Photon

~ Quantum of Energy ~

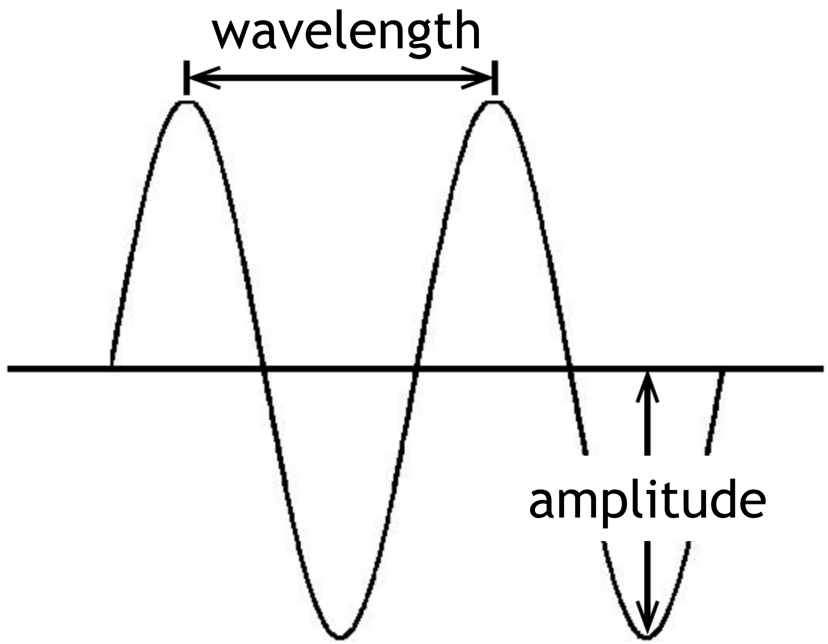
<u>Outline</u>

- Light as Waves
- Light as Particles
    . Photoelectric Effect - photon energy
    . Compton Effect - photon momentum

In physics, a quantum is the minimum unit of any physical entity involved in an interaction. The word comes from the Latin “quantus” for “how much.”

Acknowledgement:
Some of slides are adopted from PHY106 Particle Physics Module at Syracuse University by Dr. Steve Blusk

Light Waves



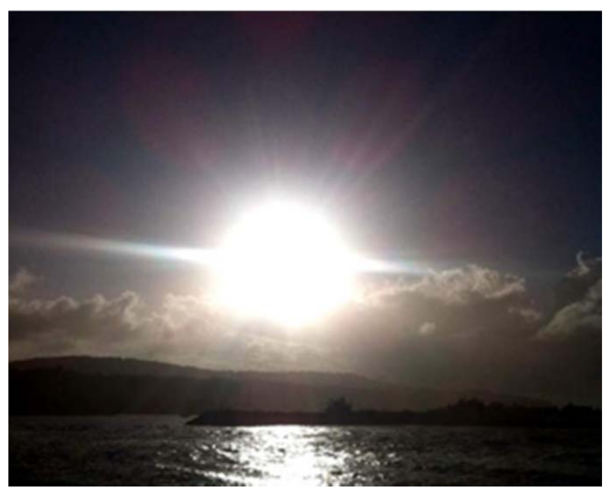
Light waves:

<u>Characterized by:</u>

- Amplitude (A)
- Frequency (ν)
- Wavelength (λ)

Maxwell Showed us that
Energy of EM wave ~ A^2

EM FIELDS FOR WARMING EARTH



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EM FIELDS FOR LASER DRILLING

$$\frac{P}{H} = EH$$

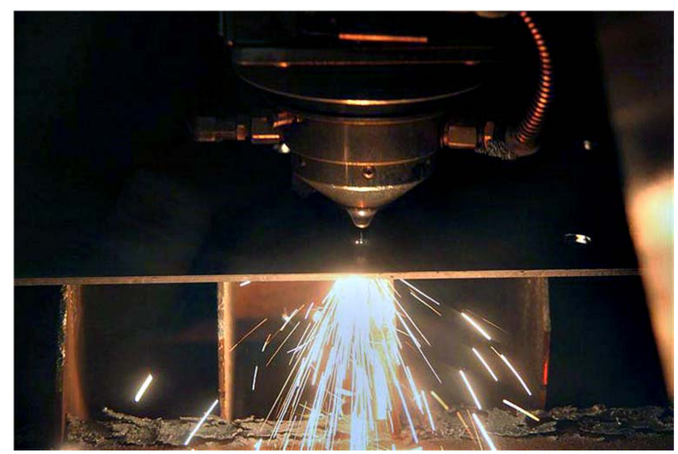


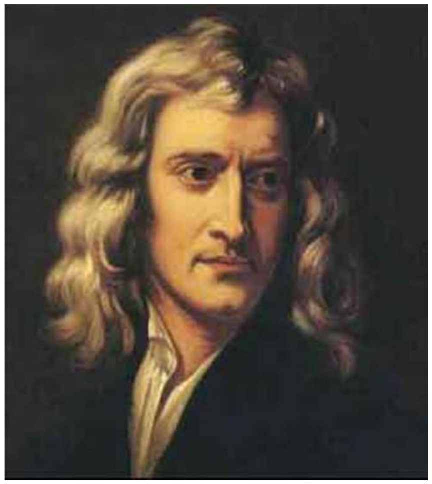
Image by Metaveld BV http://commons.wikimedia.org/wiki/File:Lasersnijden_laserkop.jpg on Wikimedia Commons

Until about 1900, the classical wave theory of light described most observed phenomena

Are Photons Particles or Waves ?

Newton believed that light was particles:

- light travels in straight lines !



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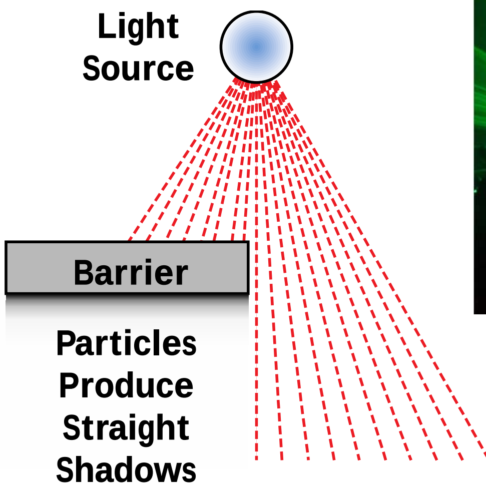

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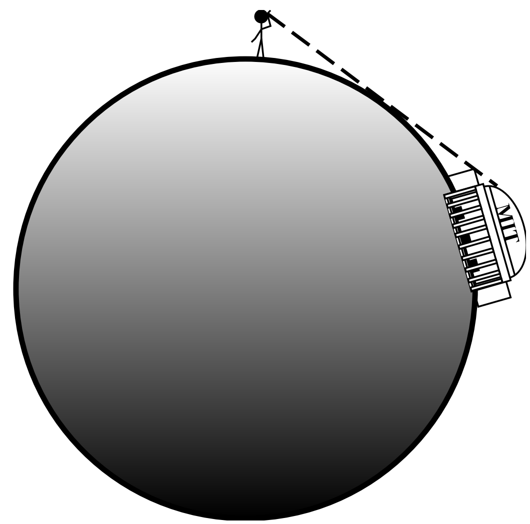

- what is ‘waving’ in an EM wave ?

