



GEST 011, Newton's Clock & Heisenberg's Dice, Fall 2013

The 20th Century Quantum Odyssey

Mahn-Soo Choi (Korea University)

September 20, 2013 (v5.13)



2001: A SPACE ODYSSEY

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The 20th Century Quantum Odyssey



2001: A SPACE ODYSSEY

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Photograph by The Korea Cultural Heritage Newspaper (2013)

전남 순천시 순천만



Girl with a Pearl Earring (Johannes Vermeer, circa 1665)

Let there be Light!



THE BIG BANG
BY KEEPWALKING07

Let the **Light** guide us!

Image from Flickr

The Pigeon Point Lighthouse, California

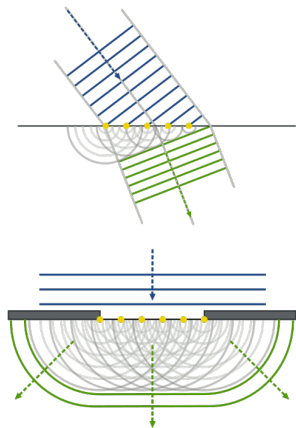
What is Light?

Light is a Wave?

(Treatise of Light, 1678)



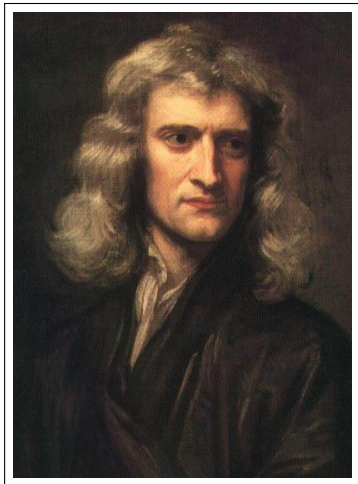
Christiaan Huygens (1629–1695)



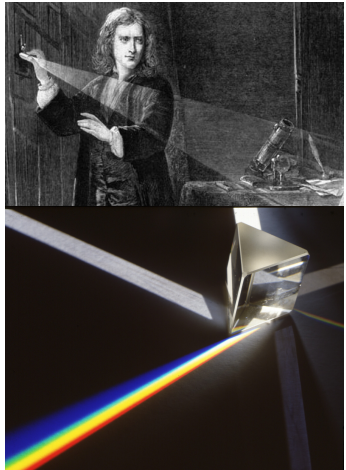
<http://wikipedia.org/>

Light Consists of Particles?

Opticks (Newton 1704)



Sir Isaac Newton (1643–1727)

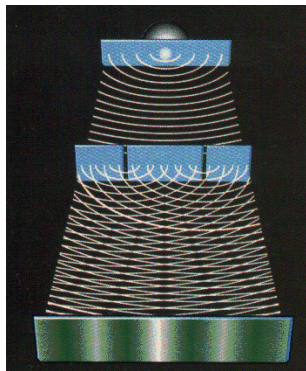


Light is a Wave!

(Young, 1803*)



Thomas Young (1773–1829)



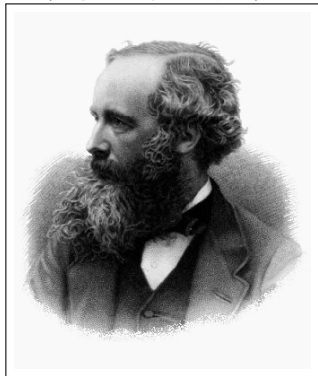
*Young, Royal Society of London Philosophical Transactions Series I (1804)

All images courtesy of Wikipedia

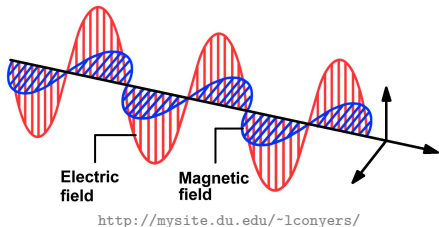
Light is an Electromagnetic Wave!

