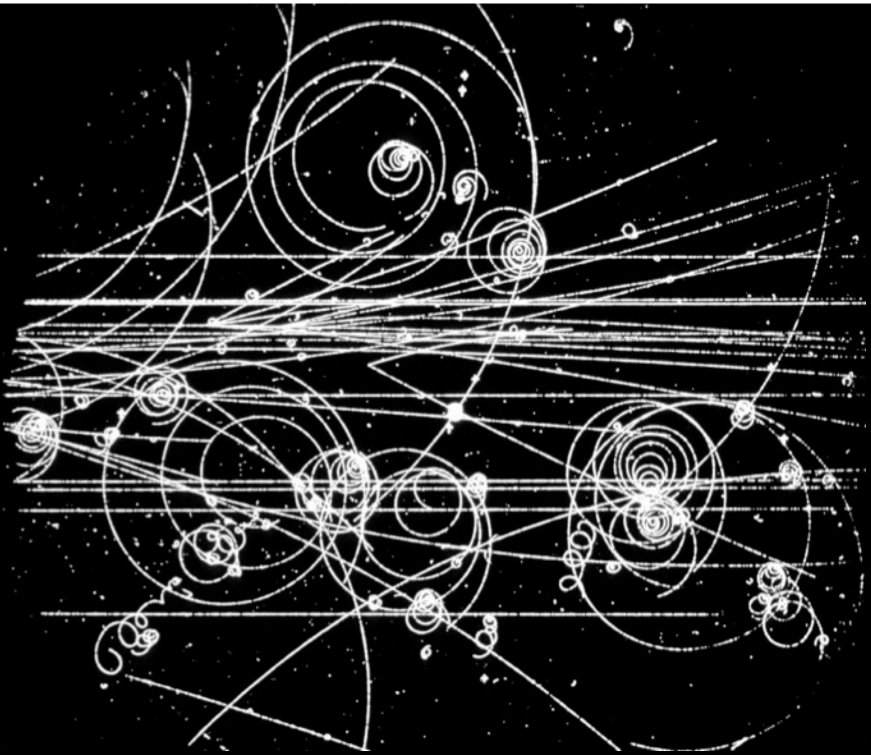
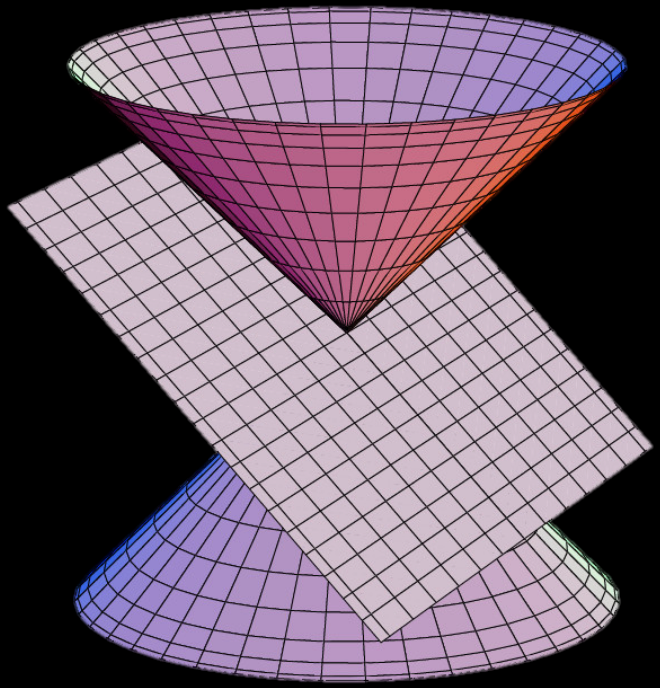
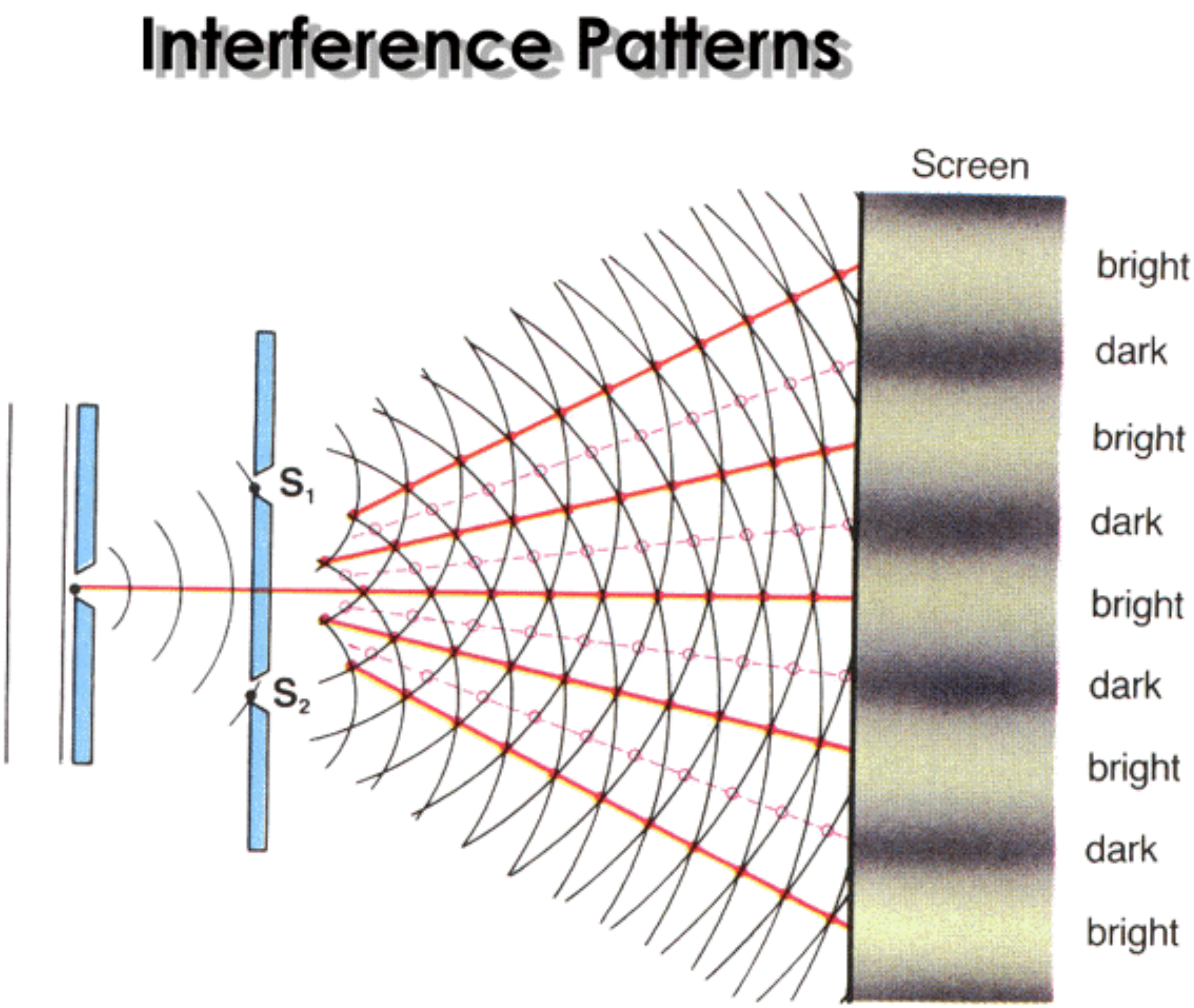




