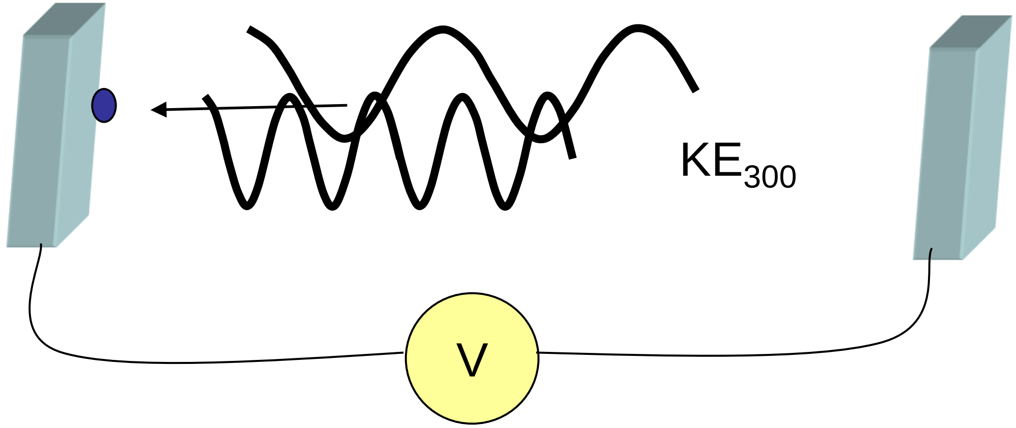
After decide on answer, don’t stop thinking/discussing!

Think of as many reasons as possible to support your answer and/or rule out other answers. Other perspectives, other situations and information that may have relevance.

“Line on electron energy vs frequency graph must go to zero before zero frequency, because sunlight hits stuff but doesn’t make electrons come out of everything.”

Ability to think of multiple ways to test ideas and conclusions, ability to relate to many different contexts, is a learned skill of expert scientists and engineers.

Useful in many aspects of life and work, tested for in interviews.



CQ: A photon at 300 nm will kick out an electron with an amount of kinetic energy, KE_{300}. If the wavelength is halved to 150 nm and the photon hits an electron in the metal with same energy as the previous electron, the energy of the electron coming out is

a. less than ½ KE_{300}.

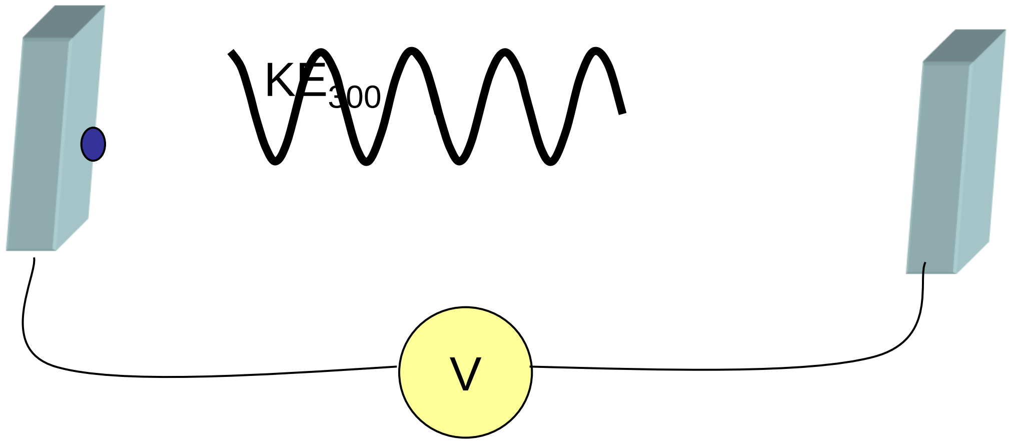
b. ½ KE_{300}

c. = KE_{300}

d. 2 x KE_{300}

e. more than 2 x KE_{300}

(remember hill/kicker analogy, draw pictures to reason out answer, don't just pick answer without careful reasoning)



CQ: Shine in light of 300 nm. The most energetic electrons come out with kinetic energy, KE_{300}. A voltage diff of 1.8 V is required to stop these electrons. What is the work function Φ for this plate? (e.g. the minimum amount of energy needed to kick electron out of metal?)

a. 1.2 eV
b. 2.9 eV
c. 6.4 eV
d. 11.3 eV
e. none of the above