In the mid-18th century, Maxwell unified electricity and magnetism with his now famous equations and showed that light is an electromagnetic wave.

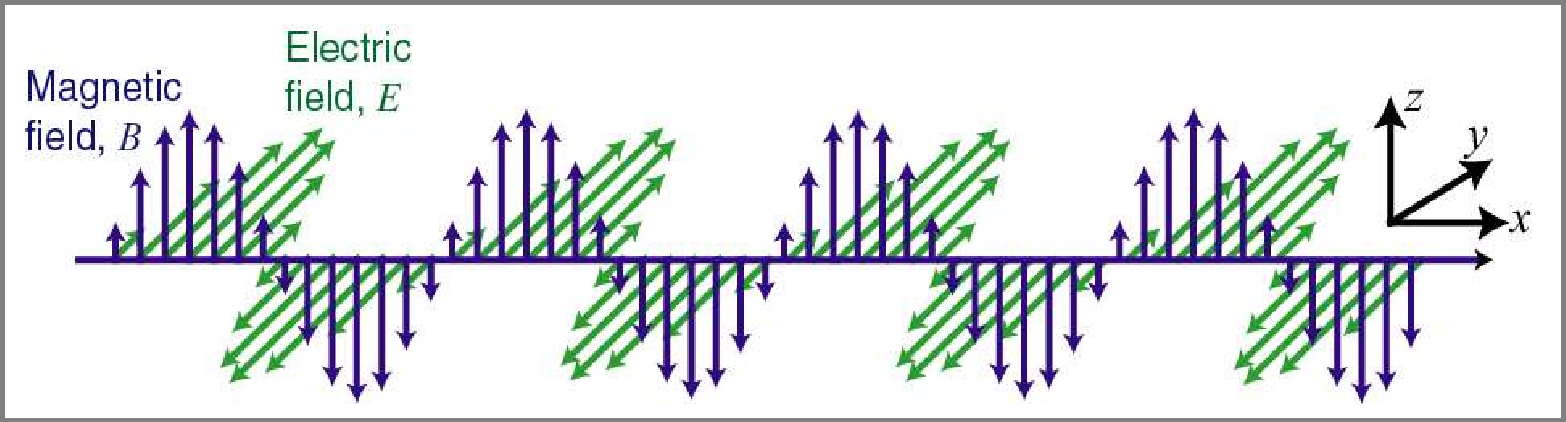
$$\vec{\nabla}\cdot\vec{E} = 4\pi\rho \qquad \vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\times\vec{B} = \frac{1}{c}\left(4\pi\vec{J} + \frac{\partial\vec{E}}{\partial t}\right)$$

James Clerk Maxwell
(1831-1879)

where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, $\vec{J}$ is the electric current density and c is the velocity of light.

Light is an electromagnetic wave.