Modern Physics (Phys. IV): 2704

Professor Jasper Halekas
Van Allen 70
MWF 12:30-1:20 Lecture

The Wavelike Nature of Light



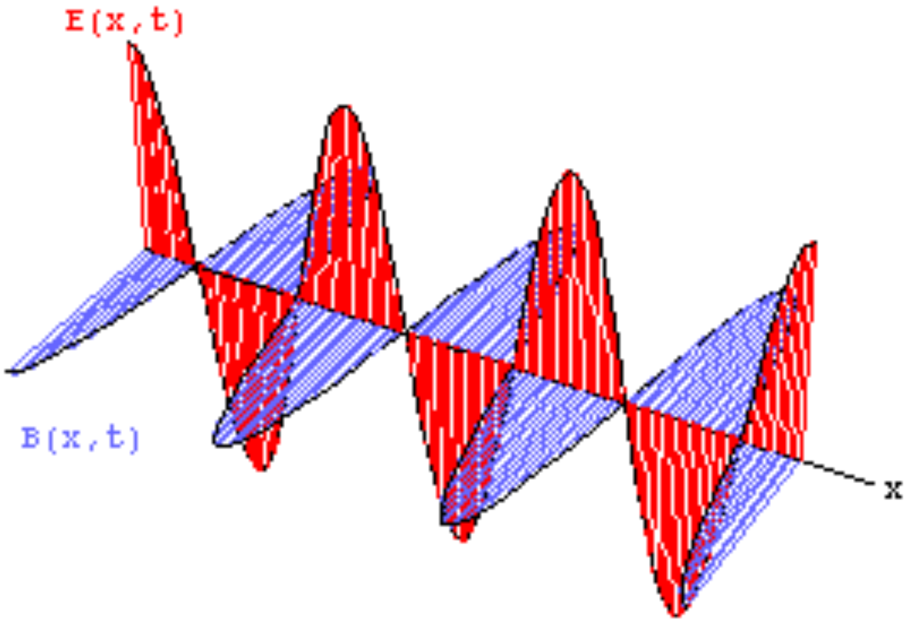
Maxwell's Equations: Integral Form

Maxwell's Equations — Differential form	Maxwell's Equations — Integral form
$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$	$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$
$\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$	$\oint \vec{E} \cdot d\vec{l} = \boxed{-\int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{a}}$
$\nabla \cdot \vec{B} = 0$	$\oint \vec{B} \cdot d\vec{a} = 0$
$\nabla \times \vec{B} = \mu_0 \vec{J} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}$	$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \boxed{\mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}}$

Maxwell's Equations: Plane Wave

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}$$

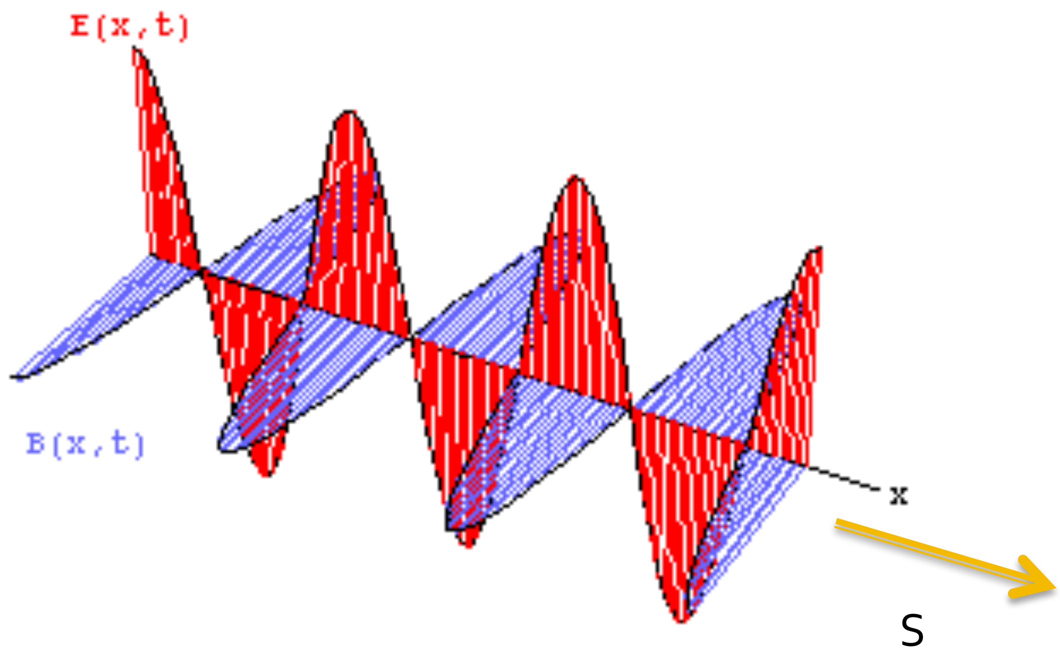


$\mathbf{E} = \mathbf{E_o} \cos(kx-\omega t)$
$\mathbf{B} = \mathbf{B_o} \cos(kx-\omega t)$