(Maxwell, Philosophical Magazine and Journal of Science, 1861)

(Image courtesy of Wikipedia)

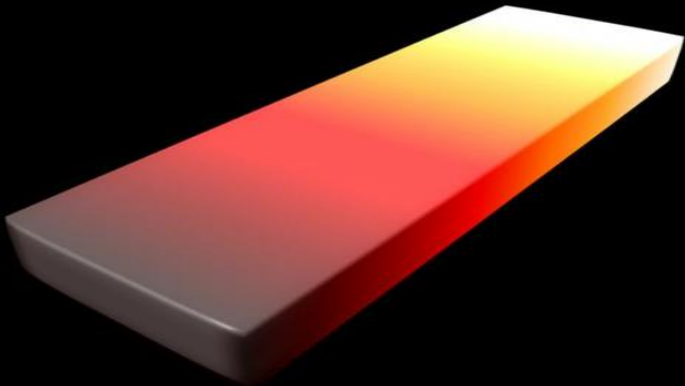


James C. Maxwell (1831–1879)

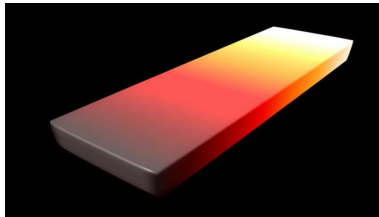


- Faraday's induction law: "Change in magnetic field induces electric field."
- Ampere's induction law: "Change in electric field induces magnetic field."
- Even no need for medium!

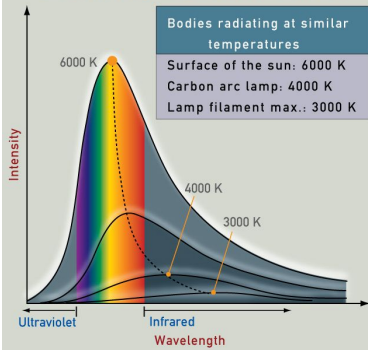
New Challenges to the Theory of Light



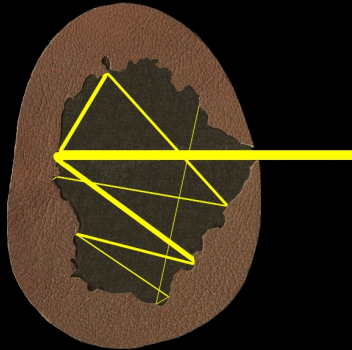


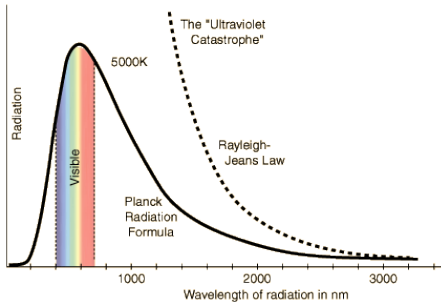
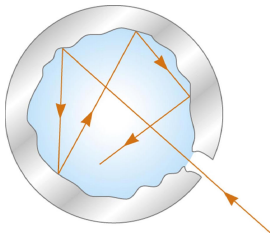


Blackbody Radiation Curves



Cavity as a Black-Body



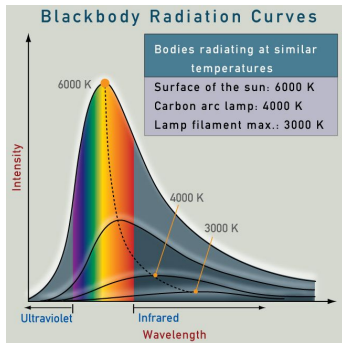


Black-Body Radiation

(Planck, Ann. Physik, 1900a; Planck, Ann. Physik, 1900c; Planck, Verh. D. Phys. Ges. Berlin, 1900b)