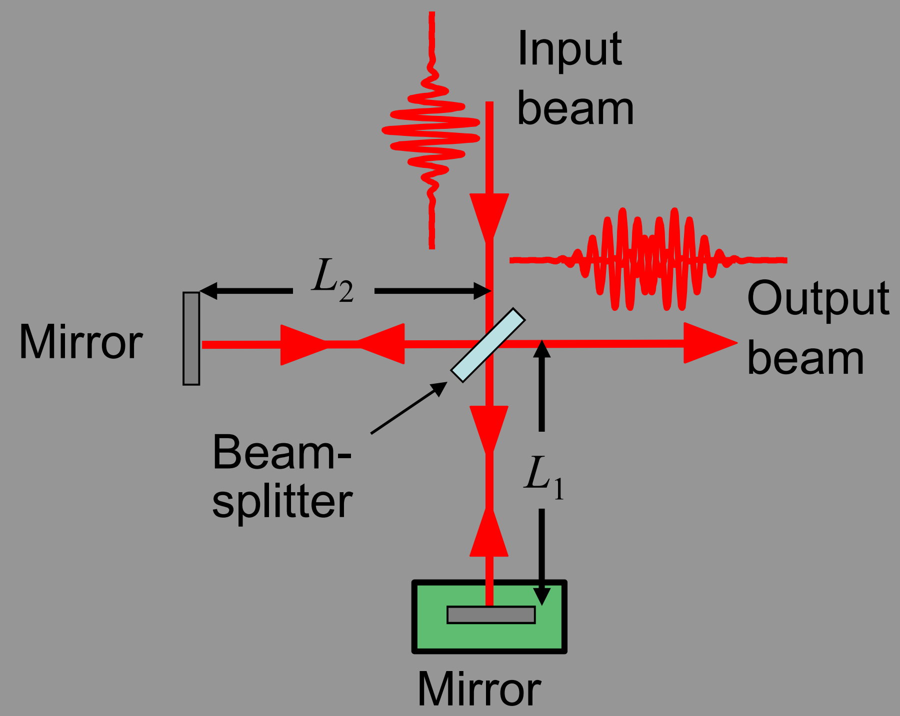


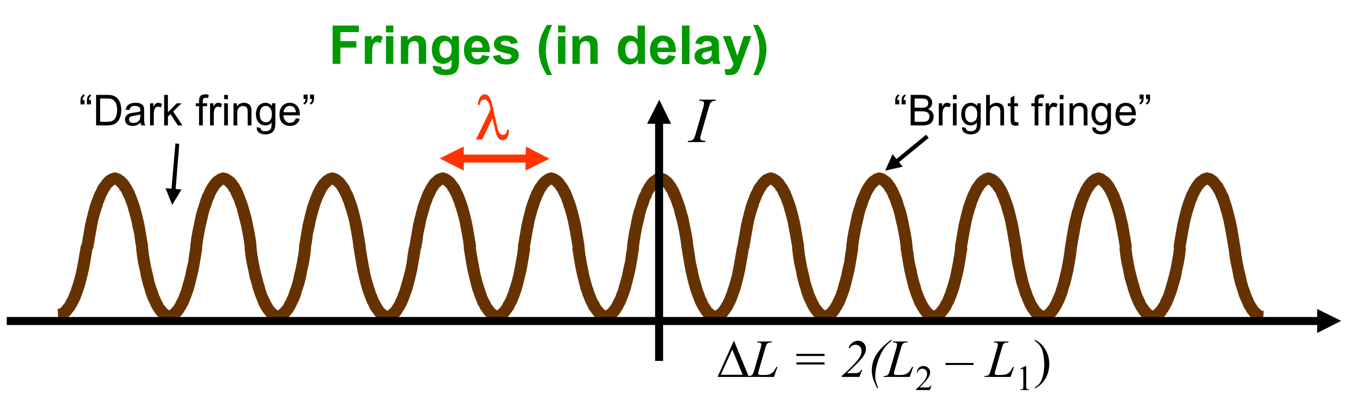
The electric field, the magnetic field, and the propagation direction are all perpendicular.

Waves can interfere.

The Michelson Interferometer

The Michelson Interferometer deliberately interferes two beams and so yields a sinusoidal output intensity vs. the difference in path lengths.



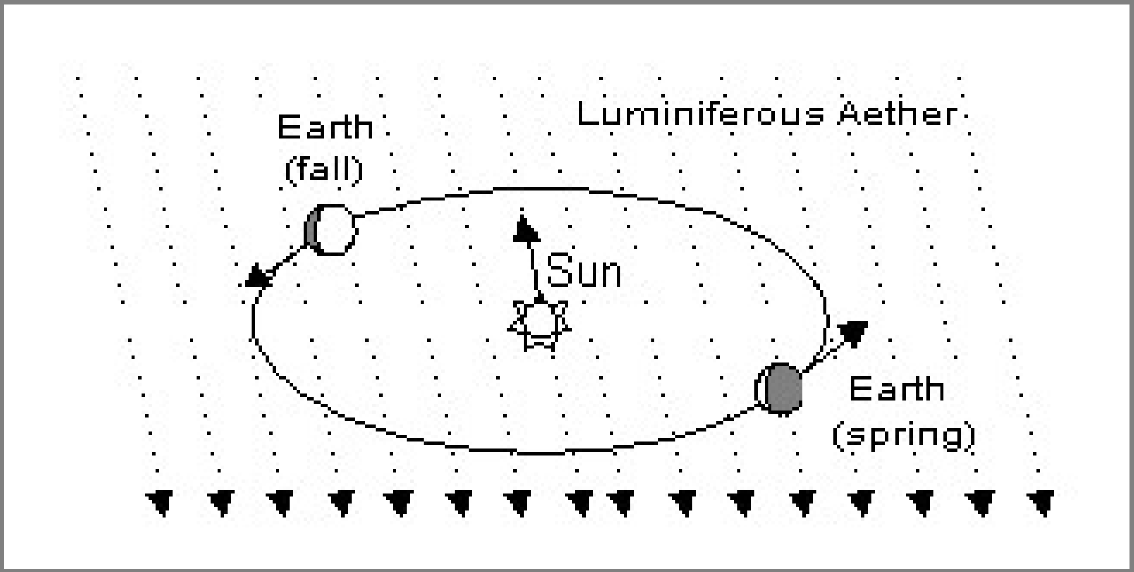


Michelson & Morley

Waves typically occur in a medium. So in 1887 Michelson and Morley attempted to measure the earth's velocity with respect to what was then called the aether and found it always to be zero, effectively disproving the existence of the aether.