$\omega/k = c$
$E_o/B_o = c$

Poynting Flux

- **S** = (**E x B**)/μ_o is the Poynting flux of an EM wave
  - **S** has units of energy per time per area = power per area
  - Intensity I = <|**S**|>
  - Energy = S*A*t



Concept Check

- How does the intensity of light I change if the electric field amplitude is doubled?

A. I stays the same
B. I doubles
C. I increases by a factor of four
D. I decreases by a factor of two

Concept Check

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Light Waves

$$\vec{E} = E_0 \cos(kx - \omega t)\,\hat{j}$$
$$\vec{B} = B_0 \cos(kx - \omega t)\,\hat{k}$$

$k = 2\pi/\lambda$ "wave number"

$\omega = 2\pi\nu$ "angular frequency"

$$\omega/k = \nu\lambda = c$$
$$E_0/B_0 = c$$

$$\vec{S} = \frac{\vec{E}\times\vec{B}}{\mu_0} = \frac{E_0 B_0}{\mu_0}\cos^2(kx - \omega t)\,\hat{i}$$

$$|\vec{S}|_{max} = \frac{E_0 B_0}{\mu_0} = E_0^2/\mu_0 c$$

$$\langle|\vec{S}|\rangle = E_0^2/\mu_0 c \;\langle\cos^2(kx-\omega t)\rangle$$
$$= E_0^2/2\mu_0 c$$

Intensity $I = \langle|\vec{S}|\rangle$

$$= E_0^2/2\mu_0 c$$

Concept Check

- How does the intensity of light I change if the frequency is doubled?

A. I stays the same
B. I doubles
C. I increases by a factor of four
D. I decreases by a factor of two

Concept Check

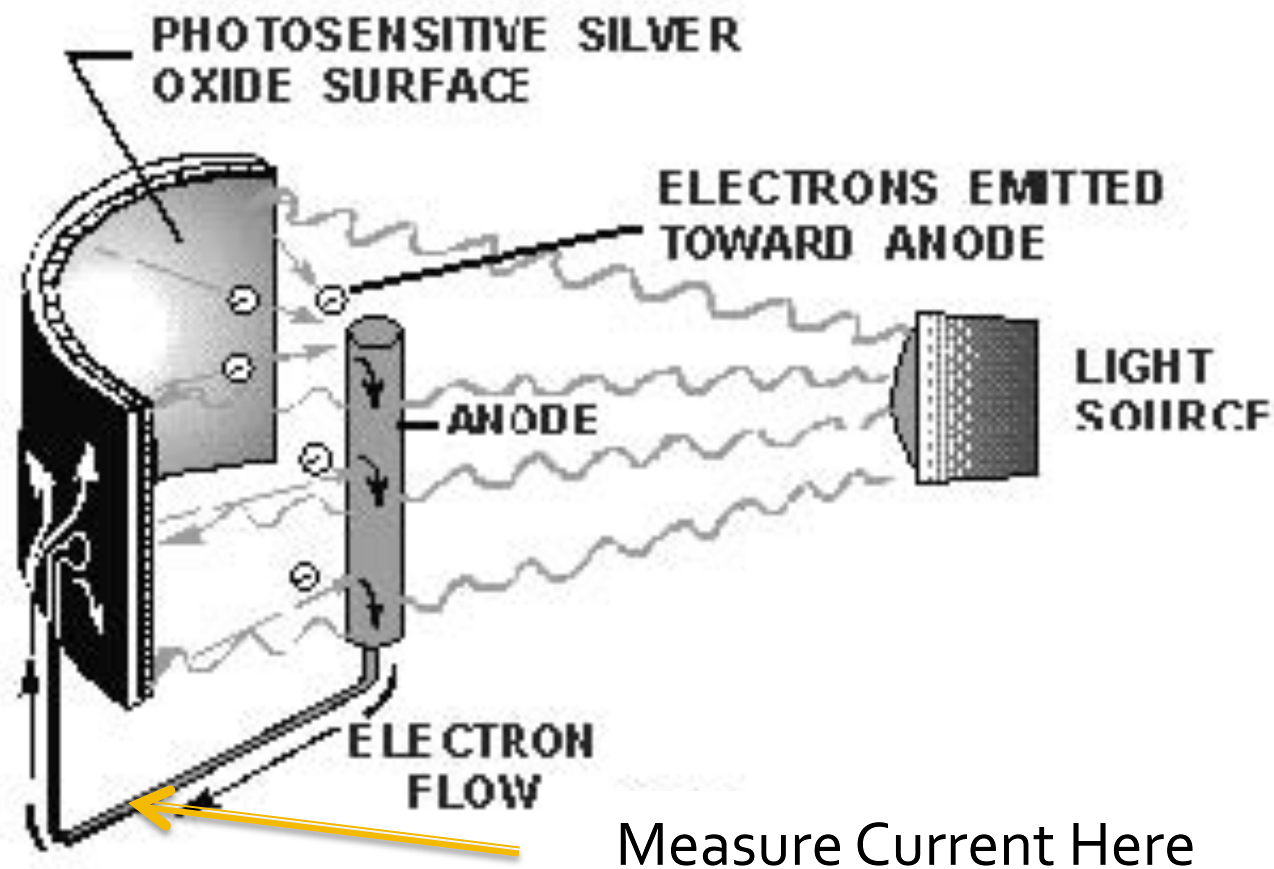
- How does the intensity of light I change if the frequency is doubled?

