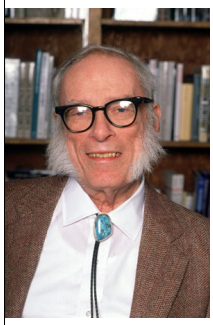
Planck's Hypothesis

Planck's "quantum hypothesis":
maybe when a body emits or absorbs light of frequency f,
it can't emit any old amount of energy it likes, because there is some "special energy": it emits energy in "steps" of E=hf.

Energy per frequency:
Planck's constant: $h = 6.6 \cdot 10^{-34}$ J s [or J / Hz, since Hz = 1/s]

How could we prove this theory?



"Science does not purvey absolute truth, science is a mechanism. It's a way of trying to improve your knowledge of nature, it's a system for testing your thoughts against the universe and seeing whether they match." -- Isaac Asimov

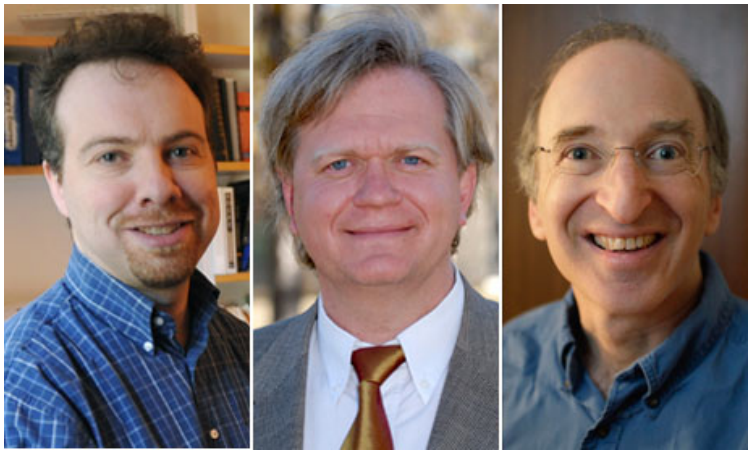
Science is much closer to myth than a scientific philosophy is prepared to admit. It is one of the many forms of thought that have been developed by man, and not necessarily the best. It is conspicuous, noisy, and impudent, but it is inherently superior only for those who have already decided in favour of a certain ideology, or who have accepted it without ever having examined its advantages and its limits.

--- Paul Feyerabend, one of the most radical philosophers of science

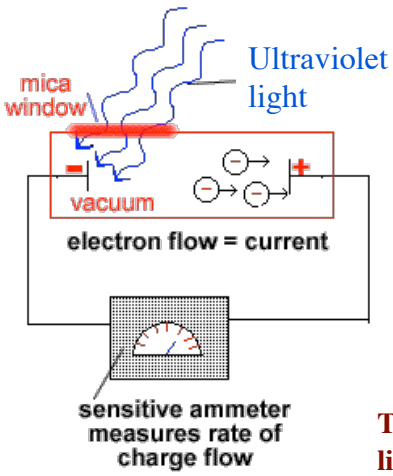
Science is a constant effort to *disprove* everything, not to prove it!

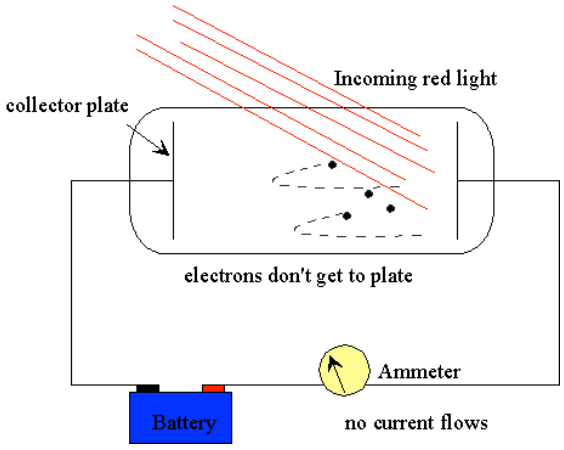
Adam Riess on his Nobel Prize for discovering the acceleration of the universe's expansion:

"I remember thinking, I've made a terrible mistake and I have to find this mistake."