A wave is a vibration of some medium through which it propagates, e.g., water waves, waves propagating on a string

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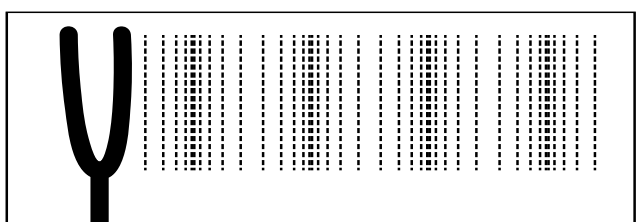
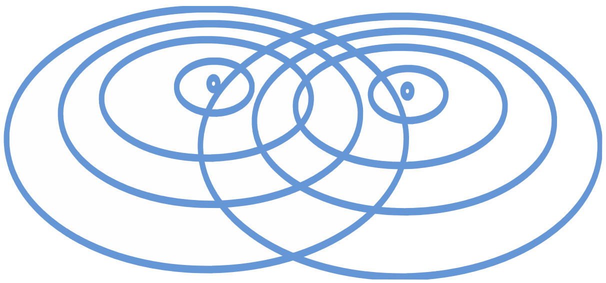
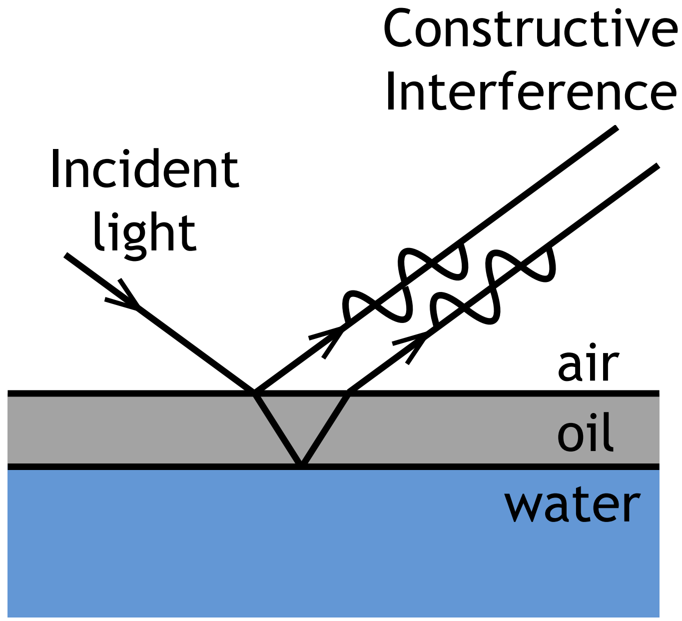
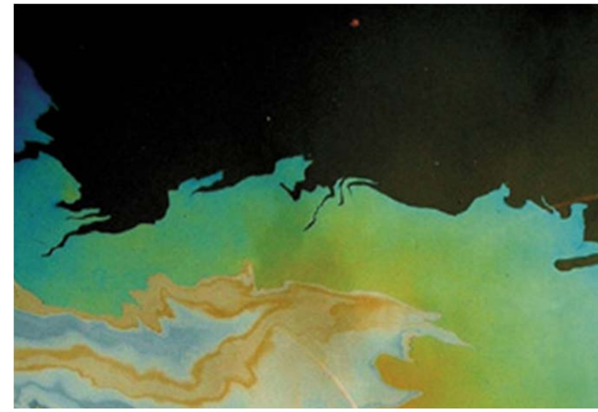


We described them as WAVES up till now







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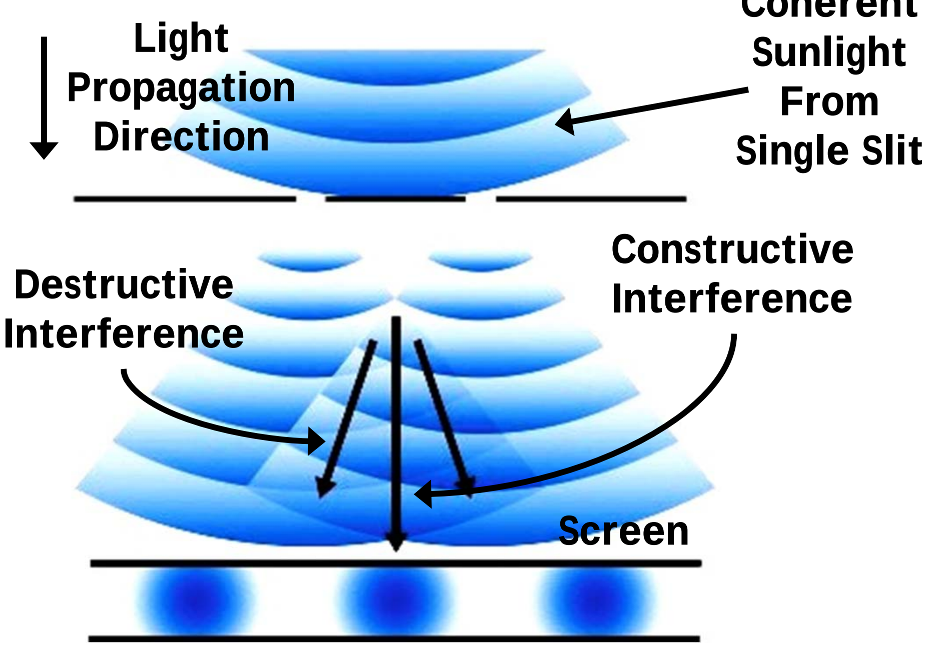
Young's Double Slit Experiment



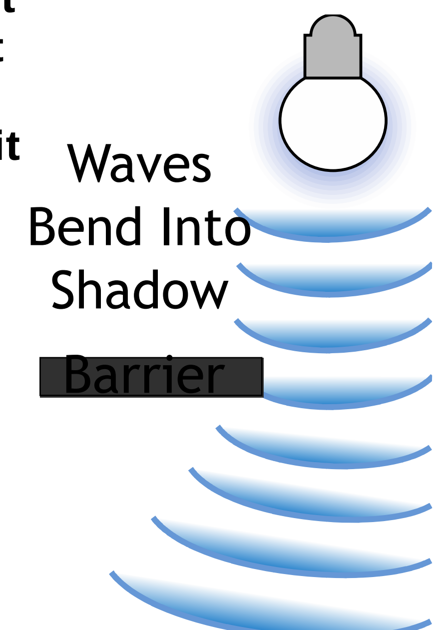
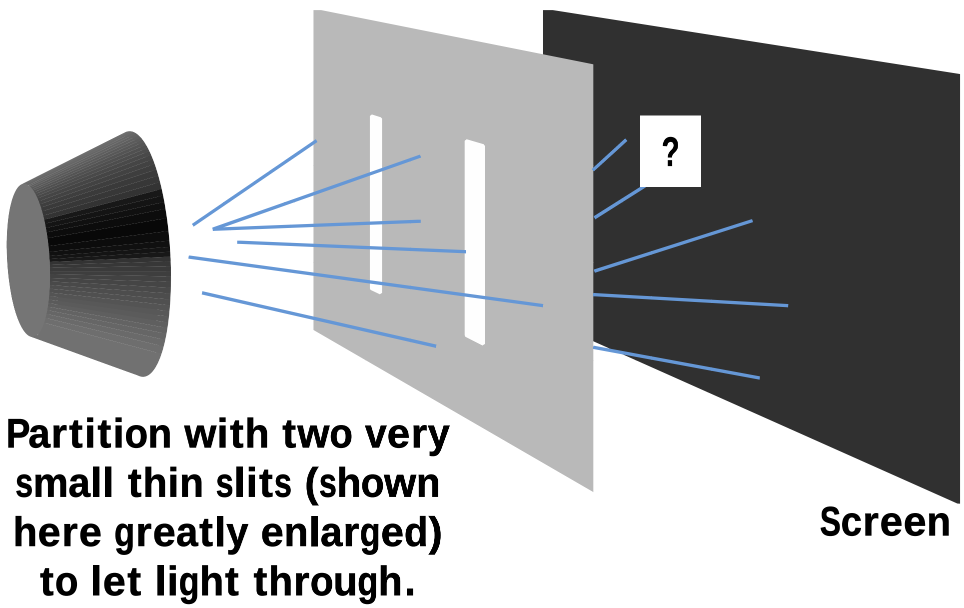


Image by Pieter Kuiper http://commons.wikimedia.org/wiki/File:Compact-Disc-spectrum Mercury.jpg on wikimedia commons