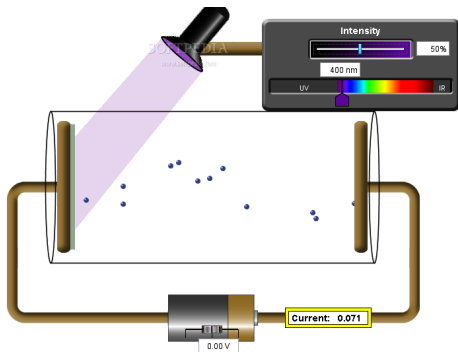


Max Planck (1858–1947)

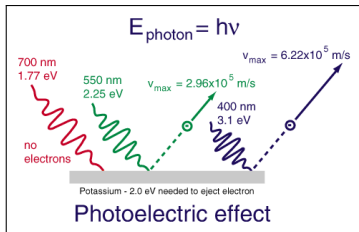


$$\text{Intensity} \propto \frac{1}{\exp(h\nu/k_B T) - 1}$$

$$(\text{energy})_{\text{photon}} = h \times (\text{frequency})$$



<http://www.brothersoft.com/>



<http://hyperphysics.phy-astr.gsu.edu/>

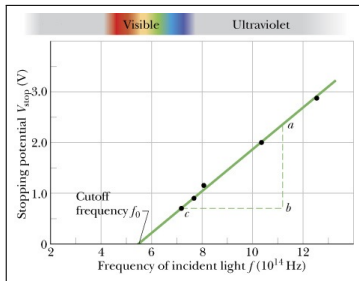
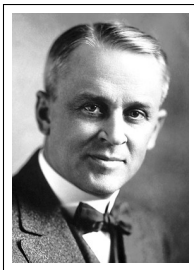
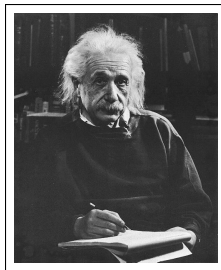
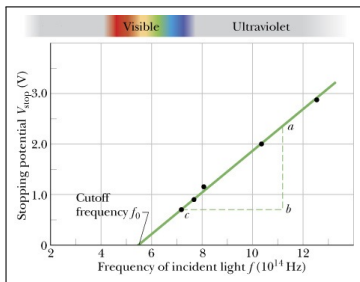
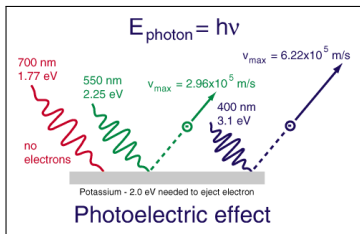


Image courtesy of Halliday, Resnick & Walker

(2005)

Photoelectric Effect

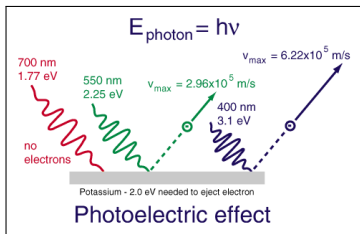
(Einstein, Ann. Phys., 1905)



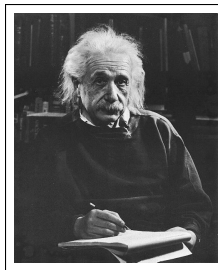
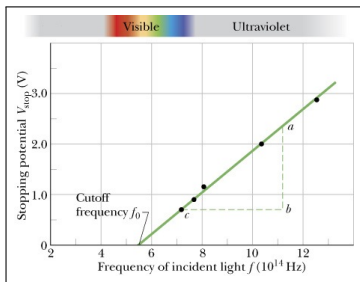
Albert Einstein & Robert A. Millikan
(Originally, Millikan was trying to *disprove* Einstein's theory.)

