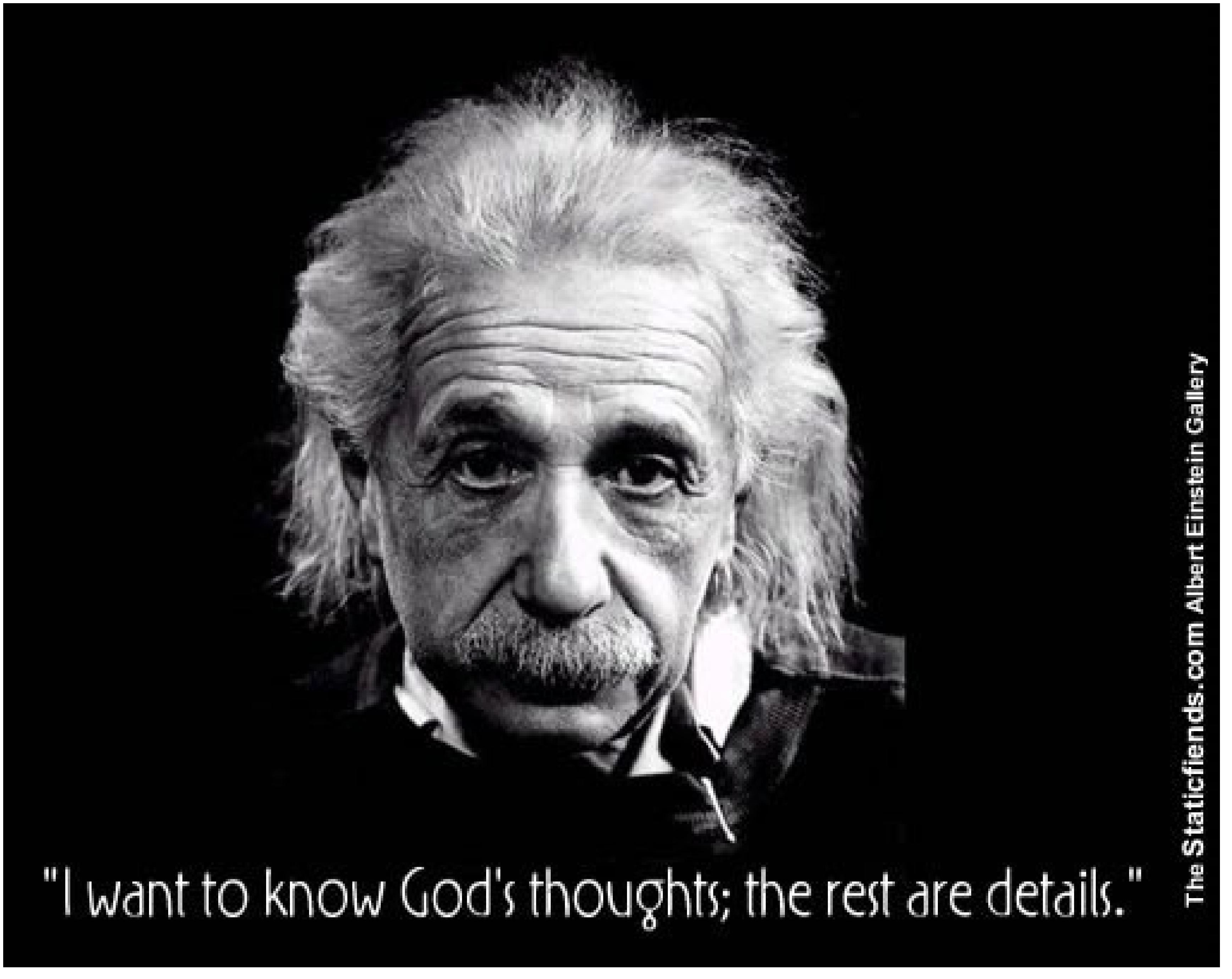
Chapter 24 - Quantum



Revised 6.7.2020 Some diagrams from Pearson Physics by Walker. Used with permission

“Quantum (a noun - quanta is the plural form)
in physics, discrete natural unit, or packet, of energy, charge, angular momentum, or other physical property.” (Encyclopedia Britannica.)