A. I stays the same
B. I doubles
C. I increases by a factor of four
D. I decreases by a factor of two

Work Function

Electrons need surplus energy equal to or greater than the work function of a material to escape

Photocell


PHOTOSENSITIVE SILVER OXIDE SURFACE
ELECTRONS EMITTED TOWARD ANODE
ANODE
LIGHT SOURCE
ELECTRON FLOW
Measure Current Here

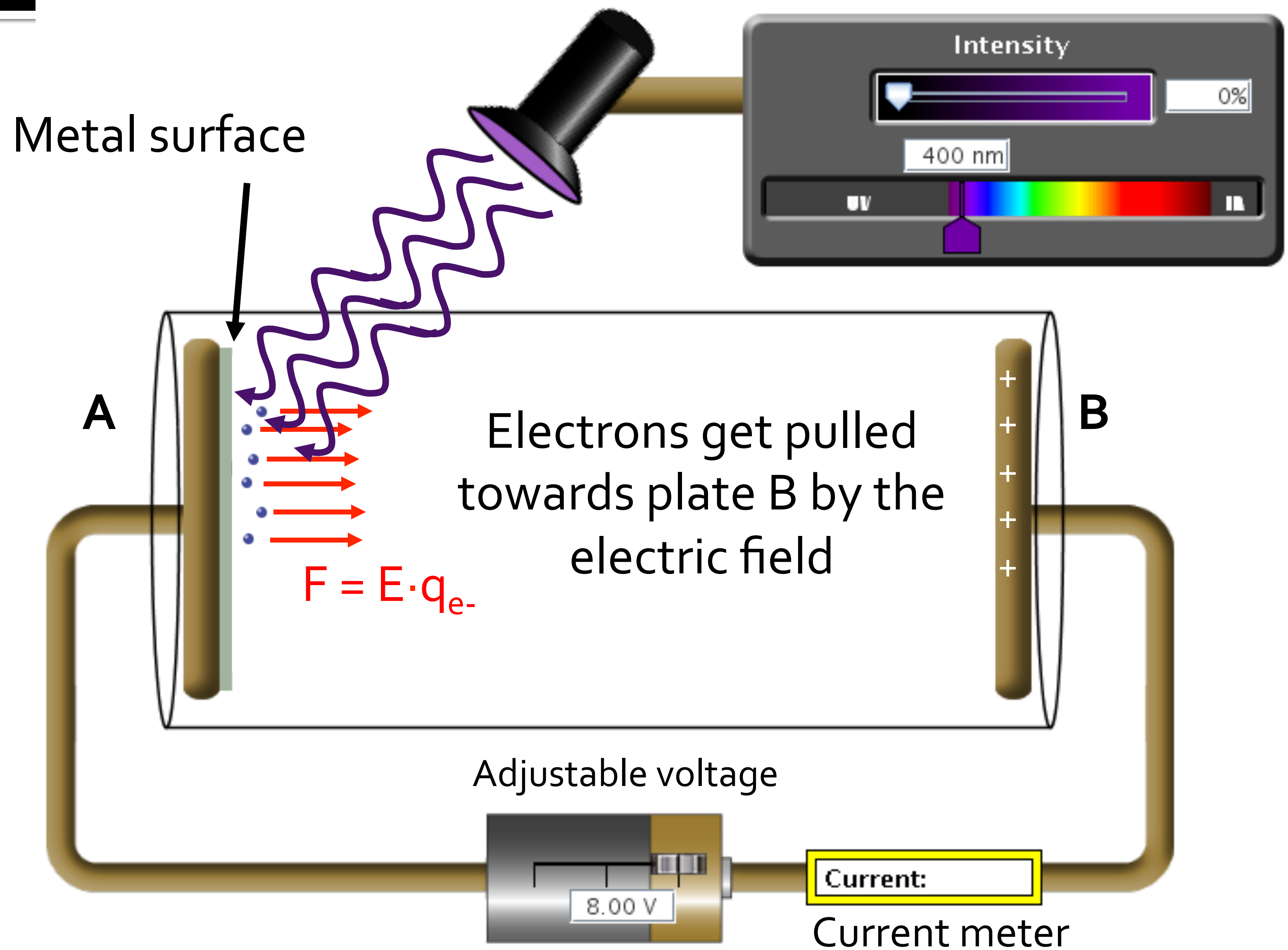
Photelectric Classical Prediction

I. Maximum kinetic energy of the electrons should be proportional to intensity of light (since qE accelerates them!)

II. Electrons should be ejected by light of any frequency/wavelength

III. Electrons may not be ejected immediately (takes time to deliver enough energy)