Thomas Young's Double Slit Experiment



Interference is the defining characteristic of <u>waves</u>

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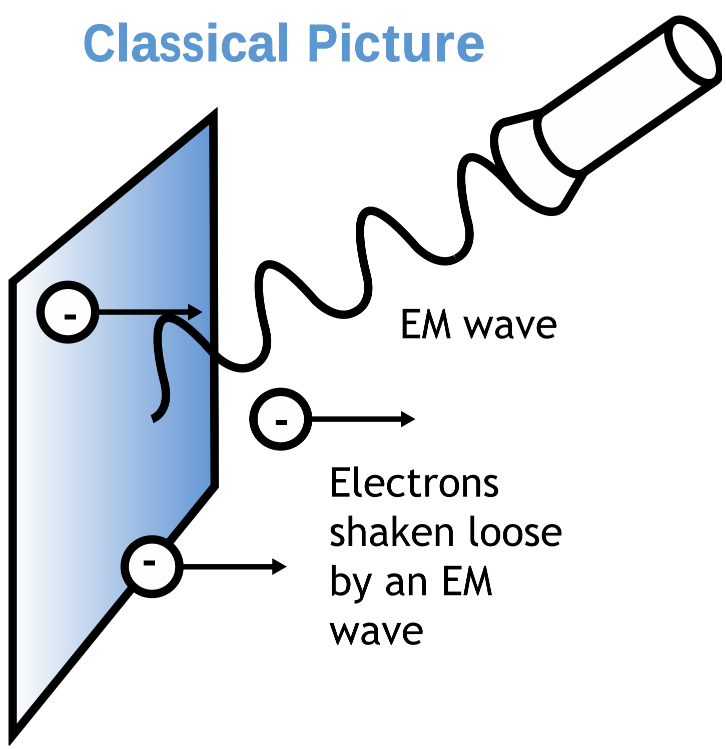
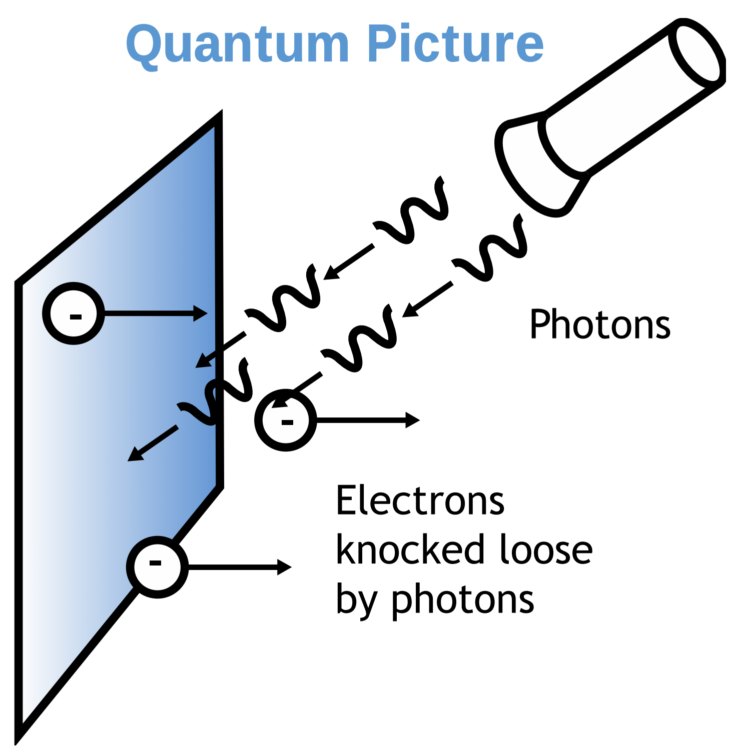
But what happens when we <u>reduce the intensity</u> of incident light … everything should just get dimmer … Right ?

Photoelectric Effect

- When light is incident on certain metallic surfaces, electrons are emitted from the surface
  - This is called the *photoelectric effect*
  - The emitted electrons are called *photoelectrons*

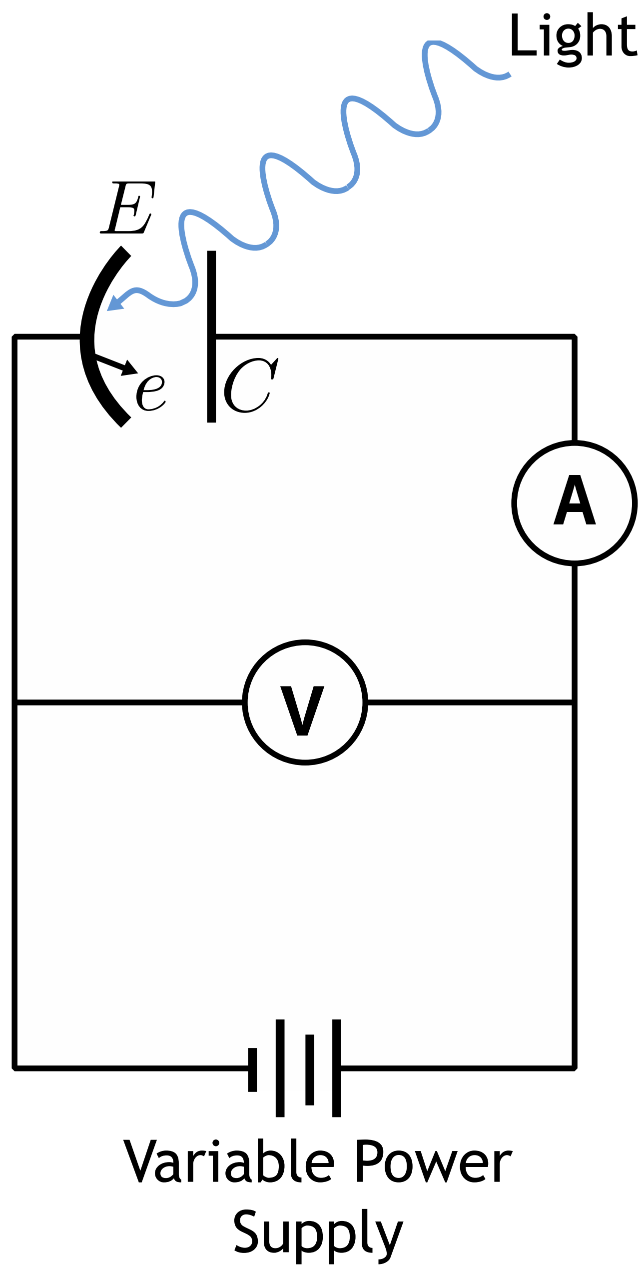
- The effect was first discovered by Hertz
- The successful explanation of the effect was given by Einstein in 1905
  - Received Nobel Prize in 1921 for paper on electromagnetic radiation, of which the photoelectric effect was a part





Photoelectric Effect Schematic

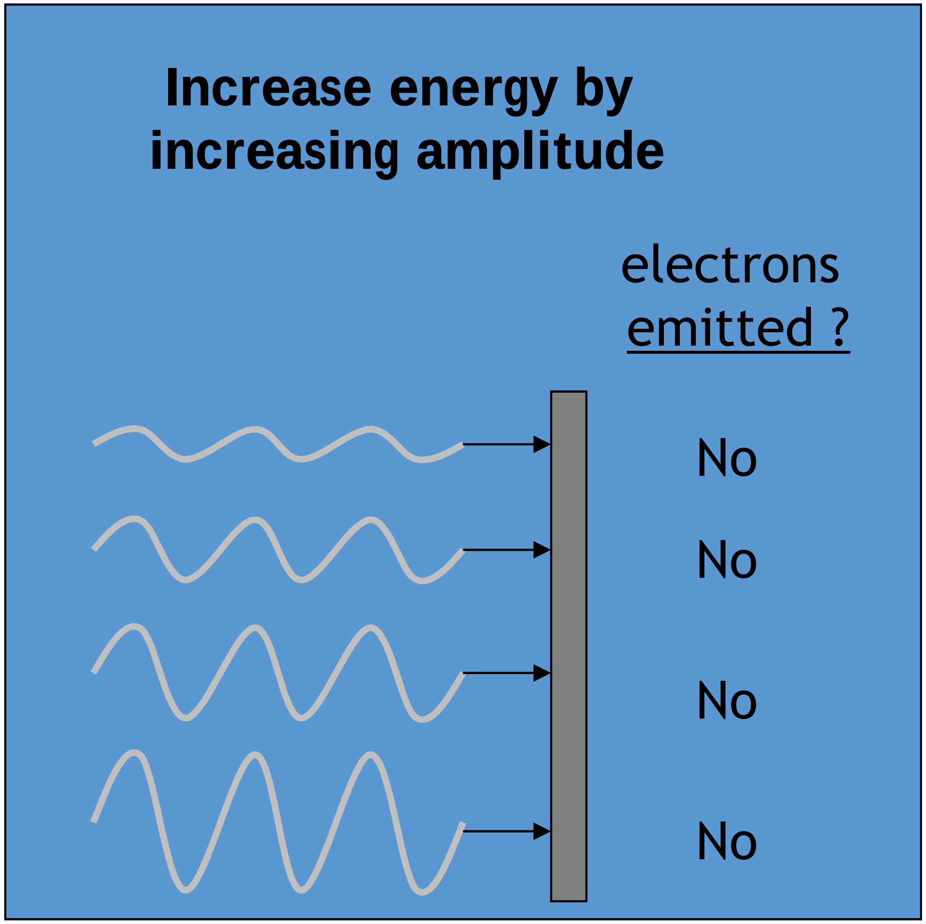
- When light strikes E, photoelectrons are emitted
- Electrons collected at C and passing through the ammeter are a current in the circuit
- C is maintained at a positive potential by the power supply