Albert Michelson
(1852-1931)

Edward Morley
(1838-1923)

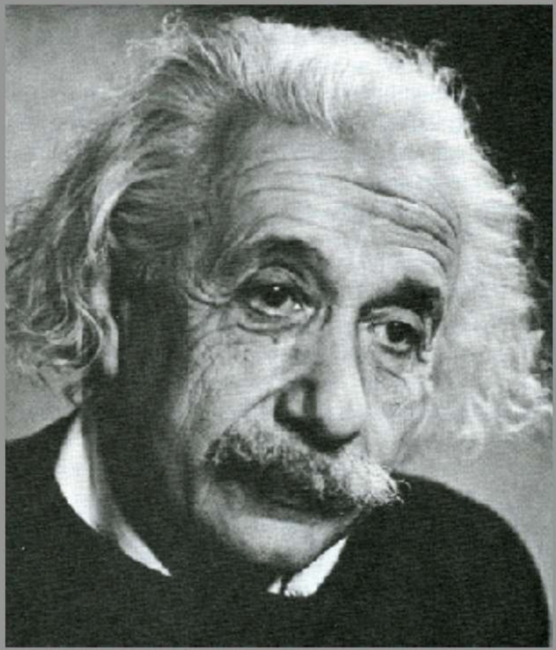


In 1905, Einstein had a very good year.

In 1905, Einstein explained Brownian motion and the photoelectric effect (for which he later won the Nobel prize).

Einstein also explained Michelson's and Morley's experiment: he realized that light didn't need a medium and was a property of free space.

And it traveled at the same velocity no matter what speed you were going. This is **Special Relativity**.

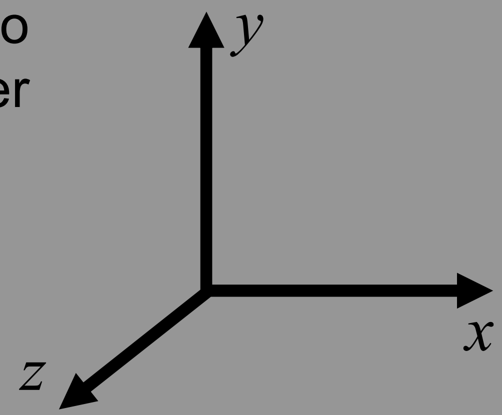


Albert Einstein (1879-1955)

Oh, and he graduated from grad school that year, too.

Before Special Relativity

One frame
moving at
velocity v with
respect to
another



$$x' = x - \mathrm{v}t$$
$$y' = y$$
$$z' = z$$
$$t' = t$$

Basically, this seems so obvious as to not to be necessary to say it.

Unfortunately, it's wrong.