Stopping Potential Experiment



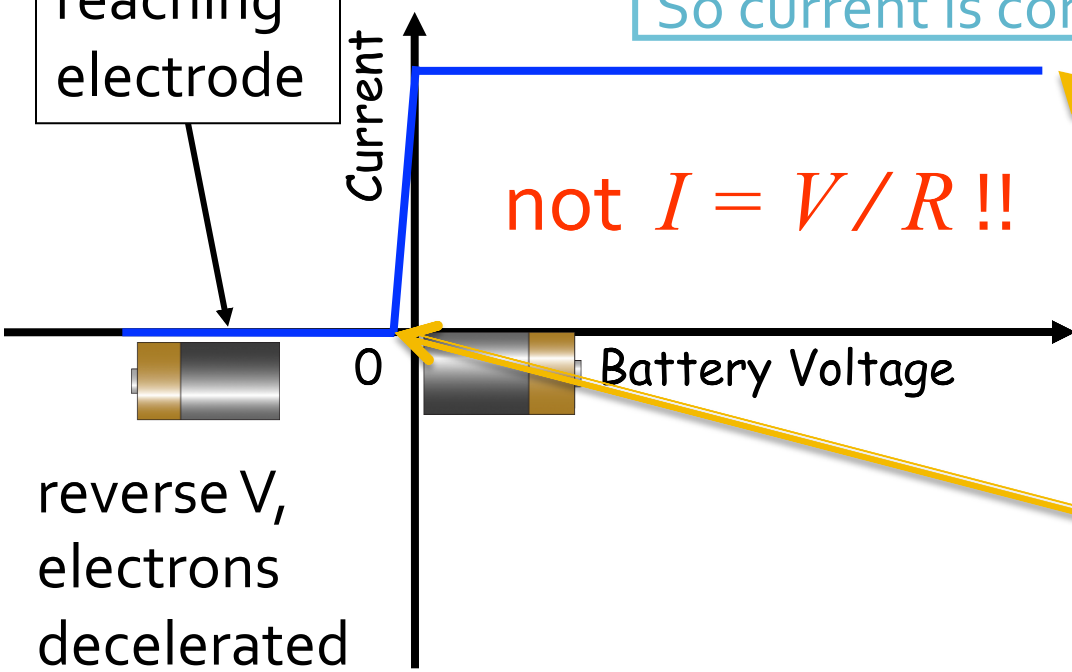
Classical Prediction

Each electron that pops out is accelerated and hits the plate on the right side.

$$\frac{\#\text{ of electrons}}{\text{sec}} = \text{constant}$$

So current is constant!

Here, electrons stopped before reaching electrode

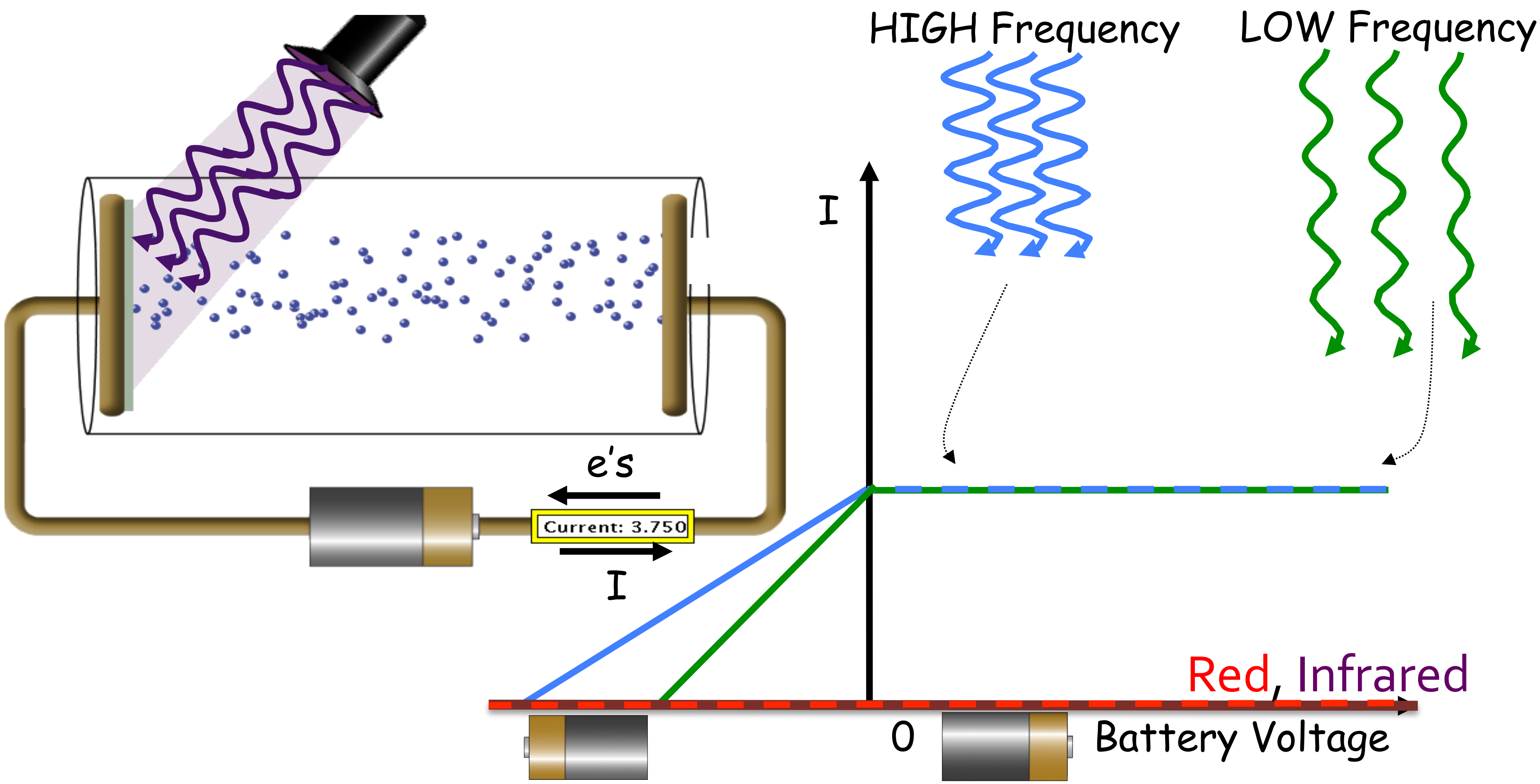


reverse V, electrons decelerated

Classically, the height would vary with intensity, but not with wavelength/frequency

Classically, the stopping potential would increase with intensity, but not with wavelength/frequency

Reality


HIGH Frequency
LOW Frequency
I
e's
Current: 3.750
I
Red, Infrared
0
Battery Voltage