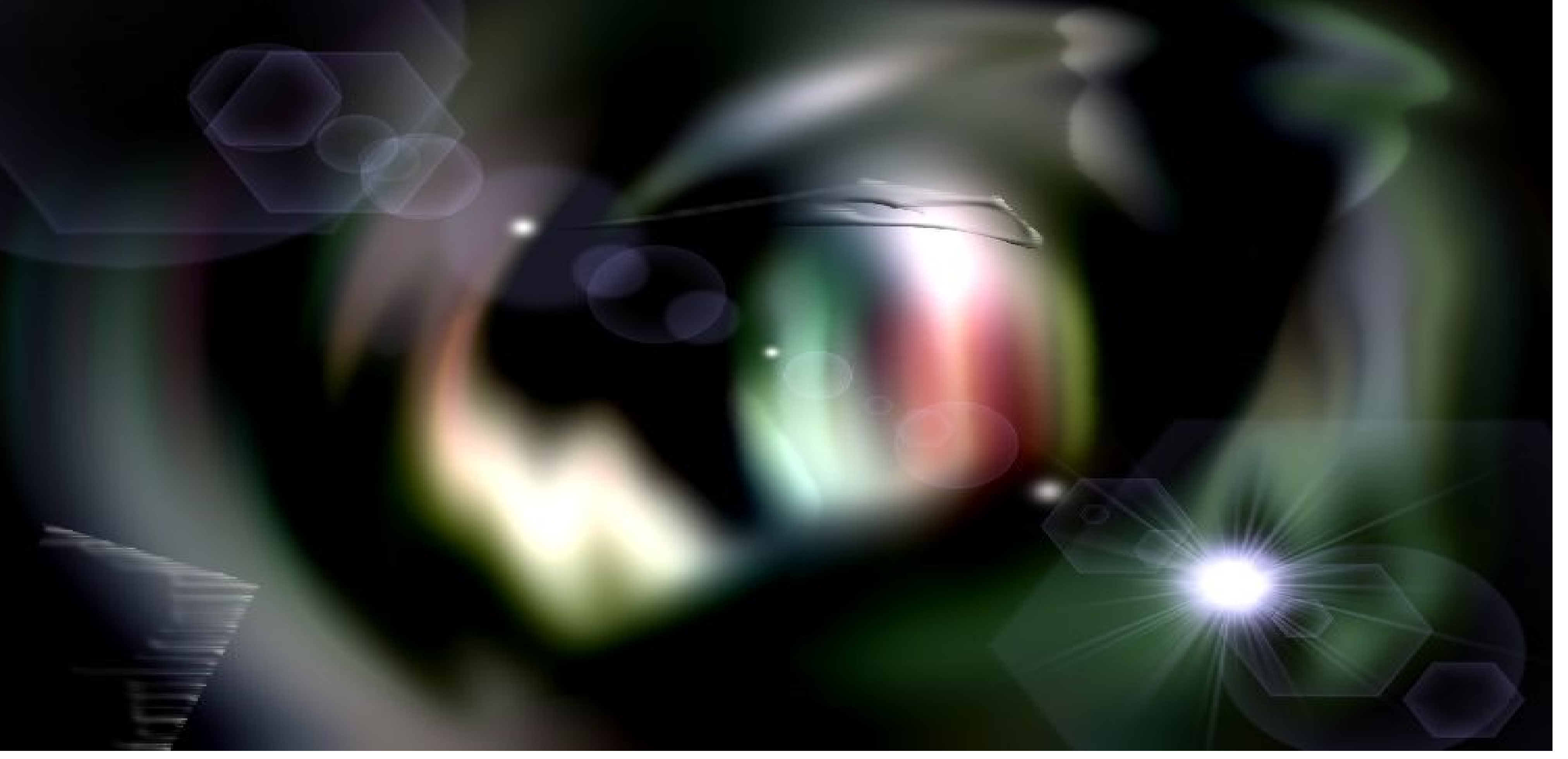
Some variables are continuous, which means they can take on any value. Others are discrete, which means they can take on only certain values.

It turns out, and it surprised the scientists, that some physical quantities are not continuous variables, but discrete. However the size of the quantum is very small, which is why it was never noticed.
For example energy of a blackbody is quantized.