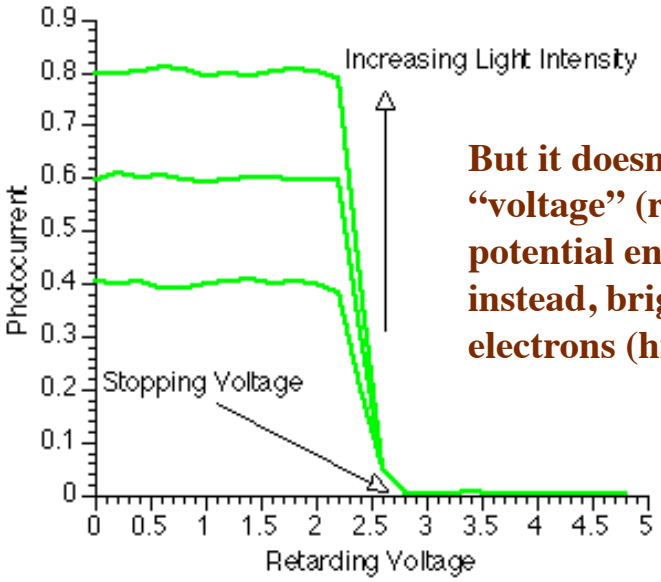
The photoelectric effect
(basically the heart of solar power, photosensors, digital cameras, ...)





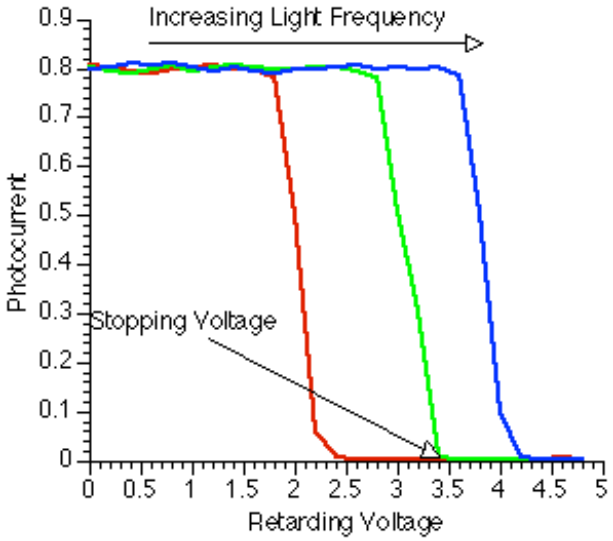
The battery's negative terminal repels electrons – it's like a "hill" for them to climb,
and if the height of the hill is too high, electrons don't have enough energy to climb it

A bigger electric field (brighter light) ought to give the electrons more energy

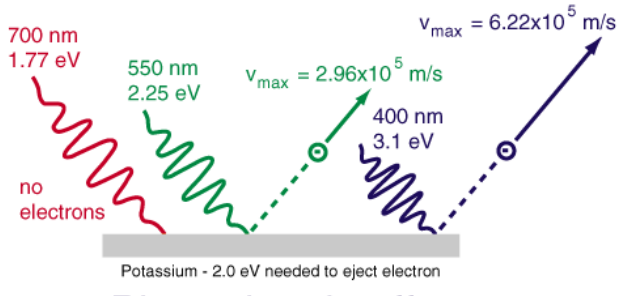


But it doesn't... it still takes the same "voltage" (remember: electrical potential energy) to stop them; instead, brighter light just gives more electrons (higher current).

On the other hand, the energy the electrons fly off with depends on the *colour* of the light



The photoelectric effect, recap



Light hitting a metal causes electrons to fly off

Brighter light (bigger electric field!) leads not to faster electrons, but to more of them

Higher-frequency ("bluer") light gives off faster electrons

No matter how dim the light (little energy per unit time), electrons start coming off instantaneously -- how do they get enough energy to escape?

Einstein's hypothesis of "light quanta" (we now call them "photons")

Not only is energy *exchanged* between light and matter in discrete steps E=hf, but this is because light is actually *made* of particles (photons), each with energy E=hf.

Intensity is total energy (per area, per time) in a beam; related to *number of photons* multipled by *energy per photon*.

Each photon knocks out one electron; the energy of the electron depends on the colour (f) of the light.

More photons -> more electrons, but the same energy to each.