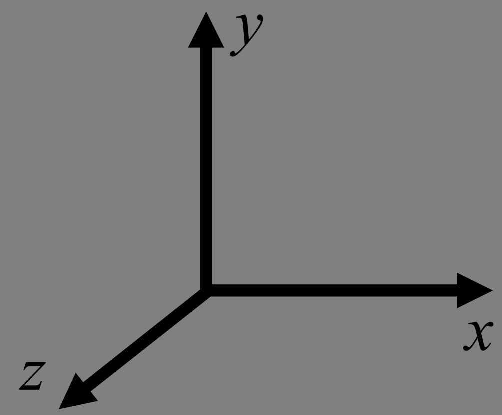
With Special Relativity

$$x' = \frac{x - \mathrm{v}t}{\sqrt{1 - \mathrm{v}^2 / c^2}}$$

$$y' = y$$

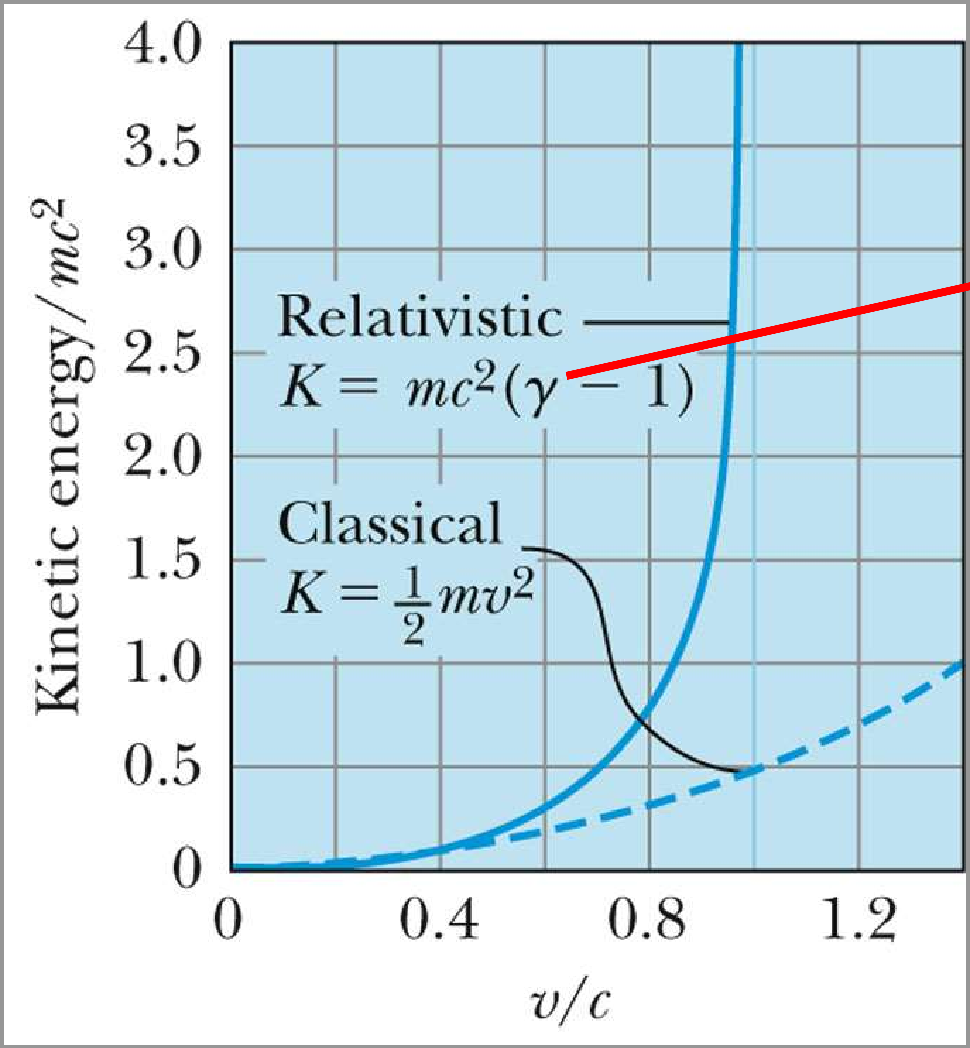
$$z' = z$$

$$t' = \frac{t - \mathrm{v}x / c^2}{\sqrt{1 - \mathrm{v}^2 / c^2}}$$



The Lorentz transformations are the correct way to transform from one frame to the other. They yield a constant speed of light and are NOT at all obvious! Lorentz himself didn't believe them.