Energy = quantum number * Planck’s constant * frequency

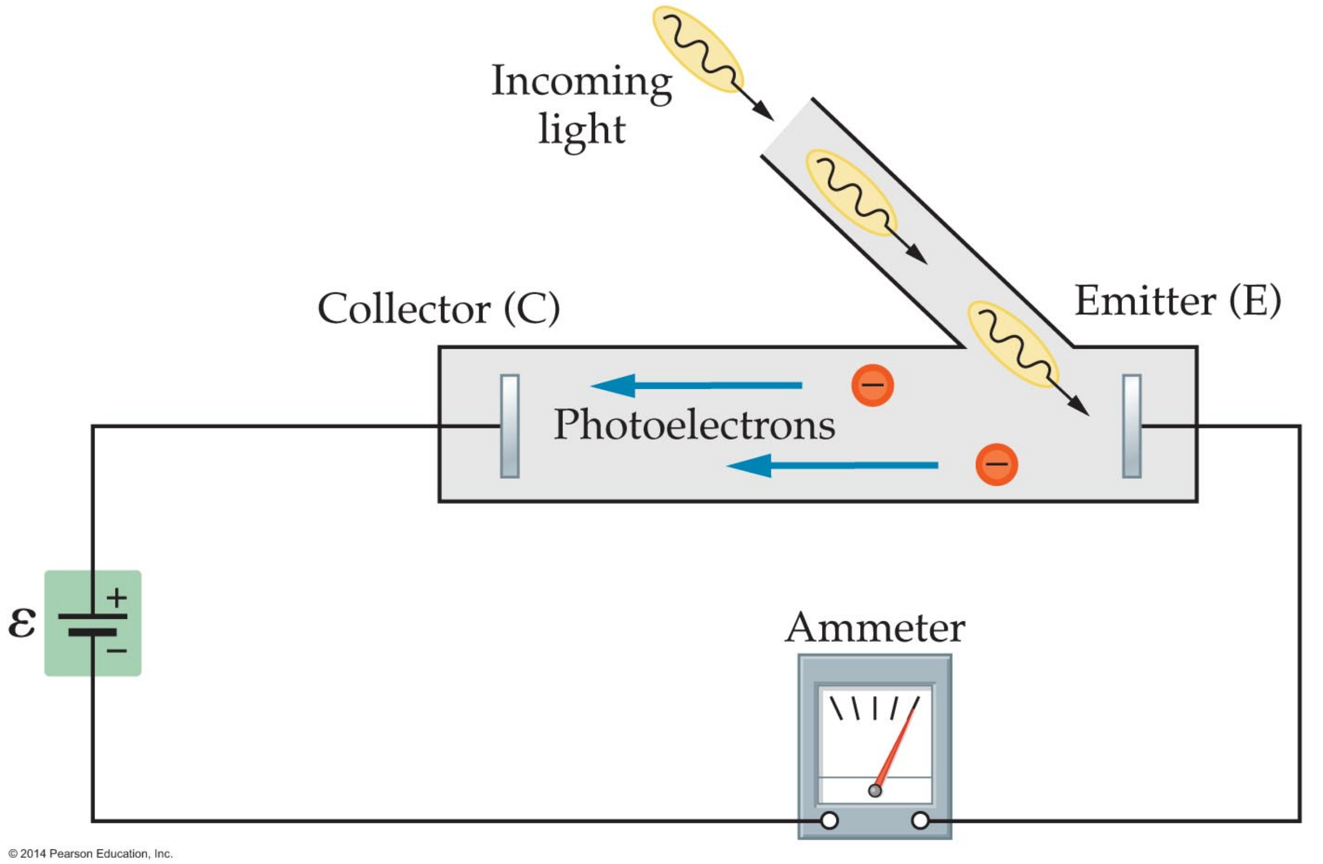
$E = n\,h\,f$

h is Planck’s constant = 6.63 x10^-34 J s



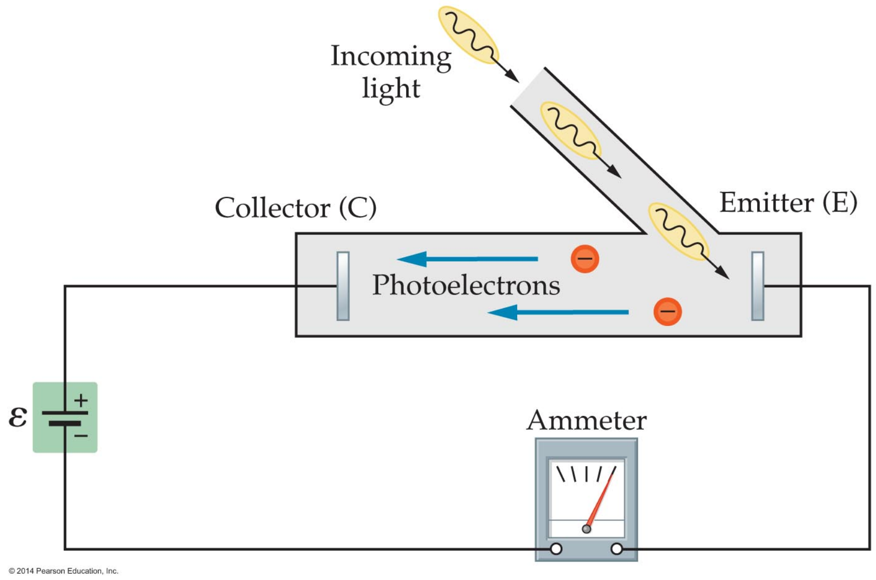
... Light, for example, appearing in some respects as a continuous electromagnetic wave, on the submicroscopic level is emitted and absorbed in discrete amounts.

Photoelectric Effect



It was found that light hits the surface of a metal it can, under certain conditions eject electrons.
However, there were two peculiarities if light were a continuous variable (as was thought)