Photoelectric Effect

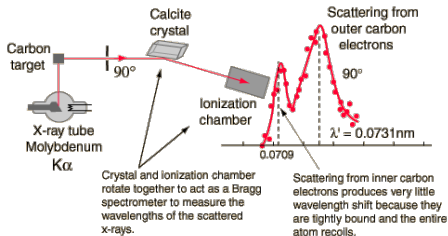
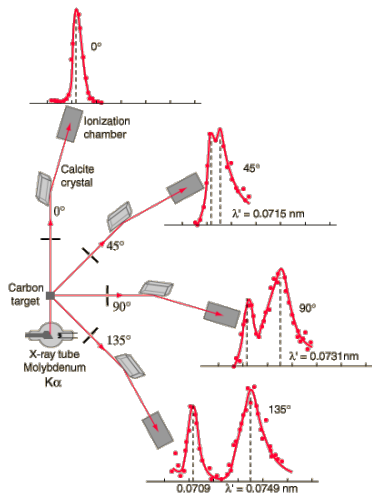
(Einstein, Ann. Phys., 1905)



$$E_{\text{photon}} = h\nu = \hbar\omega$$



Albert Einstein & Robert A. Millikan
(Originally, Millikan was trying to *disprove* Einstein's theory.)



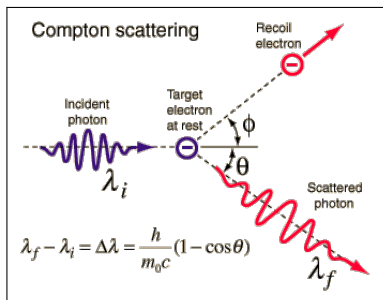
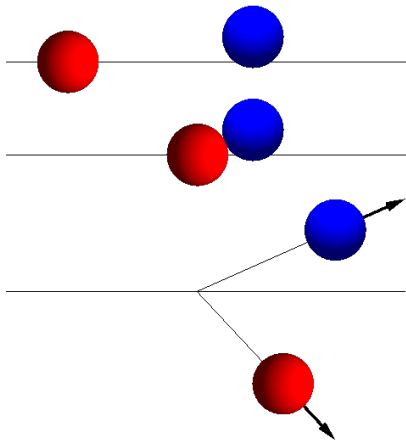


Image courtesy of HyperPhysics

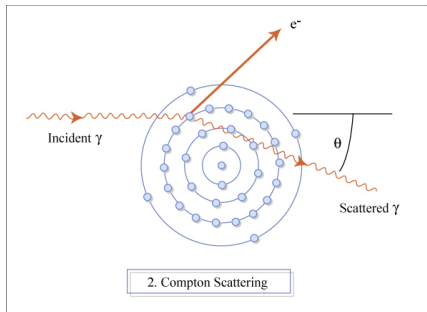
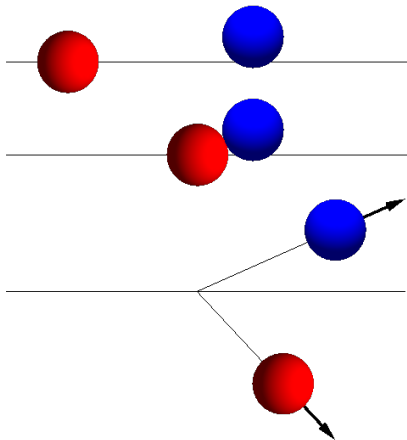
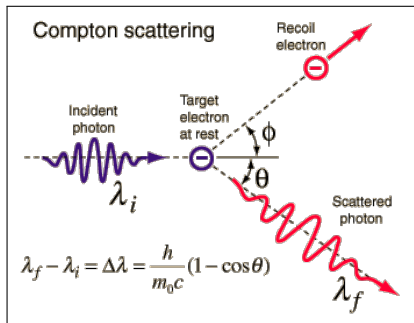
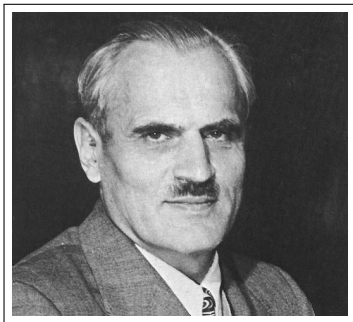