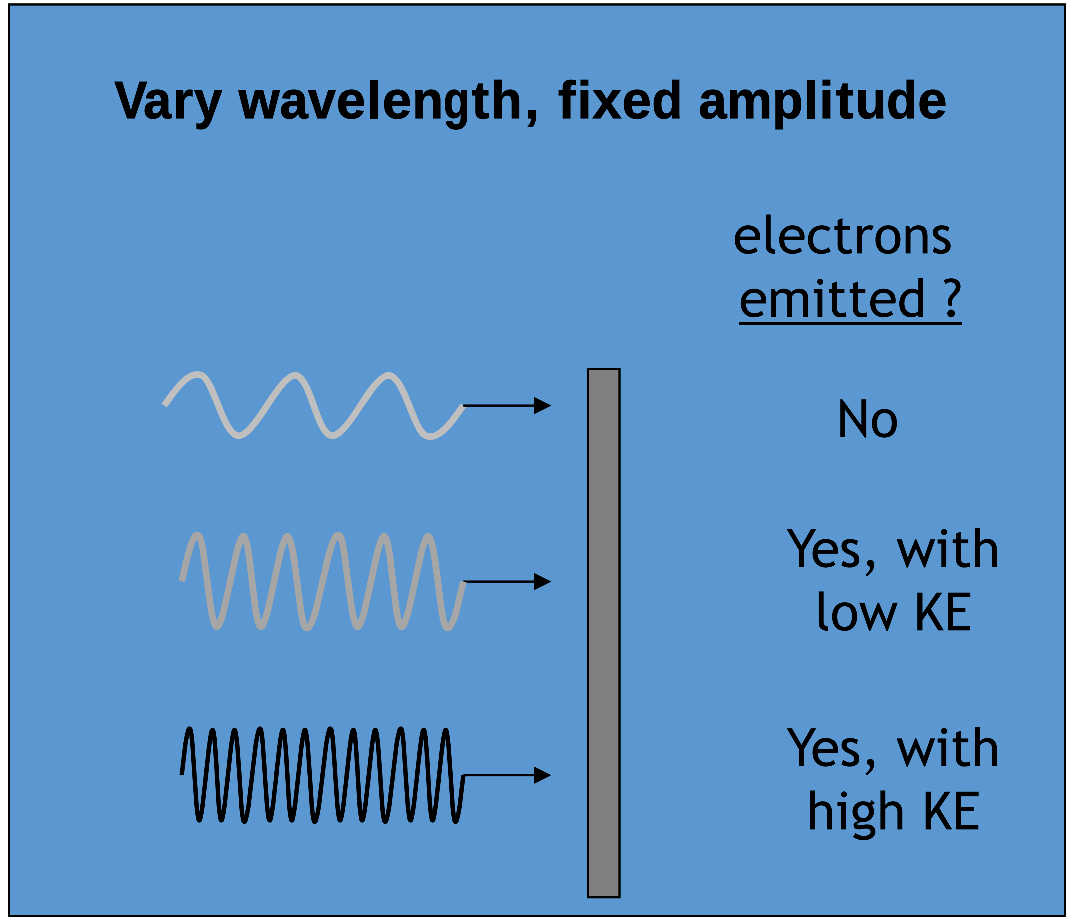
Observation of the Photoelectric Effect

... a Quantum Phenomenon

"Classical" Method



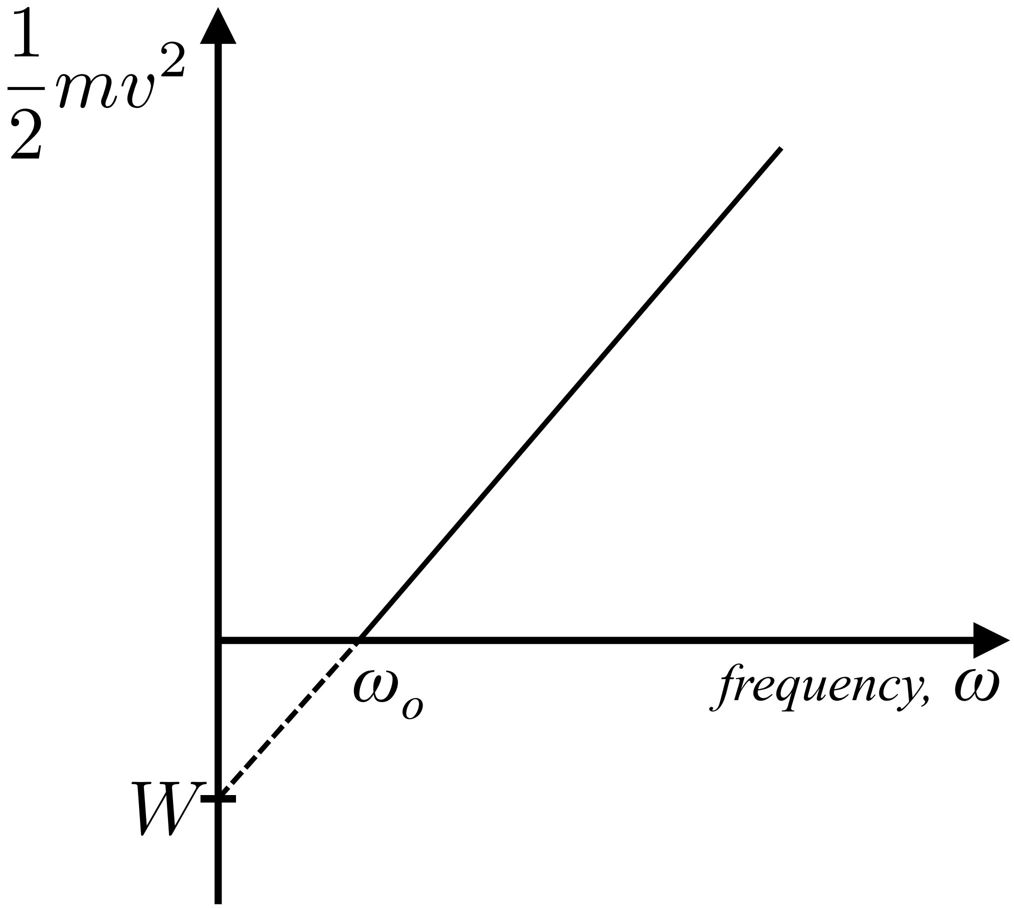
What if we try this ?

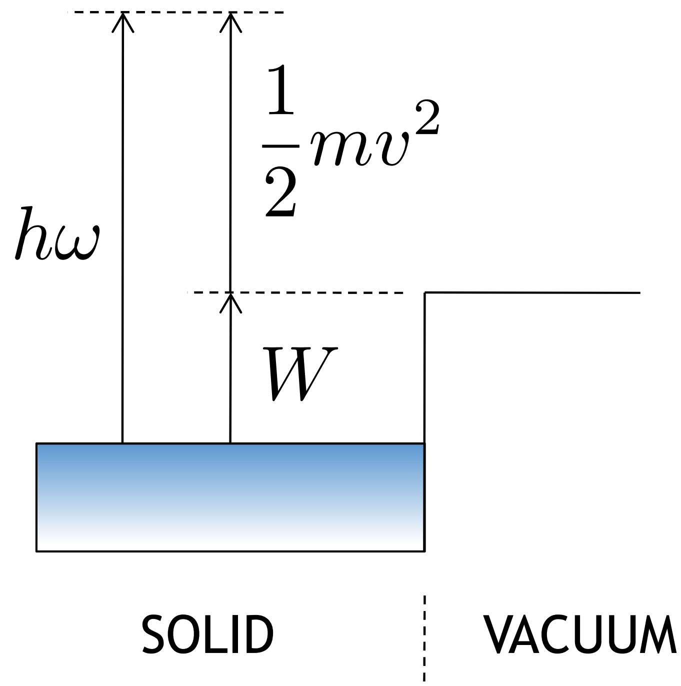


No electrons were emitted until the frequency of the light exceeded a critical frequency, at which point electrons were emitted from the surface !