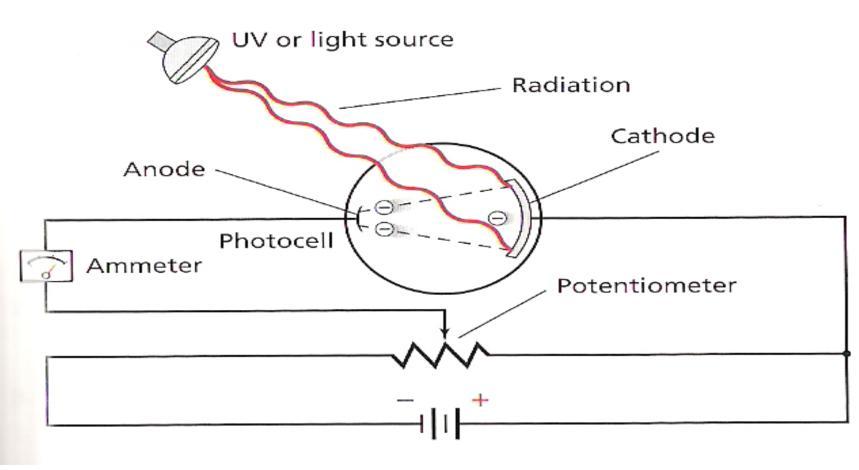
Photoelectric Effect



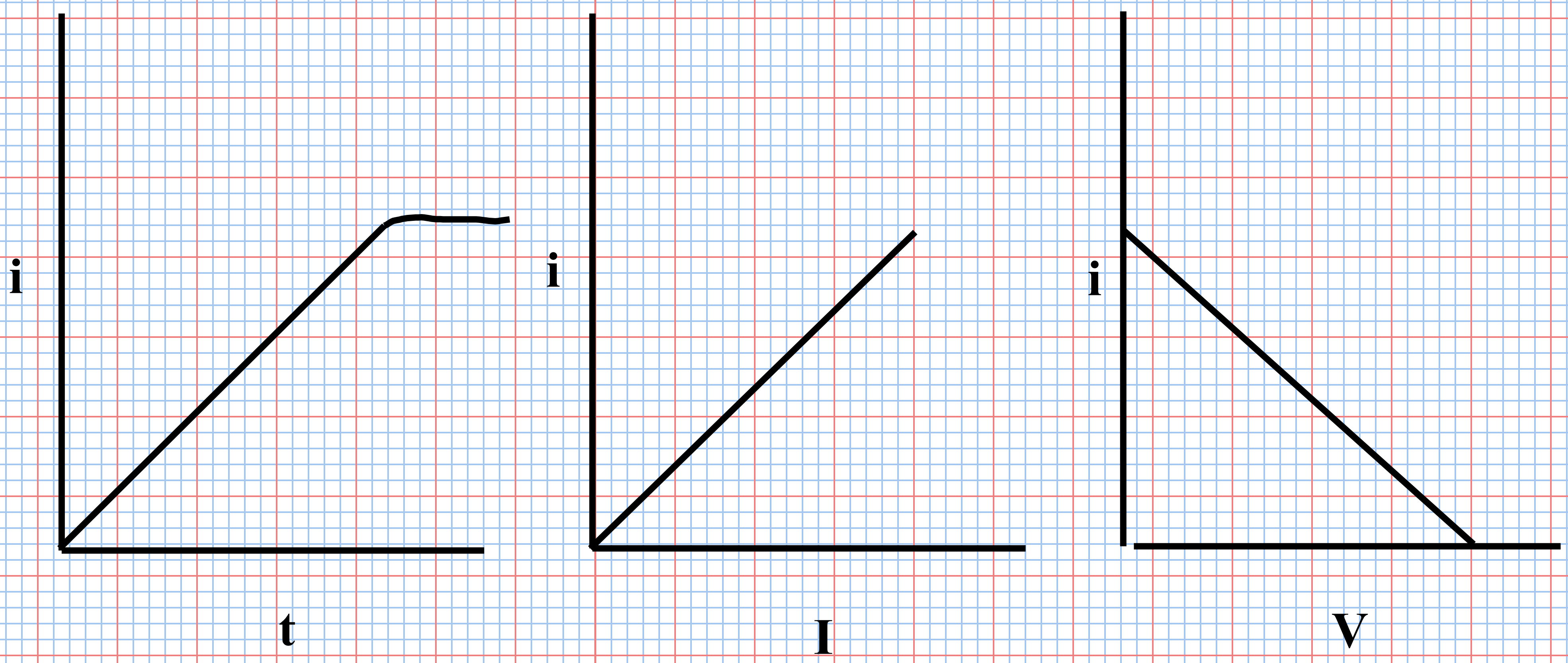
Here are two strange outcomes of the experiment:

(1) Classical physics predicted that any frequency of light should work if it were bright enough. However, it does not work that way. Only light above a certain frequency will eject electrons, no matter how intense the beam.

(2) Classical physics predicted that the maximum kinetic energy of ejected electrons should increase with the intensity of the light. Instead, the number of electrons increases, not the maximum KE.

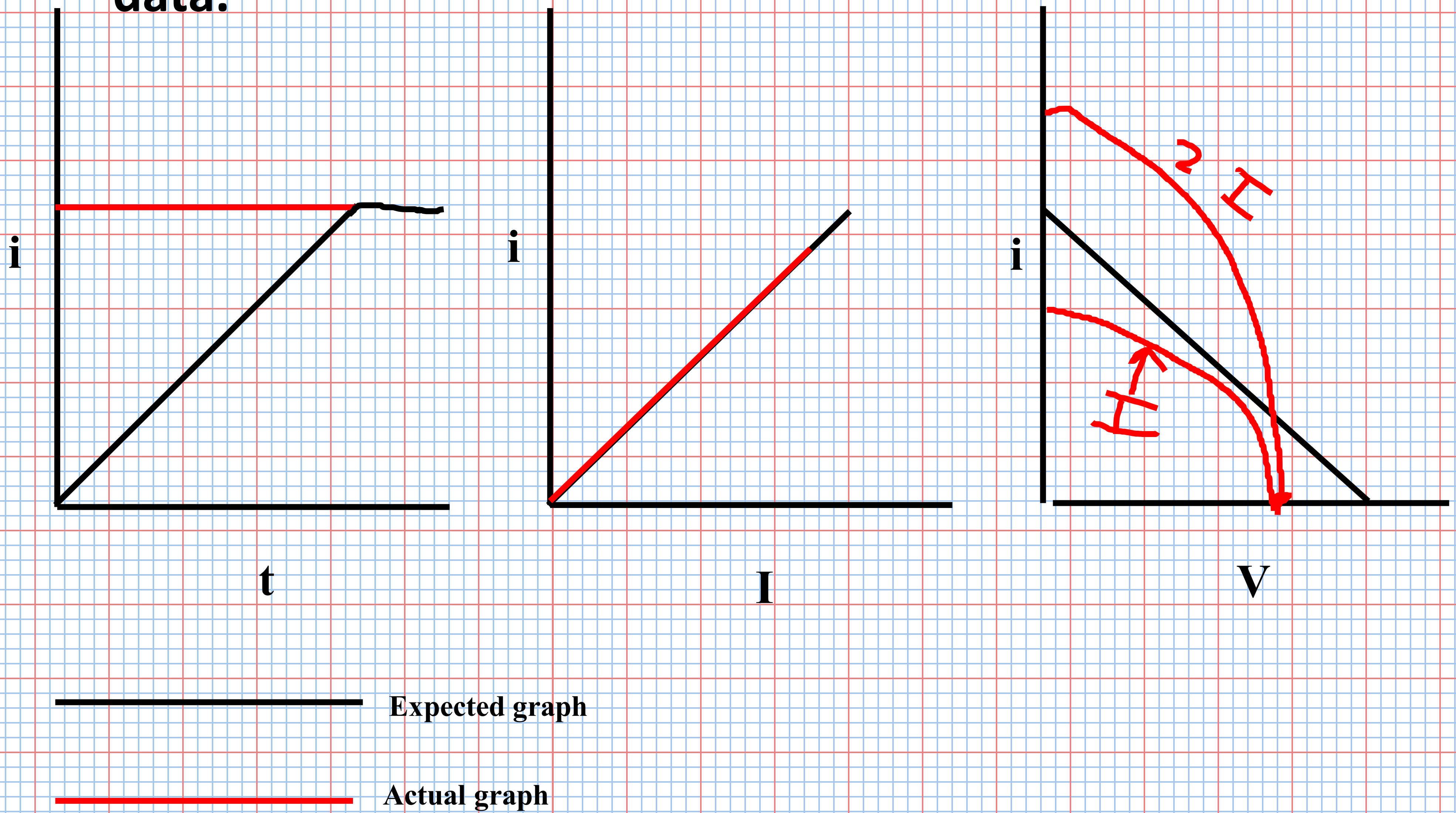


Assuming Light to be a continuous wave, this is what might be expected experimental results

