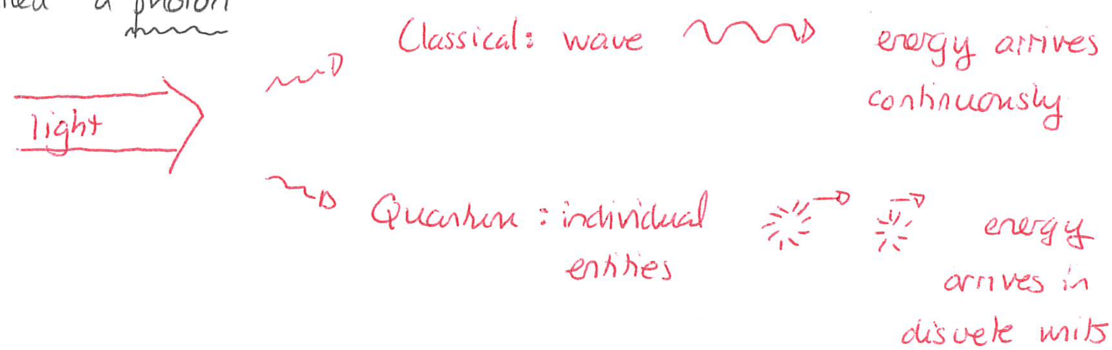
* HW 1 due by 5pm Monday
    - ↳ Drop off and D2L
    - ↳ integrity issues.

* Mon Read 3.3, 3.4

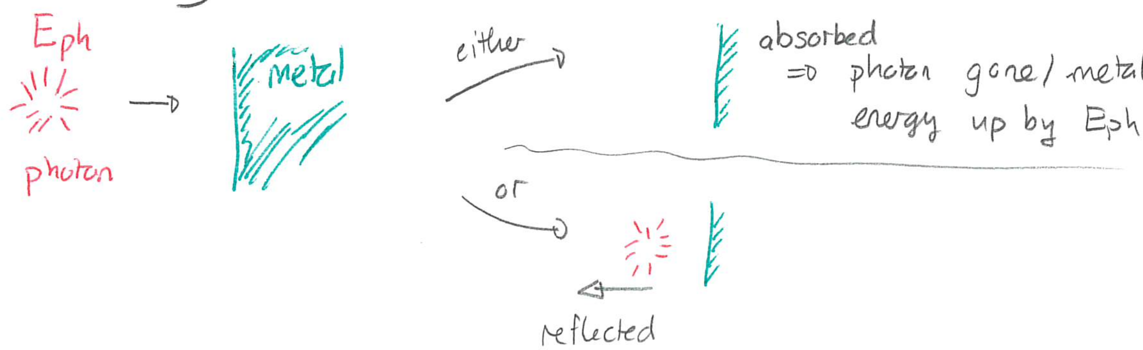
Photons + the photoelectric effect

The explanation of the photoelectric effect due to Einstein made two assumptions:

1) For light and any type of electromagnetic radiation the energy is apportioned into indivisible discrete pieces or quanta. Each piece is called a photon



2) When light interacts with matter each quanta of energy is either entirely absorbed or else not absorbed at all



A key quantitative feature of this is:

> If electromagnetic radiation has frequency f then the energy of each individual photon is
>
> $$E_{ph} = hf$$
>
> where
>
> $$h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}$$
>
> is Planck's constant.

This explains some features of the photoelectric effect:

1) A photon will only eject an electron if its energy exceeds the work function

$$E_{ph} > \phi \Rightarrow hf > \phi \Rightarrow f > \underbrace{\phi/h}_{\text{cutoff}}$$

2) It only takes one photon to eject an electron and this can happen almost immediately.

Quiz 1 100%

Note that to for electromagnetic radiation:

$$c = \lambda f \Rightarrow f = \frac{c}{\lambda} \Rightarrow \boxed{E_{ph} = \frac{hc}{\lambda}}$$

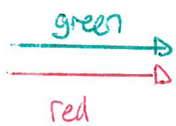
We can then rank sources:

Red light	lower f	higher λ	smaller E_{ph}	⇝ individual energy pieces smaller "Nickel"
Blue light	higher f	lower λ	larger E_{ph}	⇝ individual energy pieces larger "Quarter"

The fundamental picture of light offered by photons is very different to that of classical physics. In many ways light behaves as discrete particles

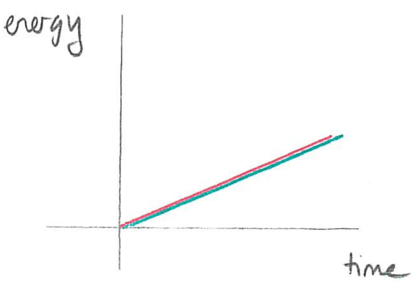
Classical	Photon
1) energy accumulates constantly	energy accumulates in steps (randomly)
2) light can be split arbitrarily	photons cannot split