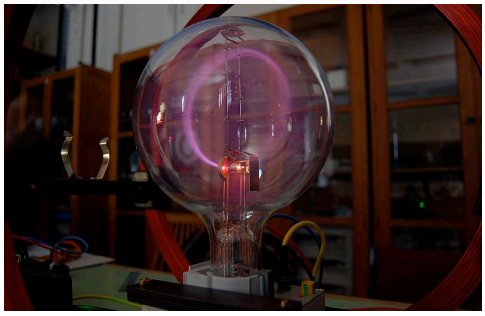
Question:

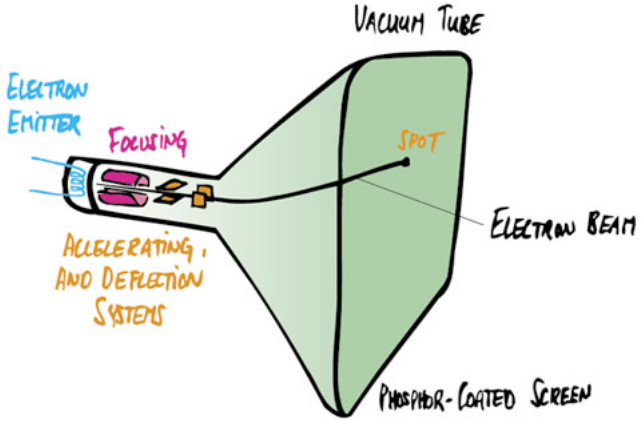
Case 1: 1W of red (low-frequency) light
Case 2: 1W of blue (high-frequency) light

Question: do the electrons in case 1 have higher, lower, or the same energy as in case 2?

Question: are there more electrons given off in case 1 or case 2, or the same in both?

Digression: cathode rays & CRTs



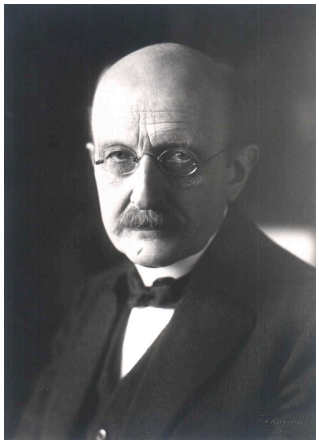


Thomson 1896: these "cathode rays" act like individual charged particles, and they seem to have the same mass no matter what metal they come from -- all matter contains "electrons"

Wasn't the explanation obvious because of Planck, even before Einstein?

Planck:

"The theory of light would be thrown back not by decades, but by centuries, into the age when Christian Huygens dared to fight against the mighty emission theory of Isaac Newton ..."



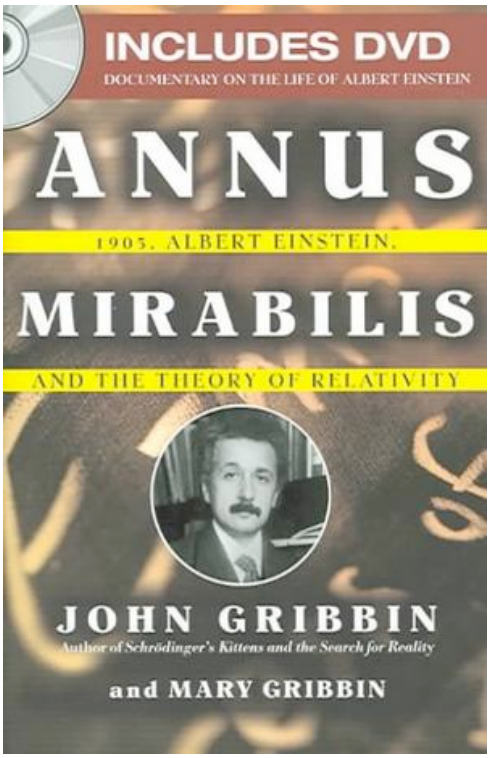
Max Planck, later: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