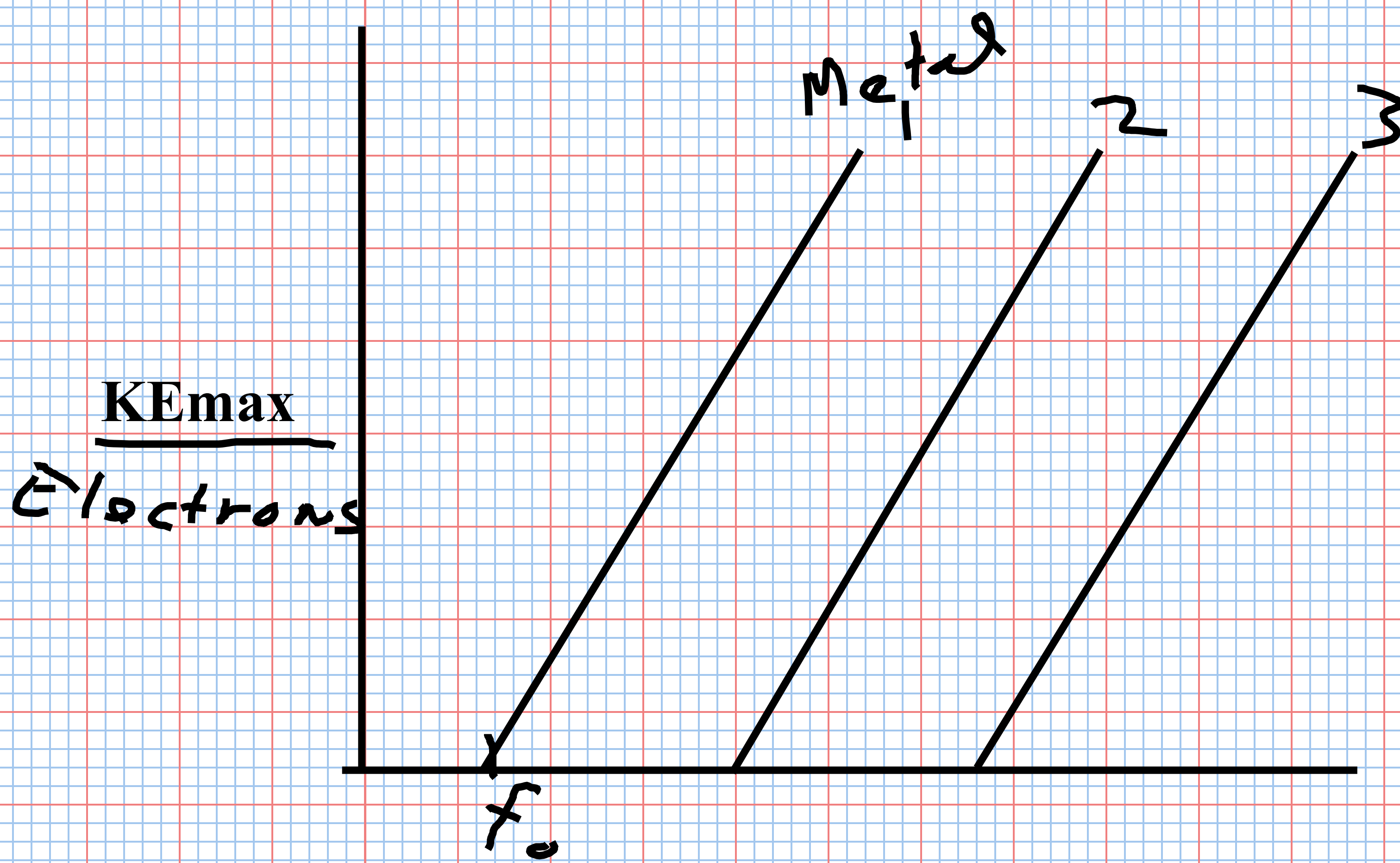


i = current
I = Intensity of the light
t = time
V = retarding voltage

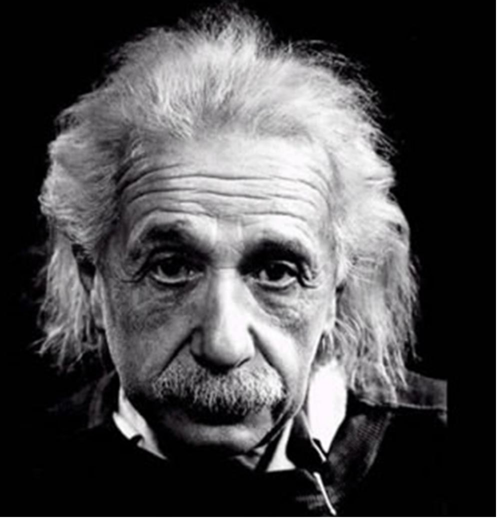
Assuming Light to be a continuous wave, the black line is what might be expected.
However, the red line represents the experimental data.