Image courtesy of mitopencourseware

Compton Scattering

(Arthur Holly Compton, 1923)



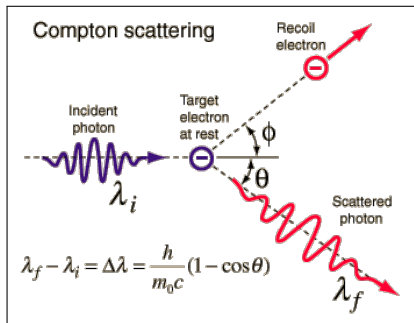
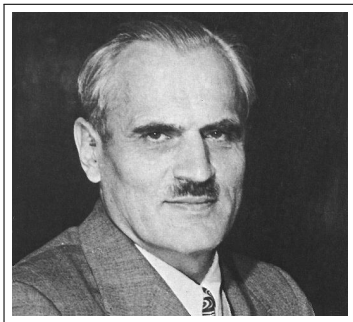
$$\lambda' - \lambda = \lambda_c(1 - \cos\theta), \quad \lambda_c = \frac{2\pi\hbar}{mc}$$

Left image courtesy of Wikipedia

Right image courtesy of HyperPhysics

Compton Scattering

(Arthur Holly Compton, 1923)



$$\lambda' - \lambda = \lambda_c(1 - \cos\theta), \quad \lambda_c = \frac{2\pi\hbar}{mc}$$

Left image courtesy of Wikipedia

Right image courtesy of HyperPhysics

$$(\text{energy})_{\text{photon}} = h \times (\text{frequency})$$

$$(\text{momentum})_{\text{photon}} = \frac{h}{(\text{wavelength})}$$

Particles or Wave?

(Self-Identity Problem of Photons)



<http://claesjohnson.blogspot.com/>

“Light Meets Dark.”



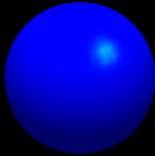
“The opposite of a correct statement is a false statement. But the opposite of a profound truth may well be another profound truth.” Niels Bohr*

Image courtesy of Wikipedia

*Chodos, APS News (2012)

We all thought that light is a wave.
But it turns out that light is a particle, too.

We all know that electron is a particle.
But could it be a wave, too?



Wave-Particle Duality

(Broglie 1924)



Louis de Broglie (1892–1987)

Image courtesy of Wikipedia

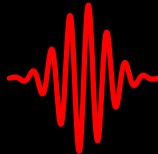
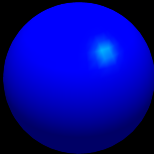
- Light (a wave) has momentum (like a particle)

$$\text{(momentum)} = \frac{h}{\text{(wavelength)}}$$

- Why not a particle with momentum behaving as a wave?

$$\text{(wavelength)} = \frac{h}{\text{(momentum)}}$$

Possible? ...?

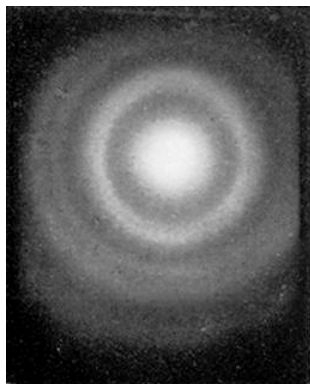


Left image from <http://newsroom.ucla.edu/>

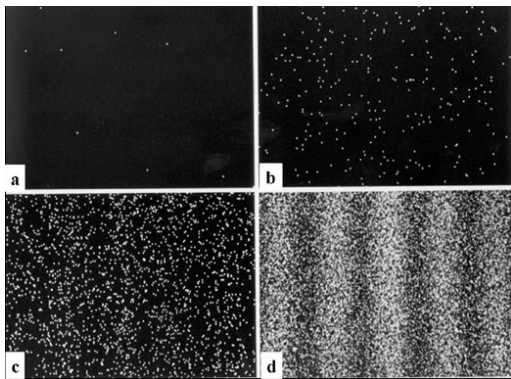
Right image from <http://www.kirksville.k12.mo.us/>