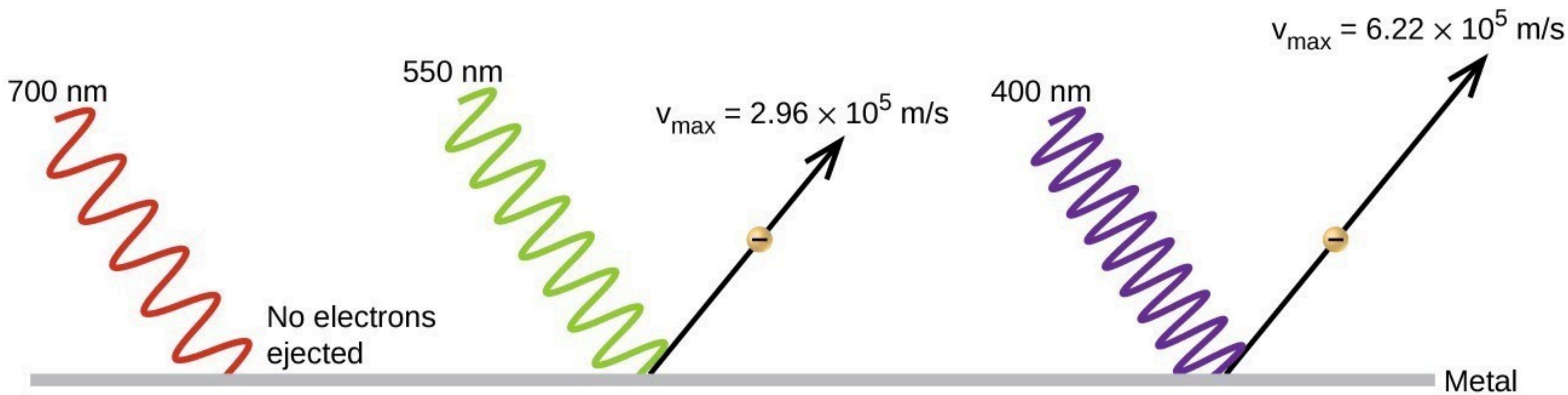
Photoelectric Reality

I. For fixed wavelength/frequency, the maximum kinetic energy of photoelectrons is independent of intensity

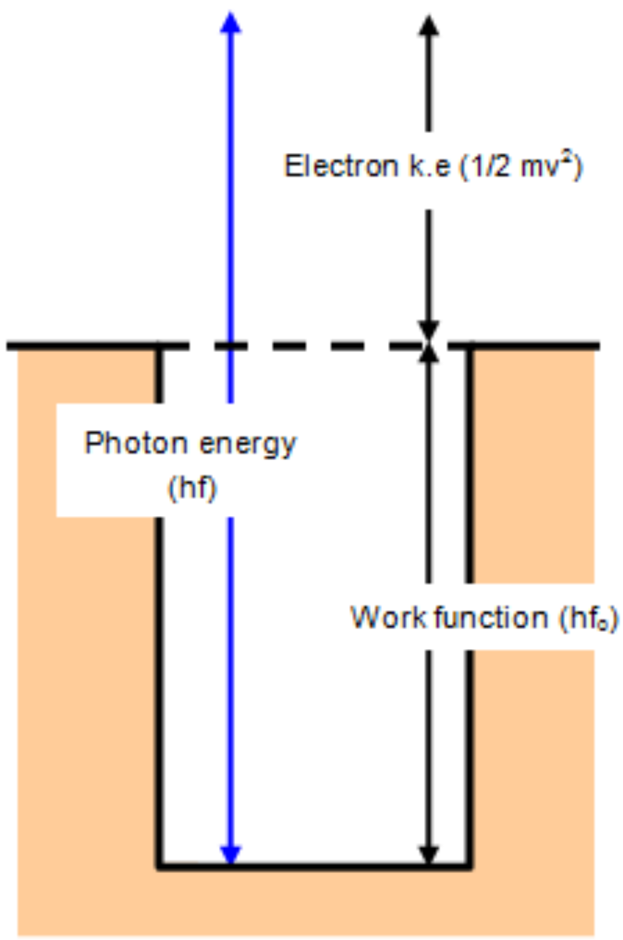
II. The photoelectric effect only occurs above a threshold frequency (below a threshold wavelength)

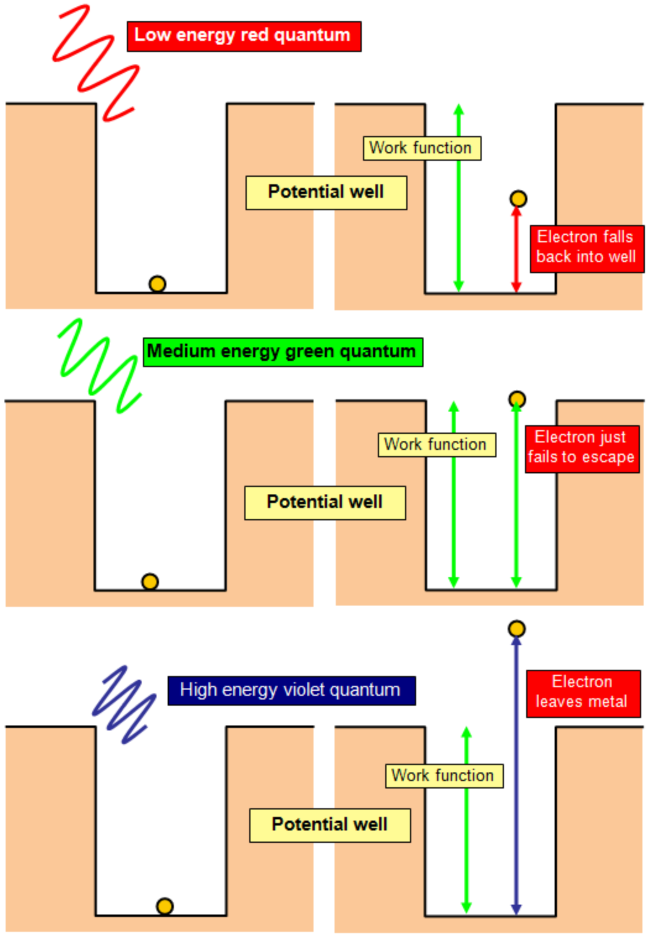
III. First photoelectrons can be emitted almost instantaneously

What's Going On?