445. Proposal for Einstein's Membership in the Prussian Academy of Sciences[1]

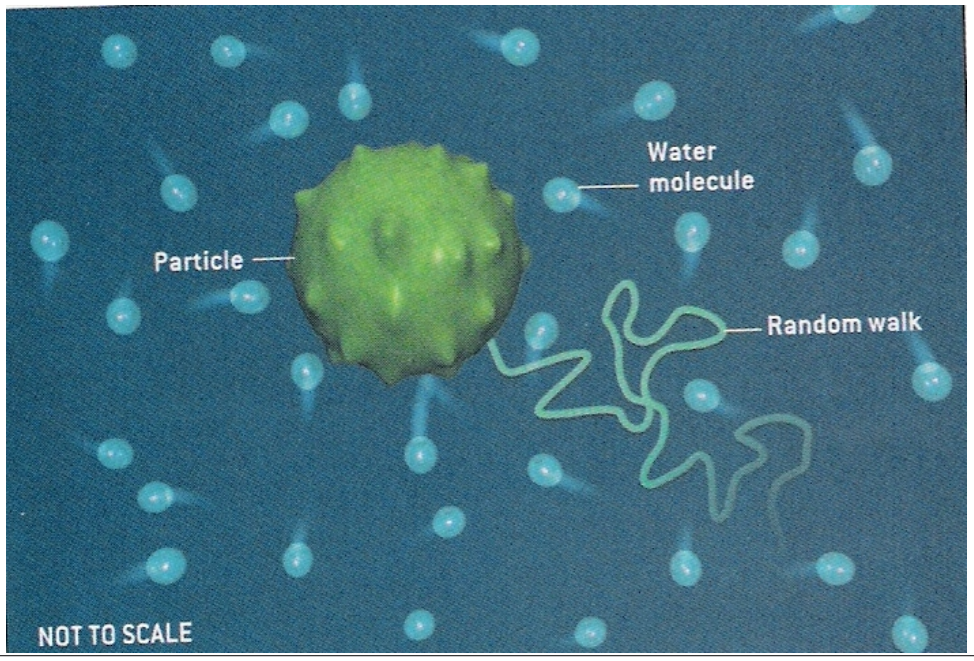
Berlin, 12. Juni 1913.

Die unterzeichneten Mitglieder der Akademie beehren sich, die Erwählung des ordentlichen Professors der theoretischen Physik an der eidgenössischen technischen Hochschule in Zürich, Dr. Albert Einstein, zum ordentlichen Mitglied der Akademie, mit einem besonderen persönlichen Gehalt <zunächst> von <6000> 12000 M., zu beantragen.[2]

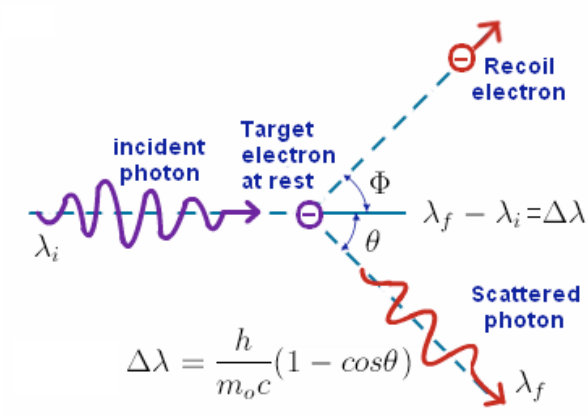
in bemerkenswerter Weise Stellung genommen hätte. Daß er in seinen Spekulationen gelegentlich auch einmal über das Ziel hinausgeschossen haben mag, wie z. B. in seiner Hypothese der Lichtquanten, wird man ihm nicht allzuschwer anrechnen dürfen; denn ohne einmal ein Risiko zu wagen, läßt sich auch in der exaktesten Naturwissenschaft keine wirkliche Neuerung einfüh-



In 1905, explaining Brownian motion was Einstein's most influential contribution -- not relativity (which he didn't even describe as revolutionary) nor the photoelectric effect (which he did)



Further evidence for particles of light: the Compton effect



After kicking an electron out of a metal, the photon has less energy – it is "redder" (lower frequency, longer wavelength). Furthermore, the bigger the angle, the longer the wavelength gets: you lose more energy in "back-scattering" than in a glancing collision.

Recap some history (just light for now; atoms in parallel)

- **Huygens, Hooke - light may be a wave; Newton - no it isn't.** **(17th cent.)**
- **Young, Fresnel, Arago - light *is* a wave!** **(1803-1818)**
- **Maxwell - light is an *electromagnetic* wave!** **(1865)**
- **Planck - "blackbody radiation": somehow, energy is exchanged in little units** **(1900)**
- **Einstein - "photoelectric effect"**

Particle or Wave?

Einstein:

Light may well travel as a wave, interfering & all that, but when you detect it, it appears one particle at a time.

A particle of light ("photon") is incredibly small – a normal light bulb gives off about 1,000,000,000,000,000,000,000 of them every second – this is why (even though in the dark, the eye is sensitive to 3 or 4 photons) we never realized this.