Relativistic and Classical Kinetic Energies

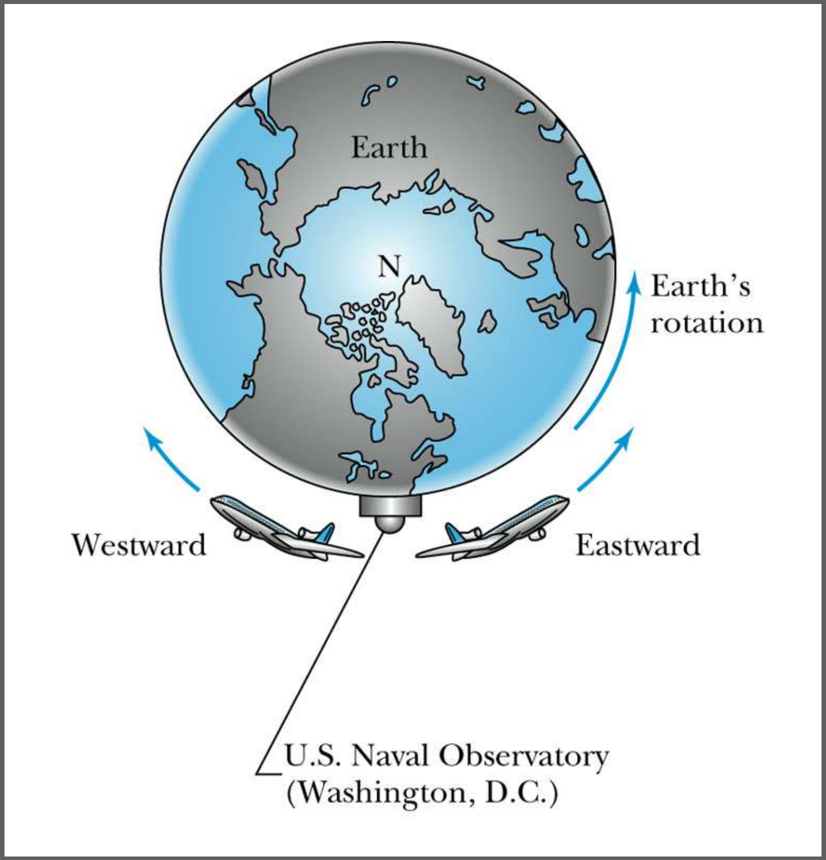


$$\gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}$$

You cannot exceed the speed of light. It's the law.

You need an infinite amount of energy to go the speed of light…

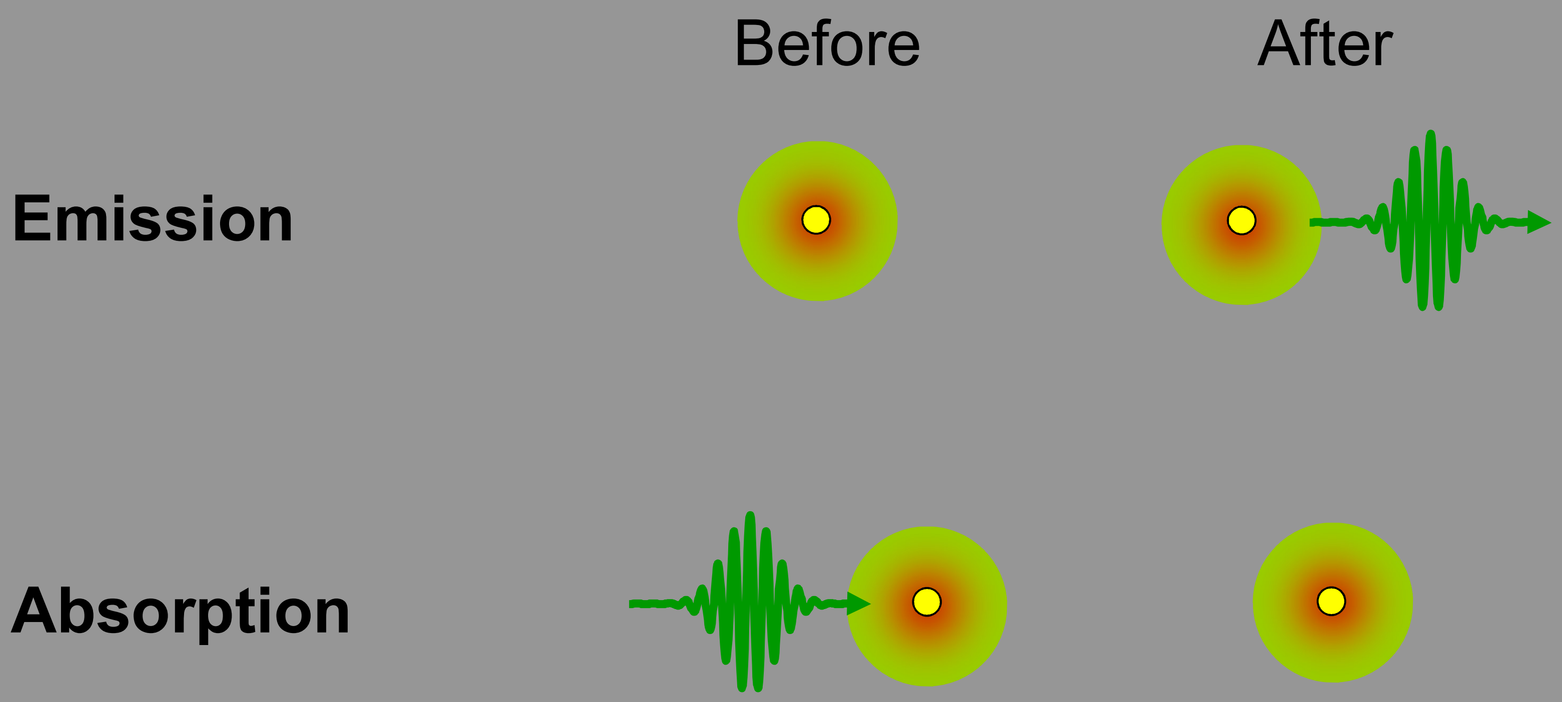
Measurements of time confirm Special Relativity



In Special Relativity, time passes at a rate that depends on your velocity.