What's Going On?





Kicker Analogy

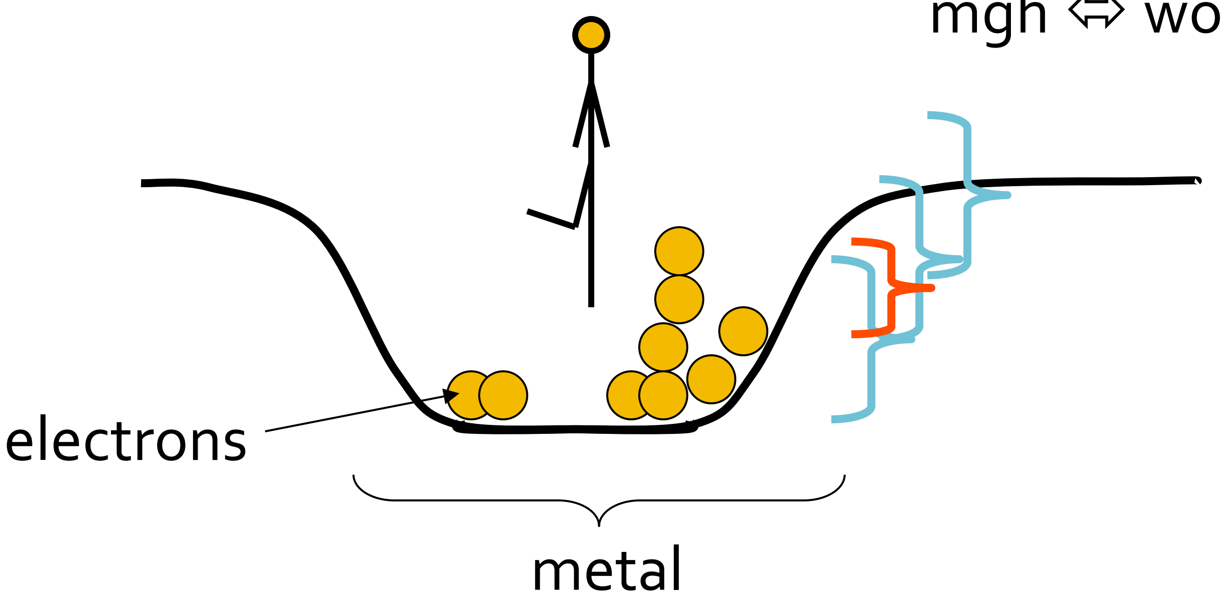
Ball emerges with:

KE = kick energy - mgh

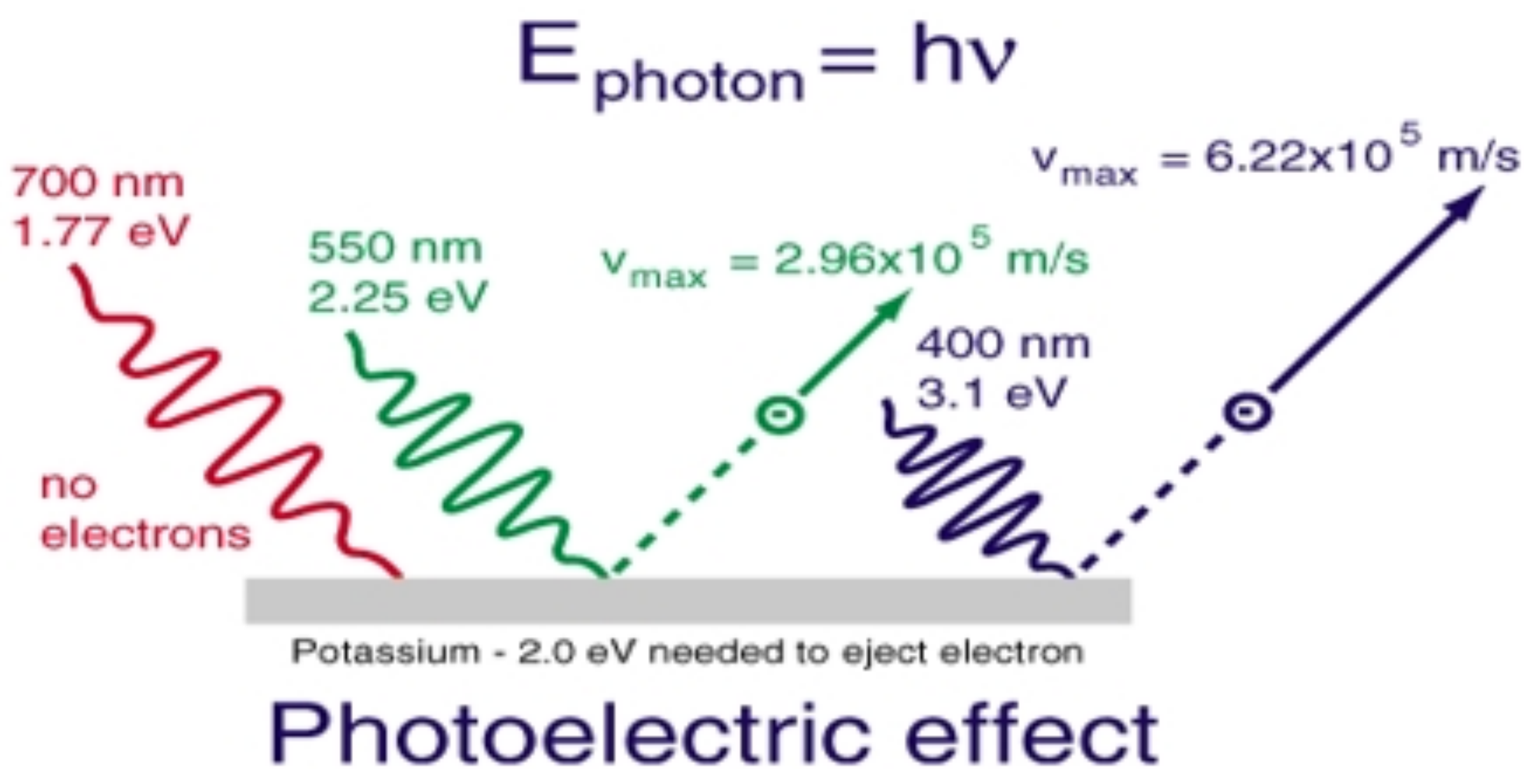
mgh = energy needed to make it up hill and out.

mgh ⇔ work function.