(Recall: small λ ➔ large ν)

Electron Energy as a Function of Frequency





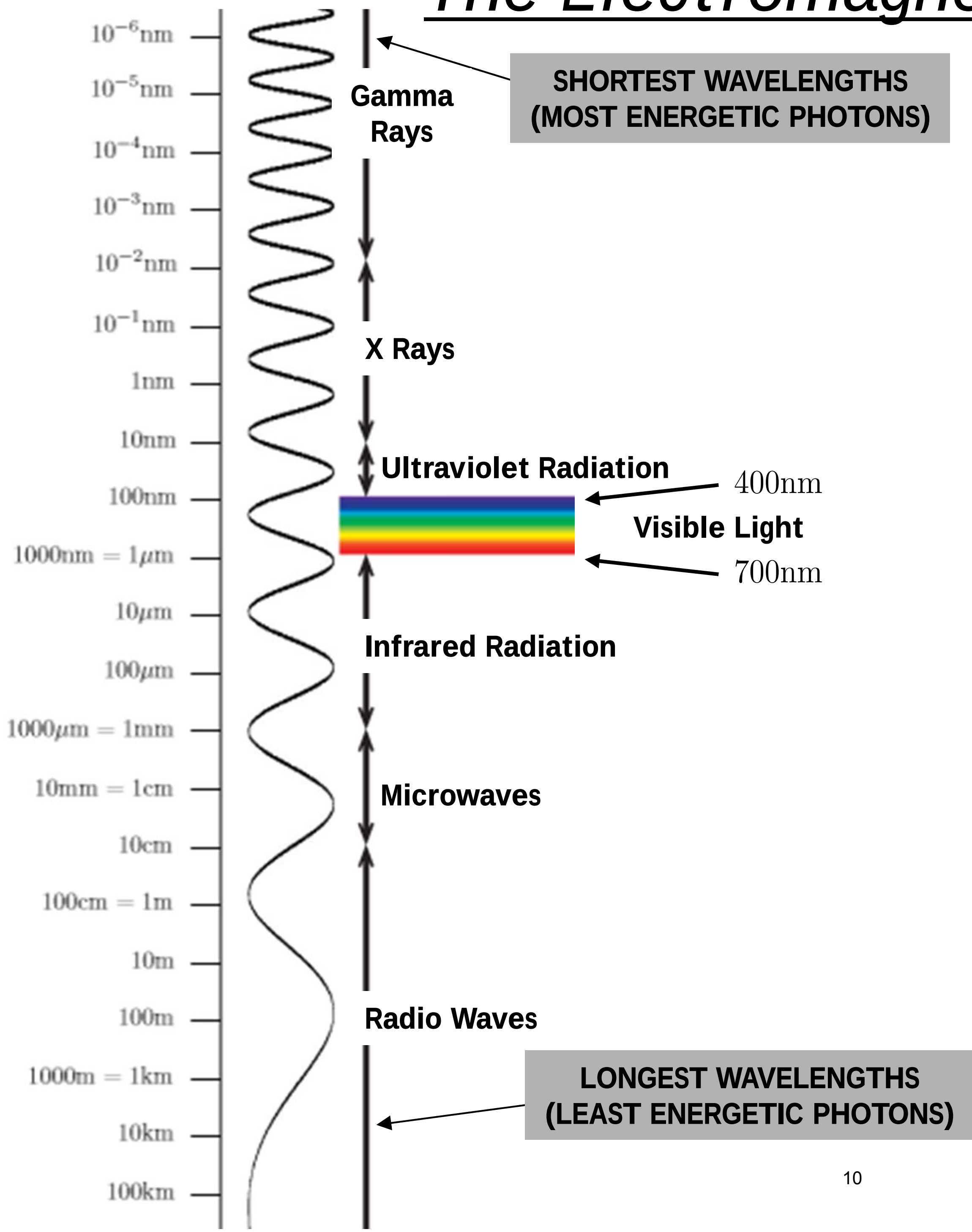
$$\hbar\omega = W + \frac{1}{2}mv^2$$

PHOTON ENERGY — **BINDING ENERGY OF ELECTRON** — **ELECTRON KINETIC ENERGY**

$$h = 6.626 \times 10^{-34}\,[J \cdot s]$$

$$\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}\,[J \cdot s]$$

The Electromagnetic Spectrum



According to **quantum theory**, a **photon** has an **energy** given by

$$E = h\nu = \frac{hc}{\lambda} = \hbar\omega$$

$$h = 6.6 \times 10^{-34}\,[\mathrm{J \cdot s}]$$

(Planck's constant)

$$\hbar = 1.05 \times 10^{-34}\,[\mathrm{J \cdot s}]$$

10 photons have an energy equal to ten times that of a single photon

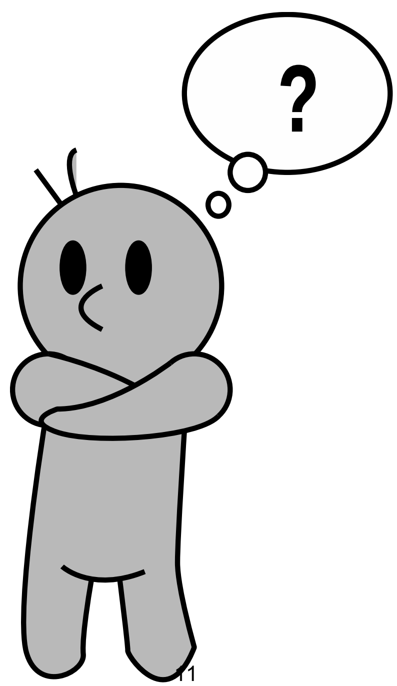
$$E[eV] = \frac{1239.84}{\lambda[nm]}$$

So how do I reconcile wave and particle pictures?

I thought that Maxwell's equations described light …

What is the connection between
Maxwell's equations and photons ?

When to use classical Maxwell's equations ?



Intensity

Classical Intensity

$$\vec{S} = \vec{E} \times \vec{H} \quad \Rightarrow \quad \frac{\text{Watts}}{\text{cm}^2}$$

Intensity in terms of Photons

$$\left|\vec{S}\right| = \frac{n\hbar\omega}{\tau A} \quad \Rightarrow \quad \frac{\text{photons}}{\text{sec cm}^2}\frac{\text{J}}{\text{photon}} = \frac{\text{Watts}}{\text{cm}^2}$$

Coarseness

Classical Maxwell's equations:

Fields can have any strength, even when weak

Experiment:

Light with finite power has limited number of photons

→ Consequences for imaging and communication

Consequences for Imaging

Image by Rory Moynihan http://www.flickr.com/photos/rtmoynihan/5613097441/ on flickr

We see that photons are detected with
probability proportional to intensity

PROBABILITY OF DETECTION OF EACH PHOTON PER UNIT AREA:

$$P(x,y) = \frac{|\vec{S}(x,y)|}{\iint |\vec{S}(x,y)|\,dx\,dy}$$

Consequences for communication

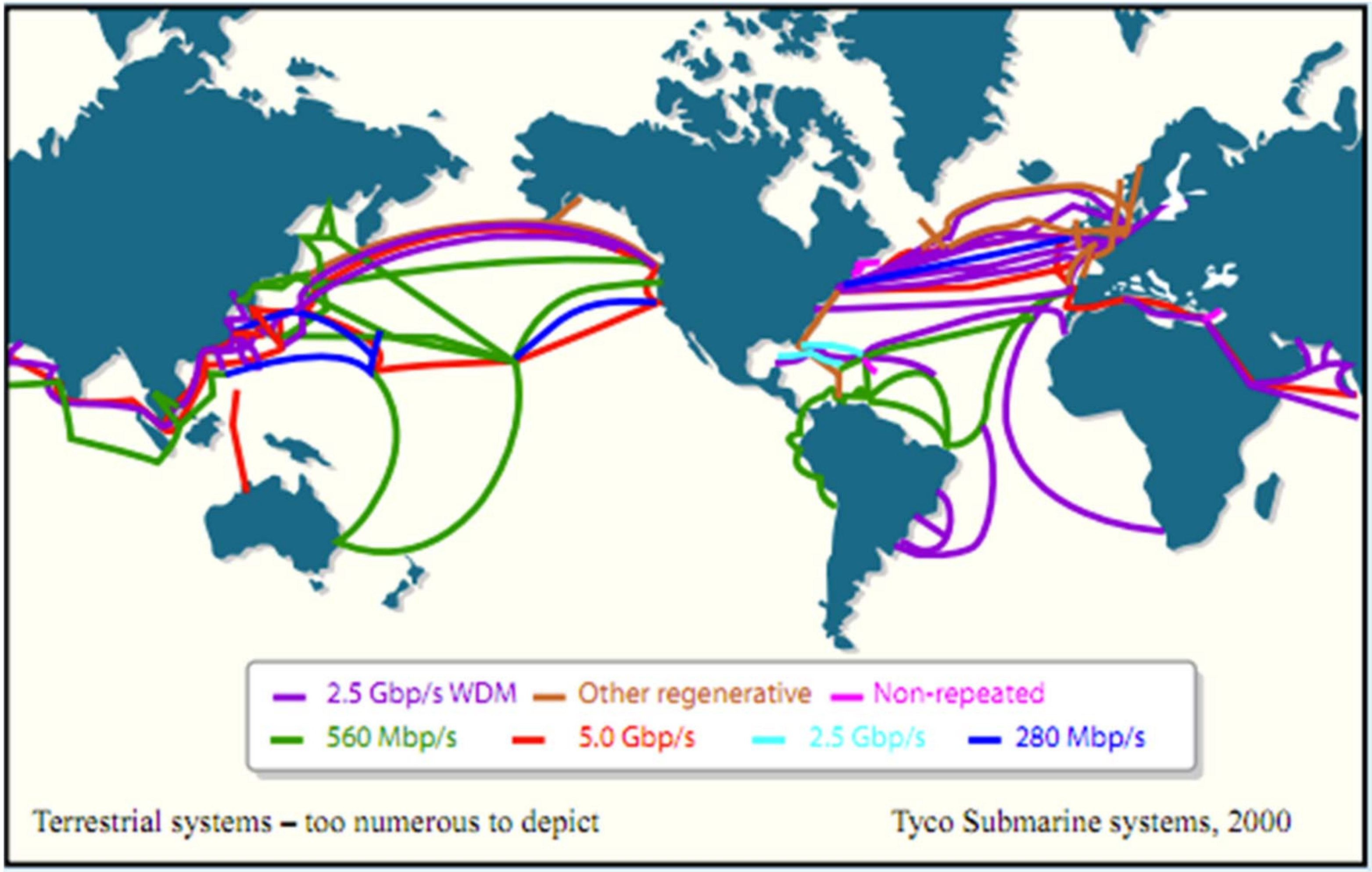


Figure by MIT OpenCourseWare

Energy per bit ≥ 300 photons $\times \hbar\omega$

$$1 \text{ terabit sec } \Longrightarrow \geq 10^{12} \times 300 \times 0.8 \frac{eV}{\text{sec}} = 40 \mu W$$

Do Photons Have Momentum ?

What is momentum ?

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(mv) \cdot v = \frac{1}{2}p \cdot v$$

Just like Energy,
TOTAL MOMENTUM IS ALWAYS CONSERVED

Photons have energy and a finite velocity so there must be some momentum associated with photons !

$$p = \frac{E}{c} = \frac{h\nu}{c}$$

Key Takeaways

LIGHT ARRIVES IN INCREMENTS CALLED PHOTONS

PHOTOELECTRIC EFFECT:

$$\hbar\omega = W + \frac{1}{2}mv^2$$

- $\hbar\omega$ — **PHOTON ENERGY**
- W — **BINDING ENERGY OF ELECTRON**
- $\frac{1}{2}mv^2$ — **ELECTRON KINETIC ENERGY**

$$E = h\nu = hc/\lambda = \hbar\omega$$

$$E\,[eV] = \frac{1240}{\lambda\,[nm]}$$

(Planck's constant) $h = 6.626 \times 10^{-34}\,[J \cdot s]$

$$\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}\,[J \cdot s]$$

LIGHT INTENSITY IN TERMS OF PHOTONS:

$$|\vec{S}| = \frac{n\hbar\omega}{\tau A}$$

PROBABILITY OF DETECTION OF EACH PHOTON PER UNIT AREA:

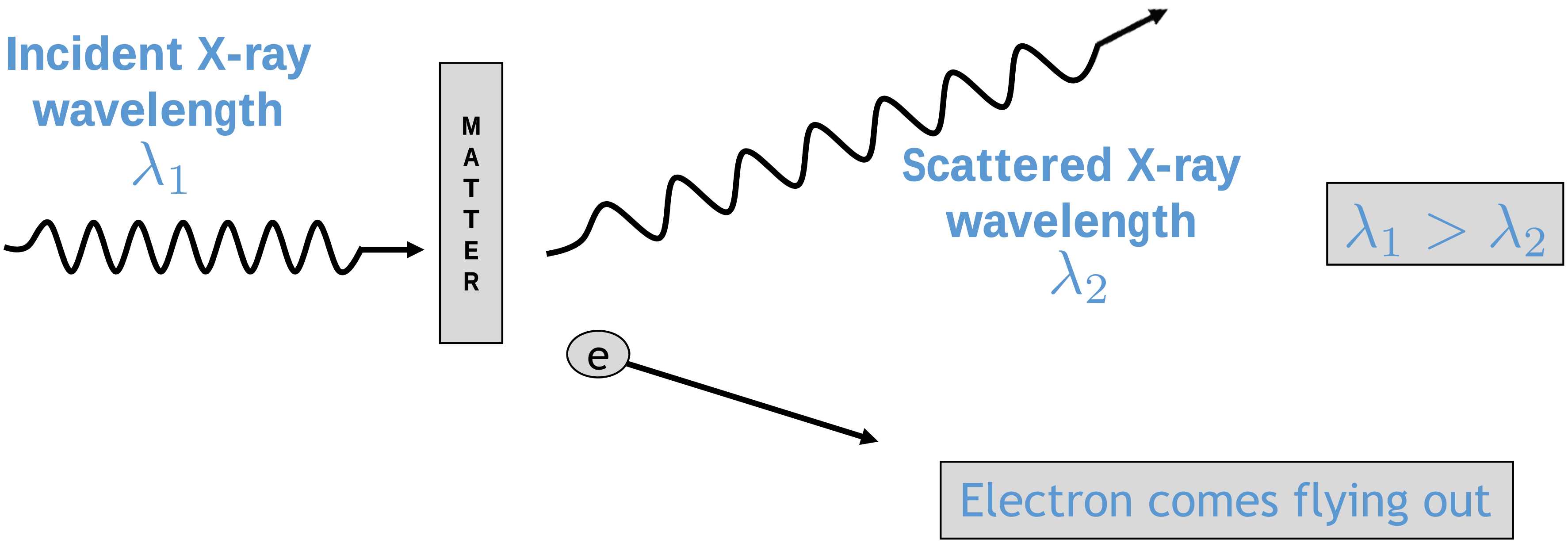
$$P(x,y) = \frac{|\vec{S}(x,y)|}{\iint |\vec{S}(x,y)|\,dx\,dy}$$