Actual experimental Data

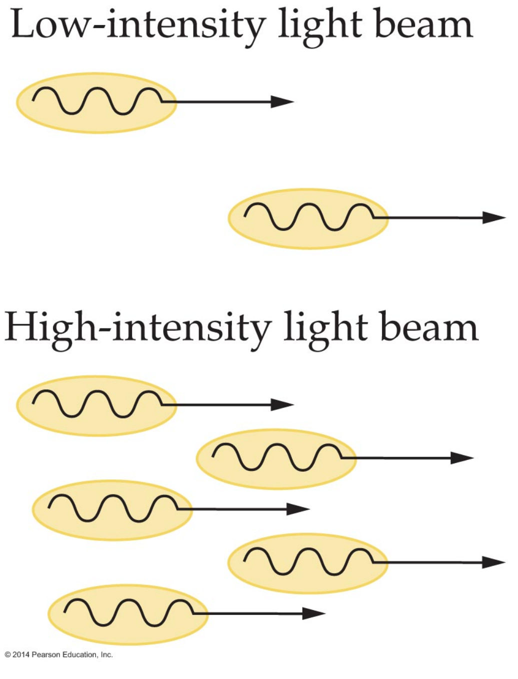


f_o = threshold frequency



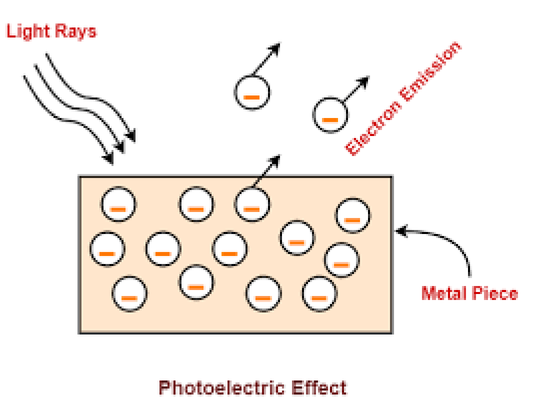
Here is the explanation:

The intensity of the light depends upon the number of photons



While the energy of each photon is given by

$$E = h\,f$$



Einstein said that light energy is quantized. The quantum of light energy is the photon. The energy of a photon is given by the formula

$E = h f$

Where h is Planck's constant.

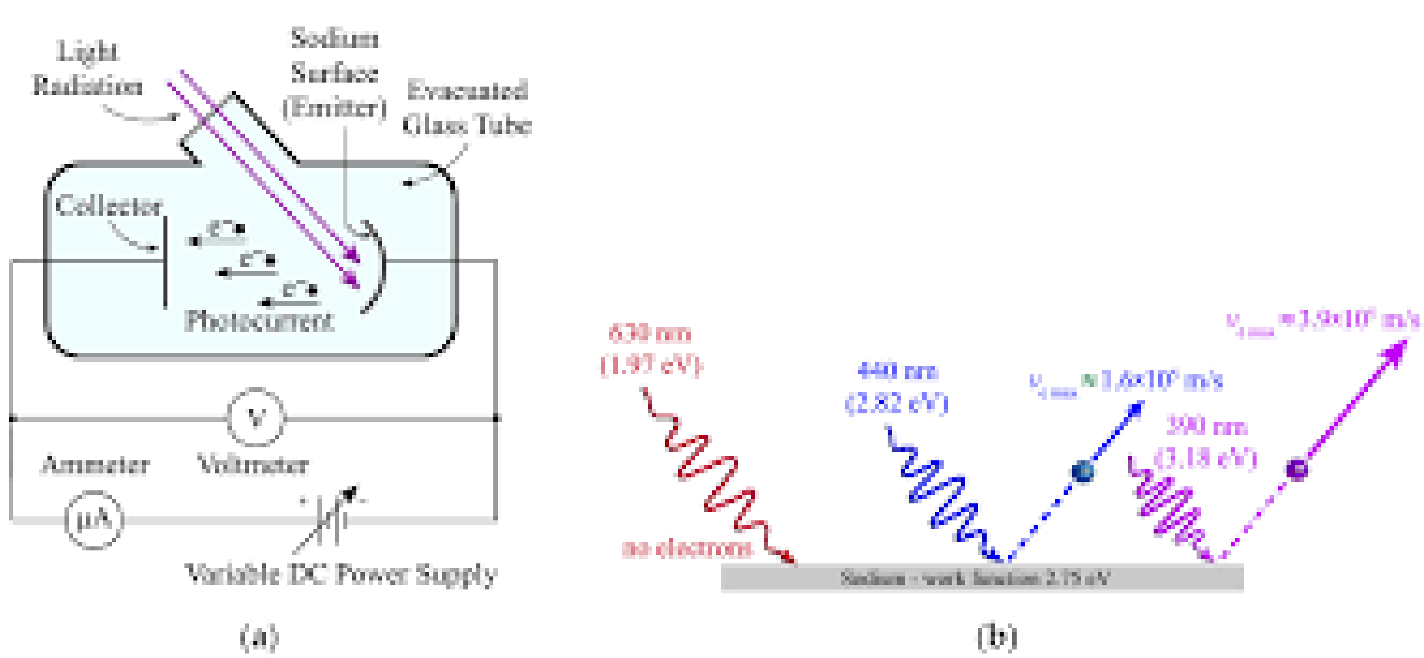
Einstein said that one photon will interact with one electron. If it does not have enough energy to eject the electron, then the electron will not be ejected.

Einstein said that each photon has an amount of energy determined by its frequency. Also, the minimum amount of energy needed to eject an electron from a particular metal is called the Work Function, Wo, of the metal. If an electron is given an amount of energy greater than the work function, then the excess appears as kinetic energy of the electron.