(movie)

See http://www.youtube.com/watch?v=MbLzh1Y9POQ
for Leiden movie of interference one photon at a time

(see also http://www.upscale.utoronto.ca/PVB/Harrison/DoubleSlit/DoubleSlit.html
and http://en.wikipedia.org/wiki/Double-slit_experiment)

Recap some history (just light

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- **Planck - "blackbody radiation": somehow,**

energy is exchanged in little units **(1900)**

- **Einstein - "photoelectric effect": light is actually**

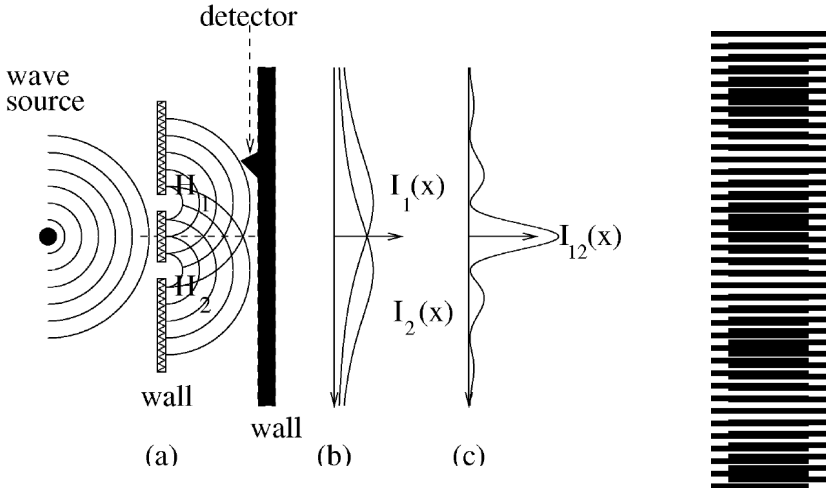
made of "quanta" ("photons") **(1905)**

- **Taylor - single photons still inferfere?!** **(1909)**
- **Compton effect: when light bounces off electrons,**

the electrons "recoil" just as if hit by particles...

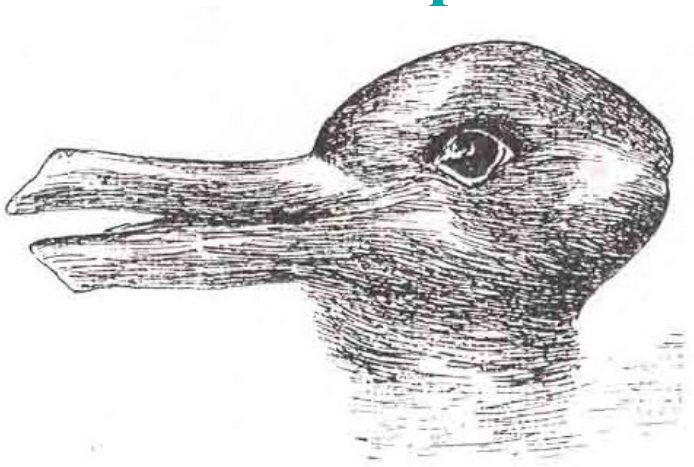
- **Jaynes - maybe we don't need that after all** **(1966)**
- **Clauser - actually we do** **(1974)**

What if I opened one slit at a time?



Richard Feynman: [Interference is...]
"a phenomenon which is *impossible*, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. **In reality, it contains the *only* mystery."**

Complementarity



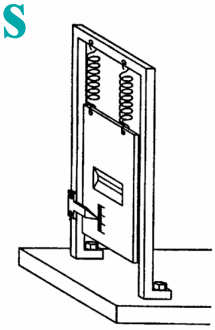
Light is neither a wave nor a particle.

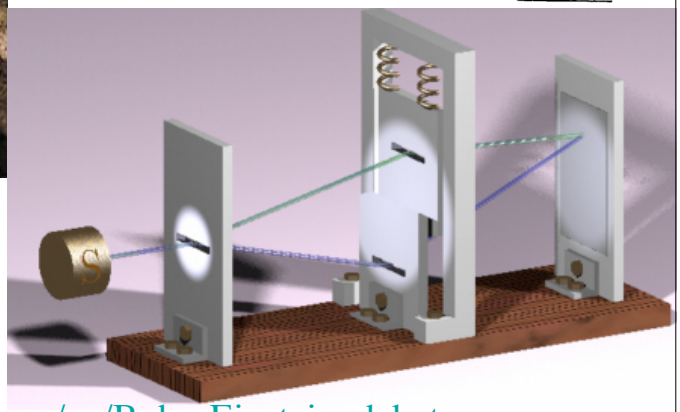
"Wave" and "particle" are two *aspects* of light, but they are "*complementary*" – we can choose to observe one or the other, but never both simultaneously.

The Bohr-Einstein debates

How can a particle go through both slits at once?
If I measured which one it went through, how could interference occur between the two of them?

Bohr-Einstein debates





Cf. http://www.viswiki.com/en/Bohr–Einstein_debates
for an unusual video recreating the debates...