Electron Diffraction Experiments

(Davisson & Germer, Nature, 1927; Thomson, Proc. R. Soc. London A, 1928)



(Thomson, Proc. R. Soc. London A, 1928)



(Hitachi Lab, 1994)

Electrons behave like a wave!

A true double-slit experiment with electrons by Jönsson, Z. Physik (1961).

The Hitachi experiment is an extension of Tonomura et al., Ame. J. Phys. (1989).

The 10 Most Beautiful Experiments in Physics

(Crease, Physics World, 2002; Crease, Physics World, 2002)

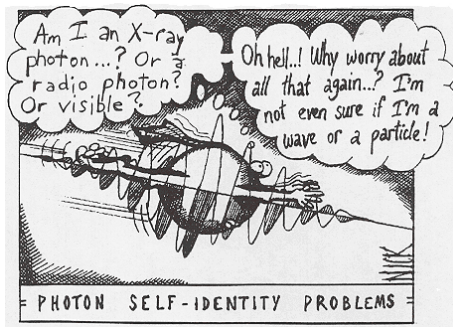
- 1 Double-slit experiment of electrons (1927, 1961)
- 2 Galileo's experiment of falling objects
- 3 Millikan's oil-drop experiment (1909)
- 4 Newton's decomposition of sunlight with prism
- 5 Young's light-interference experiment (1803)
- 6 Cavendish's torsion-bar experiment (1797-1798)
- 7 Eratosthenes' measurement of the Earth's circumference (3C BC)
- 8 Galileo's experiments with balls rolling down inclined planes
- 9 Rutherford's discovery of the nucleus (1911)
- 10 Foucault's pendulum (1851)

The 10 Most Beautiful Experiments in Physics

(Crease, Physics World, 2002; Crease, Physics World, 2002)

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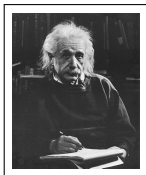
Particle or Wave?



Self-Identity Problem for ANY Particles!!

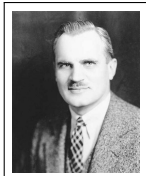
Wave-Particle Duality

(A. Einstein, 1902; A. H. Compton, 1923; L. de Broglie, 1924)



Let **light** (wave) have **discrete** energies!

$$(\text{energy}) = h \times (\text{frequency})$$



Let **light** (wave) have **momentum**!

$$(\text{momentum}) = \frac{h}{(\text{wavelength})}$$



Let **particles** behave **like a wave** with:

$$(\text{frequency}) = h \times (\text{energy}),$$

$$(\text{wavelength}) = \frac{h}{(\text{momentum})}$$

$$(\text{energy}) = h \times (\text{frequency})$$

$$(\text{momentum}) = \frac{h}{(\text{wavelength})}$$

Baron Ashura vs Jekyll & Hyde

(bad and good analogies of wave-particle duality)



Baron Ashura vs Jekyll & Hyde

(bad and good analogies of wave-particle duality)



The complementarity principle

Once wave-like, not like particles!

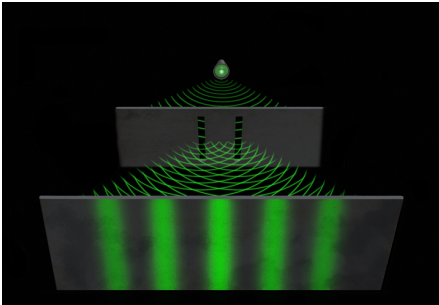
Once particle-like, not like waves!

Consequences?