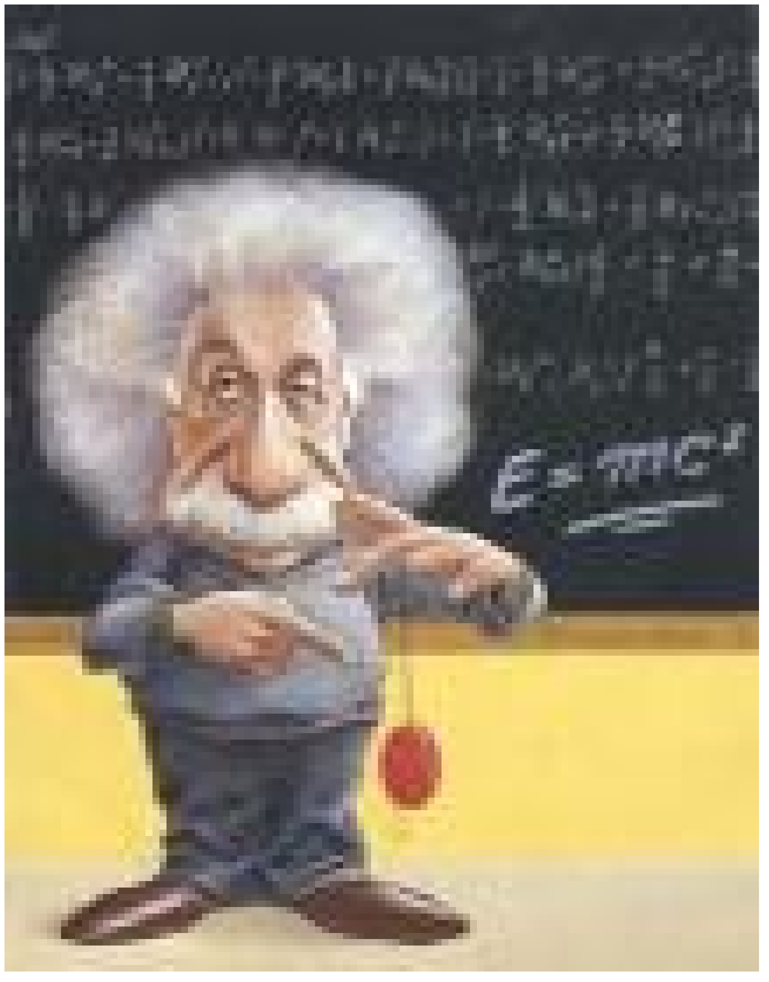
$KE(max) = E – Wo$

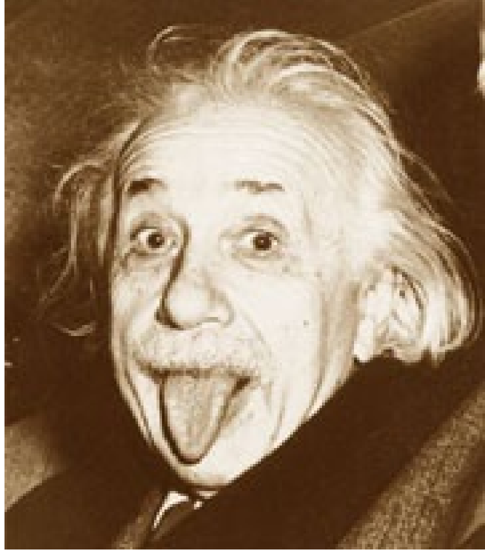
Or, if the cutoff frequency $fo = Wo/h$

Then $KE(max) = hf - hfo$



Uncle Albert won the Nobel prize for physics for explaining the photoelectric effect.





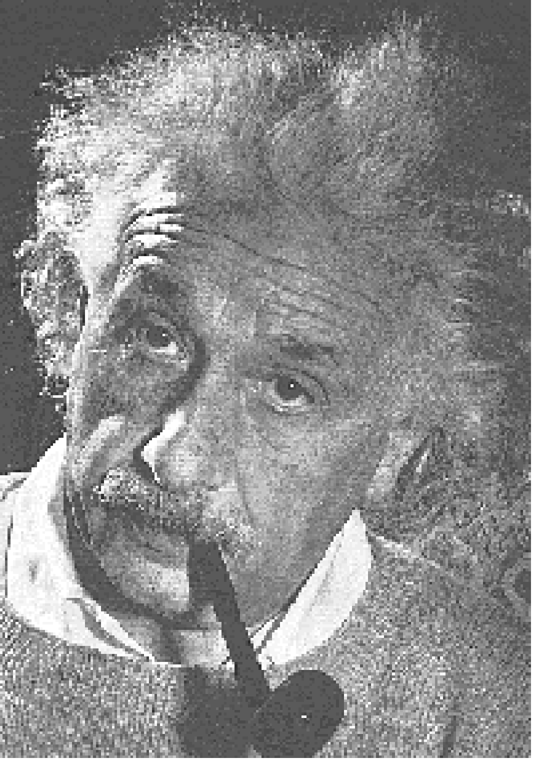
$$KE = hf - hf_o$$

KE = maximum kinetic energy of emitted electrons
hf = energy of the photon
hfo = work function of the metal

h = Planck's constant
f = frequency of the photon
fo = threshold frequency of the metal