Just like Energy, TOTAL MOMENTUM IS ALWAYS CONSERVED - Photon Momentum:

$$p = \frac{E}{c} = \frac{h\nu}{c}$$

The Compton Effect

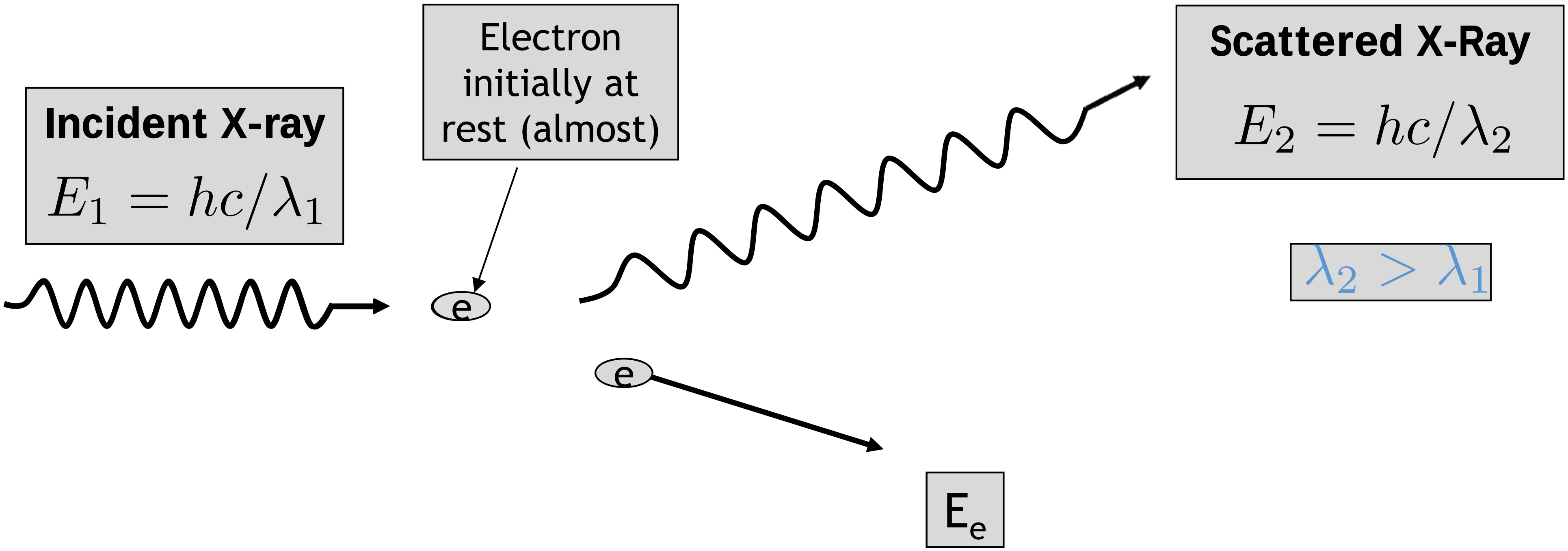
In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.



Problem: According to the wave picture of light, the incident X-ray should give up some of its energy to the electron, and emerge with a lower energy (*i.e.*, the amplitude is lower), but should have $\lambda_1 = \lambda_2$.

It was found that the scattered X-ray did not have the same wavelength !

Quantum Picture to the Rescue



Compton found that if you treat the photons as if they were particles of zero mass, with energy $E = hc/\lambda$ and momentum $p = \lambda/h$.

➔ The collision behaves just as if it were two billiard balls colliding !

Photon behaves like a particle with energy & momentum as given above!

Photon Momentum

IN FREE SPACE:

$$E = cp \quad \Rightarrow \quad p = \frac{E}{c} = \frac{\hbar\omega}{c} = \hbar k$$

IN OPTICAL MATERIALS:

$$E = v_p p \quad \Rightarrow \quad p = \frac{E}{v_p} = \frac{\hbar\omega}{v_p} = \hbar k_{vac} n$$

QUICK QUIZ

A photon (quantum of light) is reflected from a mirror.

… so is the following **True or False**:

(A) Because a photon has a zero mass, it does not exert a force on the mirror.

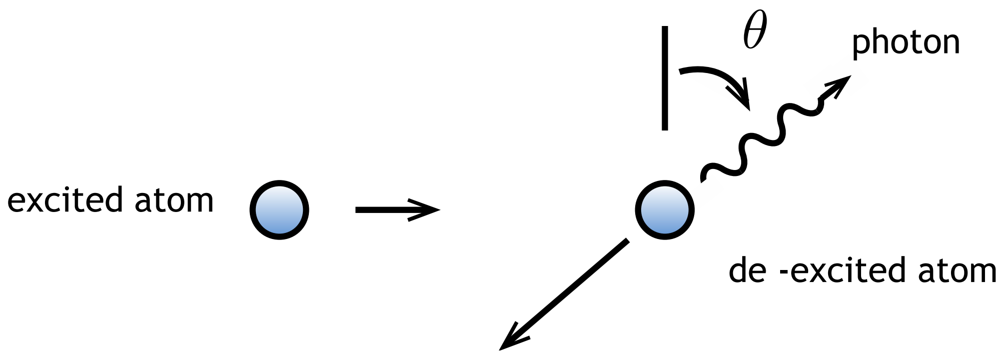
(B) Although the photon has energy, it cannot transfer any energy to the surface because it has zero mass.

(C) The photon carries momentum, and when it reflects off the mirror, it undergoes a change in momentum and exerts a force on the mirror.

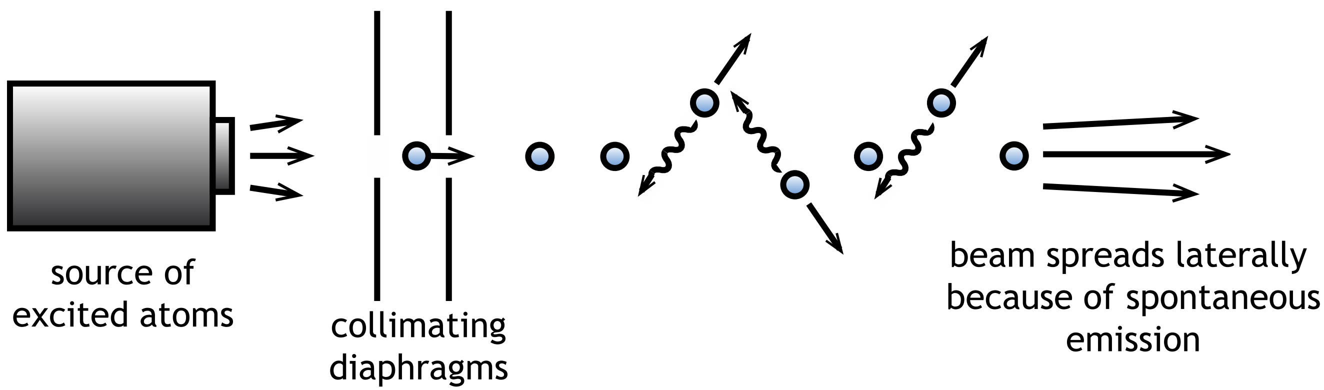
(D) Although the photon carries momentum, its change in momentum is zero when it reflects from the mirror, so it cannot exert a force on the mirror.

Manifestation of the Photon Momentum

SOURCE EMITTING A PHOTON

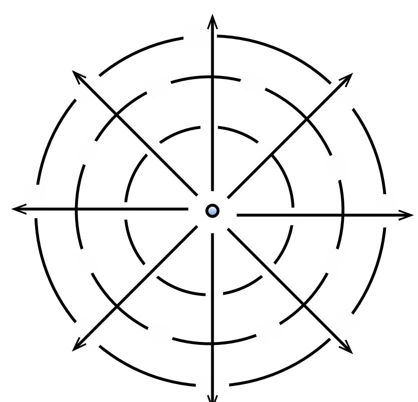


Conservation of linear momentum implies that an atom recoils when it undergoes spontaneous emission. The direction of photon emission (and atomic recoil) is not predictable.



A well-collimated atomic beam of excited atoms will spread laterally because of the recoil associated with spontaneous emission.

SOURCE EMITTING AN EM WAVE



A source emitting a spherical wave cannot recoil, because the spherical symmetry of the wave prevents it from carrying any linear momentum from the source.