1) Classical: energy accumulates constantly

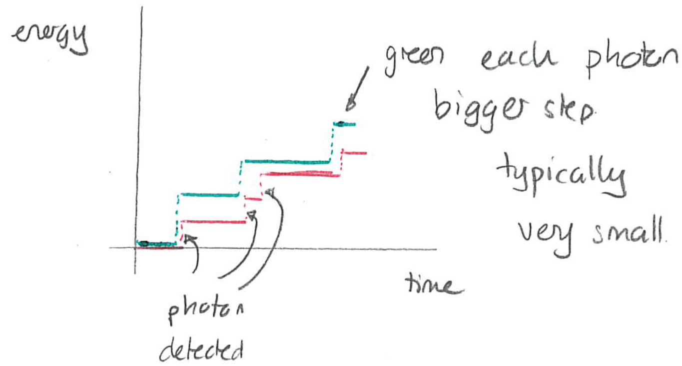


screen measures accumulated energy

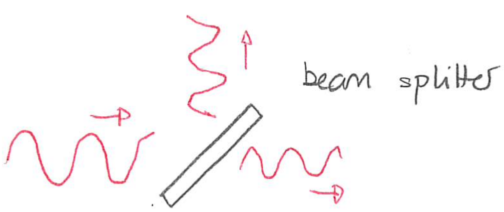
same intensity



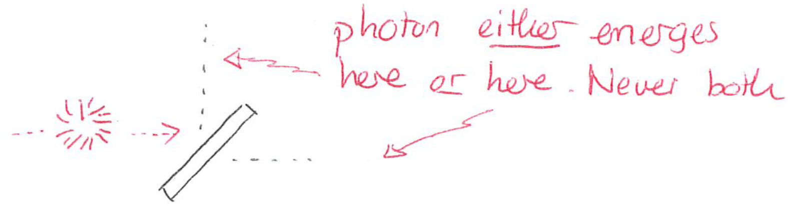
1) Photon: energy accumulates in steps (randomly)



2) Classical: light can be split arbitrarily



2) Photon: photons cannot split



Multiple photons

The typical energy associated with a single photon is small compared to light intensity scales.

Example: A red diode laser emits light with wavelength 650nm. Determine the energy of a single photon.

Answer:

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$\Rightarrow E_{ph} = \frac{6.63\times10^{-34}\,J\cdot s \times 3.0\times10^{8}\,m/s}{650\times10^{-9}\,m}$$

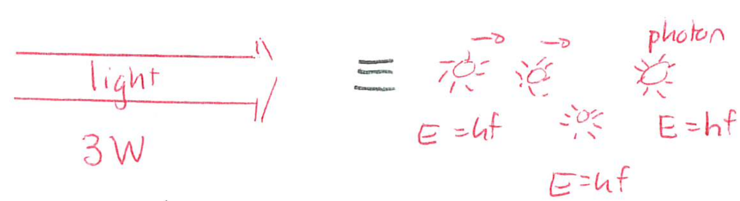
$$= 3.1\times10^{-19}\,J$$

These units are inconvenient and sometimes it is easier to use electron volts:

$$1eV = 1.6\times10^{-19}J$$

Then
$$E_{ph} = \frac{3.1\times10^{-19}J}{1.6\times10^{-19}J} = 1.9eV$$ ☒

Ordinary light sources provide much more energy each second and this is only possible if the contain many photons. So the model is



Suppose that the total number of photons in the beam is N. Then the total energy delivered by the light is

$$E = NE_{ph} = Nhf$$

Quiz 2 10% – 30%

Example: A red diode laser produces light with wavelength 650nm. The laser has power 8.0mW. The light from the laser is incident upon a detector. Determine:

a) the number of photons that arrive at the detector in 1.0ms.

b) suppose that one additional photon arrives. What fraction of the total number of photons that already arrived does this represent

c) the laser beam is passed through an attenuator that dims the light, removing 10^{11} photons every second. What is the power delivered after this? What is the fractional difference in power compared to the original source.

Answer: a) In 1.0ms the laser delivers energy

$$E = P \times \text{time} = 8.0\times10^{-3}\,W \times 1.0\times10^{-3}\,s = 8.0\times10^{-6}\,J$$

Then

$$E = E_{ph}\,N$$

and

$$E_{ph} = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\,J\cdot s \times 3.0\times10^{8}\,m/s}{650\times10^{-9}\,m} = 3.06\times10^{-19}\,J$$

$\Rightarrow$ $8.0\times10^{-6}\,J = 3.1\times10^{-19}\,J\,N$ $\Rightarrow$ $N = 2.62\times10^{13}$

b) $\dfrac{1}{2.6\times10^{13}} = 3.8\times10^{-14}$ very small fraction

c) The number of photons remaining (per ms) is

$2.62\times10^{13} - 0.01\times10^{3} = 2.61\times10^{13}$

The total energy is:

$$E = N E_{ph} = 2.61\times10^{13} \times 3.06\times10^{-19}J = 7.98\times10^{-6} J.$$

The power is

$$P = E/t = \frac{7.98\times10^{-6}J}{1\times10^{-3}s} = 7.98\,mW$$

The reduction in power is 0.02mW and the fractional reduction is

$$\frac{0.02\,mW}{8\,mW} = 0.0025 \quad \boxed{2}$$

We see that even the removal of many photons does not affect the observed power of intensity much for such ordinary sources. It will clearly require special devices to detect this discrete nature of light. There are detectors that can do this. Examples include:

1) photodiodes

2) photomultiplier tubes

Demo: Ted Baldwin: Photomultiplier.