(superposition & interference)

Interference of Particles

(How can it be possible?)



VS

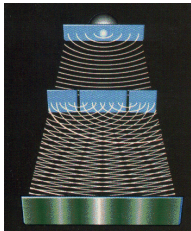


Left image by CBC Radio Messey Lectures (2012, Lecture 2).

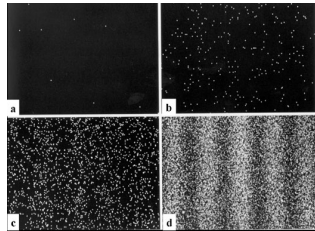
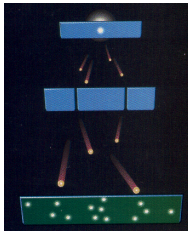
Right image from <http://moviewallpaper.net/>

Interference of “Single” Particles

(one by one)



VS

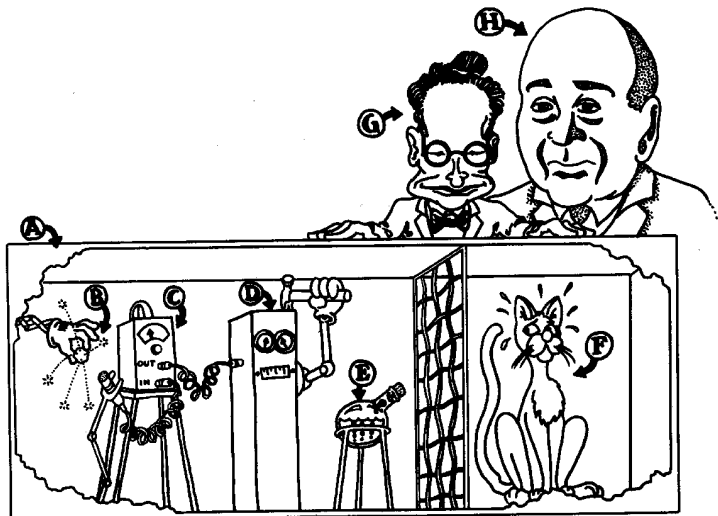


$$\Psi = \frac{1}{\sqrt{2}} (\Psi_L + \Psi_R)$$

“Superposition,” Does it Make Sense?



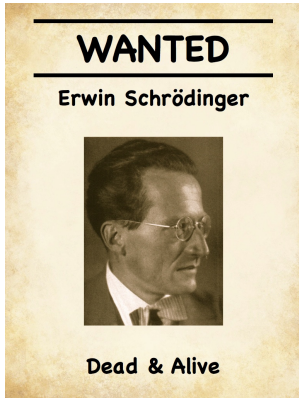
Schrödinger's Cat (1935)



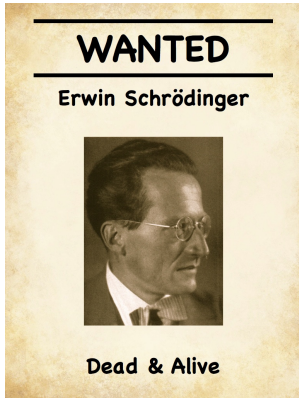
(William R. Warren, Jr., © 1985, reproduced with permission.)

William R. Warren, Jr. (1985)

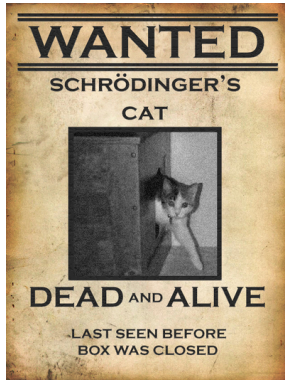
The Enemy of The School



The Enemy of The School



The Copenhagen School Wants
Schrödinger
Dead AND Alive.
Take Schrödinger into custody
dead and alive,
and you will get A+.



Bring Schrödinger's cat, too,
dead and alive,
and you'll get A++.

References

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