Photon Momentum - Moves Solar Sails

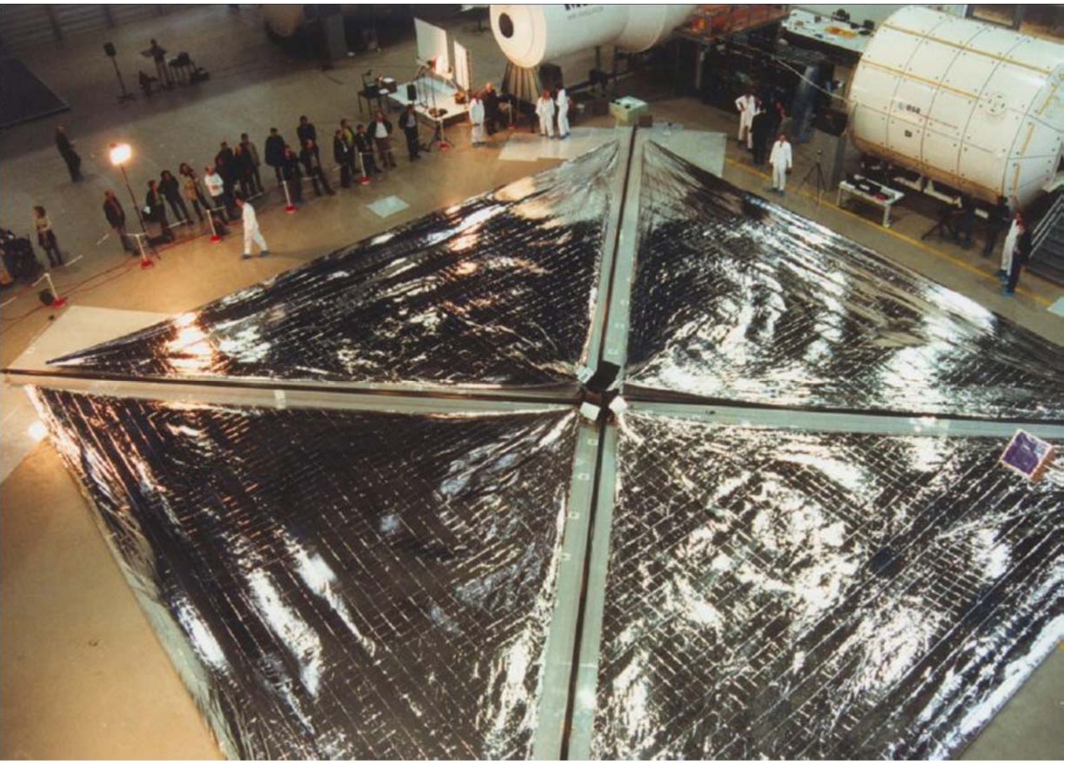
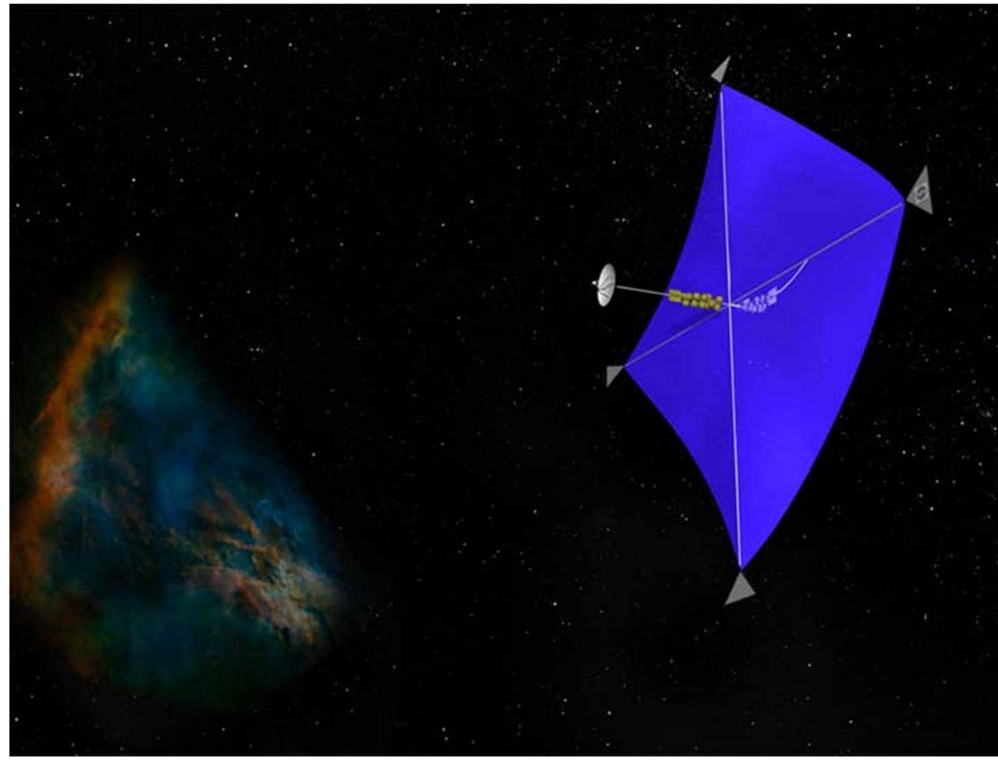


Image by D. Kassing http://en.wikipedia.org/wiki/File:SolarSail-DLR-ESA.jpg on Wikipedia



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INCOMING PHOTONS
1000 W/m² →

SOLAR SAIL
at rest

every second
photons with momentum
+ (1000 J/m²)/c impact the sail

REFLECTED PHOTONS
1000 W/m² ←

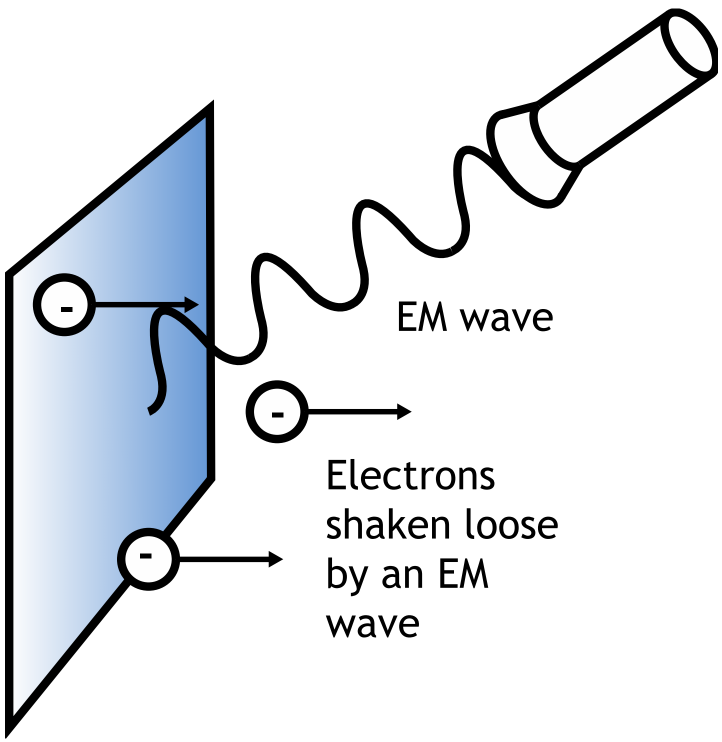
SOLAR SAIL
moves →

every second
photons with momentum
- (1000 J/m²)/c leave the sail

with momentum + (2000 J/m²)/c … and gets that much more momentum every second …

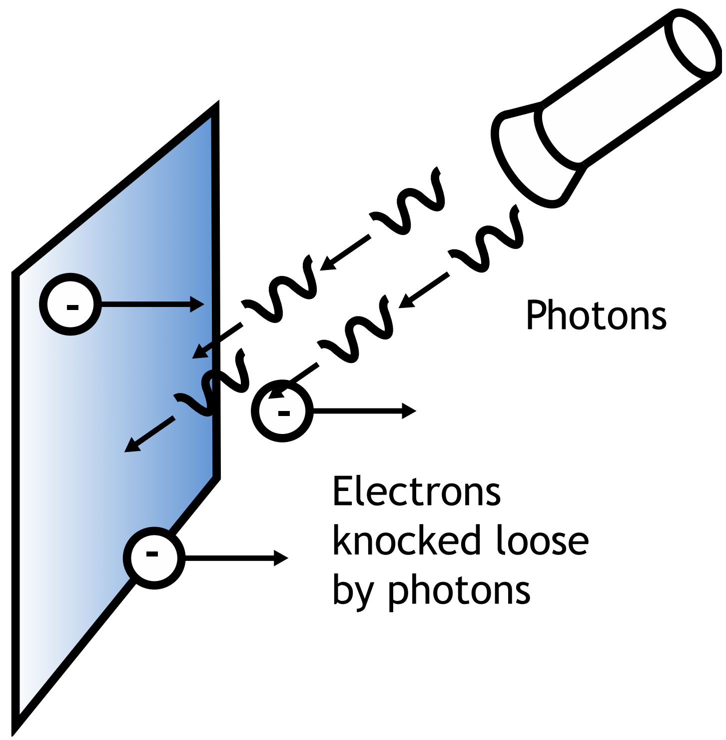
Pressure acting on the sail = (2000 J/m²) /c /second = 6.7 Newtons/km²

Classical Picture



Energy of EM wave ~ (Amplitude)^2

Quantum Picture



Energy per photon $= hc/\lambda$

photon momentum $= E/c$
$= (hc/\lambda)/c = h/\lambda$