Planck's Constant:

h= 6.63x10^-34 J s



It gets even more confusing

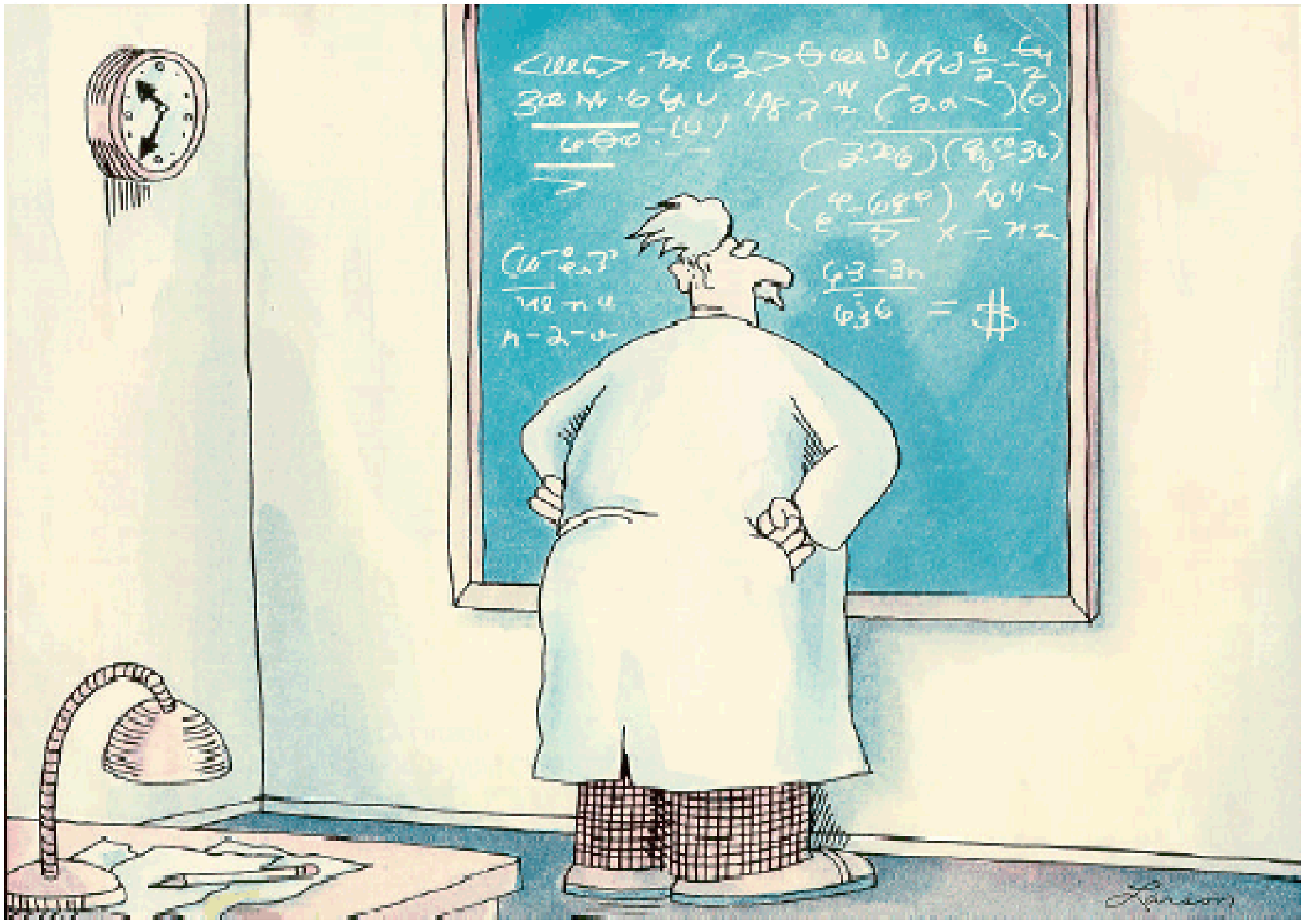
The photoelectric effect showed that photons, even though they have no mass, have kinetic energy. Einstein also predicted that photons should have momentum given by

$$p = E/c = hf/c = h/\lambda$$

$$p=h/\lambda$$

And just to balance things, anything with momentum, has an associated wavelength:

$$\lambda = h/p$$



"Einstein discovers that time is actually money" - Gary Larson

Heisenberg Uncertainty Principle

Consider measurement.
Measuring the temperature of a cup of water, you need to insert a thermometer. The thermometer will either absorb a bit of heat from the water, or give some heat to the water, thereby changing its temperature by a small amount. So, measuring the temperature will change it by some amount. It may be a small amount, but it will not be zero unless the thermometer started at the same temperature as the water was originally, which begs the question how you knew at what temperature to start the thermometer.

Even if you just look at something, photons must have bounced off it and entered your eye. You may have even shone bright light on it. Remember that photons have momentum, so they changed the momentum of the thing you are observing.

There are an infinite number of examples I could give, but the point is that the mere fact of observing a variable can change it.

You may think that the change can be arbitrarily small, but because of the quantum nature of matter, there is a minimum amount of energy or momentum by which a variable can be changed.

The Heisenberg Uncertainty Principle formalizes this as follows:
Uncertainty in momentum * uncertainty in position $\geq h/2\pi$

$$\Delta p * \Delta x \geq h/2\pi$$

There are numerous other applications, for example the uncertainty in energy * uncertainty in time $\geq h/2\pi$

$$\Delta E \Delta t \geq h/2\pi$$

So this puts a fundamental, theoretical limit on how accurate our measurements can be. That limit is completely independent of limitations of our measuring instruments.

However, remember how small Planck's constant is

Planck's Constant:

h= 6.63x10^-34 J s

That is why we do not notice Heisenberg's uncertainty – or the quantum nature of energy – under normal circumstances. However, when we get into the realm of the extremely small, this poses a fundamental limit.