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



Photoelectric Effect



Photoelectric Effect

- Electron kinetic energy

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

- threshold when stopping potential is zero, or $K_{max} = 0$

$$\Rightarrow h\nu = \varphi$$

critical frequency

$$\nu_c = \varphi / h$$

critical wavelength

$$\lambda_c = c/\nu_c = hc/\varphi$$

Note $E = h\nu$ for photon

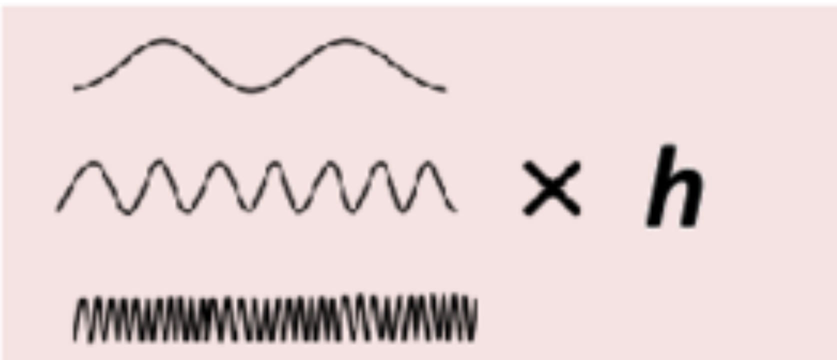
$$E^2 = (pc)^2 + (mc^2)^2$$
$$= (pc)^2$$

$$\Rightarrow h\nu = pc \quad \Rightarrow p = h\nu/c$$
$$= h/\lambda$$

Planck's Constant

The Planck Constant: h

a proportionality between frequency (ν) and energy



$$E = h\nu$$

$h = 6.626 \times 10^{-34}$ J s

$$\hbar = h/(2\pi)$$

Typical energies

Each photon has: Energy = hν = Planck's constant * Frequency

(Energy in Joules)

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

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

(Energy in eV)

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

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

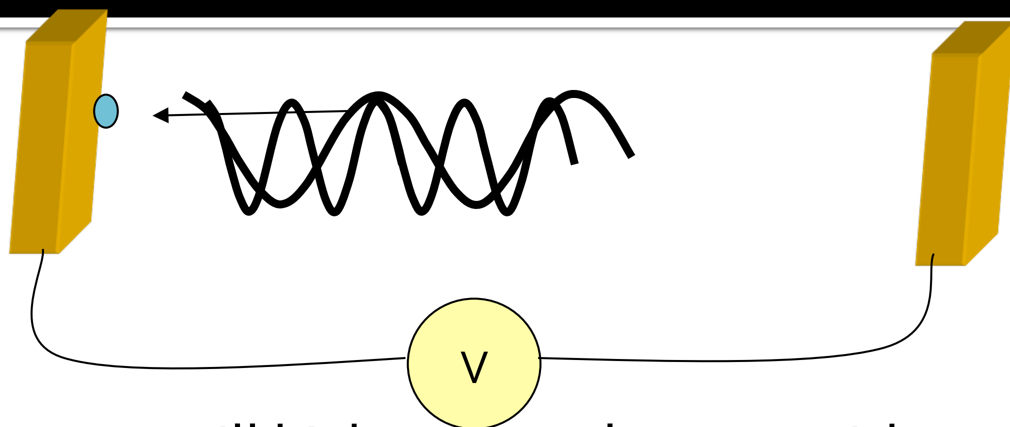
Red Photon: 650 nm

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

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

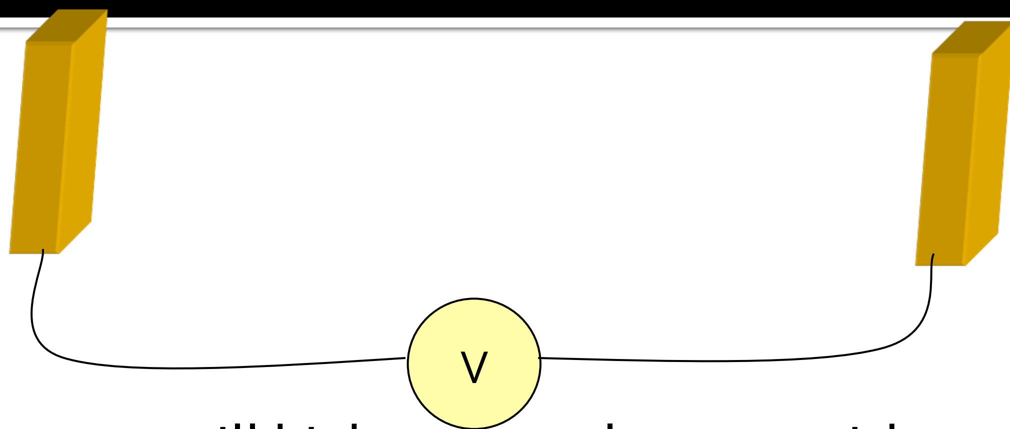
Concept Check



A photon at 300 nm will kick out an electron with an amount of kinetic energy, KE_{300}. If the wavelength is halved, 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}

Concept Check



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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}

$$KE_{300} = h\nu - \varphi$$

$$KE_{150} = 2h\nu - \varphi$$

$$= 2(h\nu - \varphi) + \varphi$$

$$= 2KE_{300} + \varphi$$

$$> 2KE_{300}$$