Two airplanes traveled east and west around Earth as it rotated. Atomic clocks on the airplanes were compared with similar clocks kept at the observatory to show that the moving clocks in the airplanes ran slower.

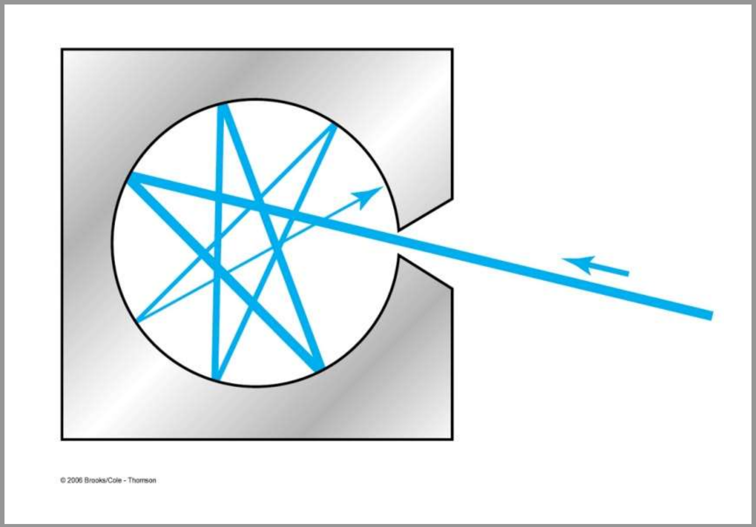
Interactions of light and matter



Blackbody Radiation

When matter is heated, it not only absorbs light, but it also spontaneously emits it.

A blackbody is a medium that can spontaneously emit and absorb all colors.



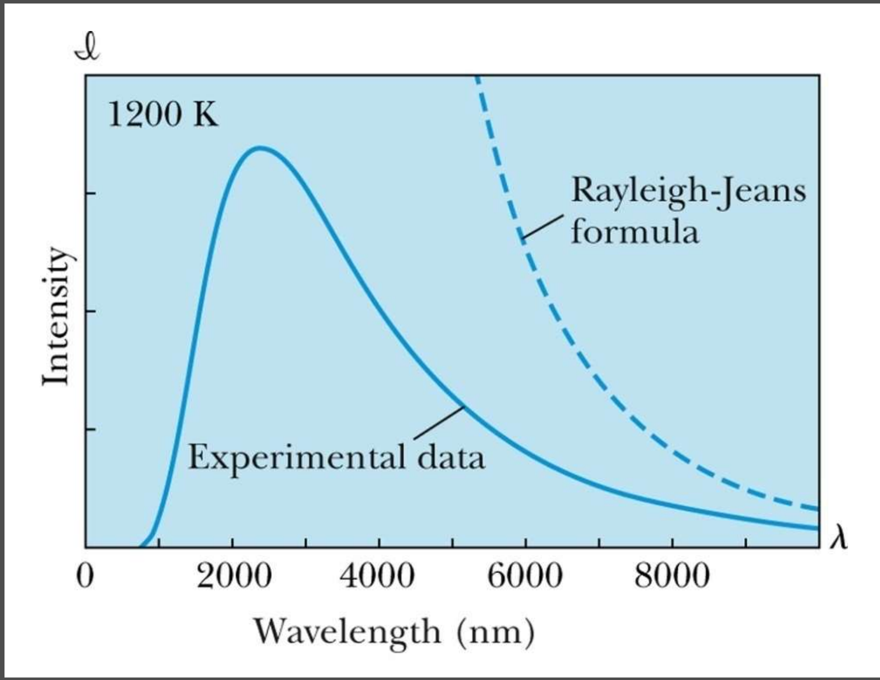
Blackbodies are interesting because their optical properties are independent of the material and only depend on the temperature.

The Ultraviolet Catastrophe

Lord Rayleigh used the classical theories of electromagnetism and thermodynamics to show that the blackbody spectrum should be:

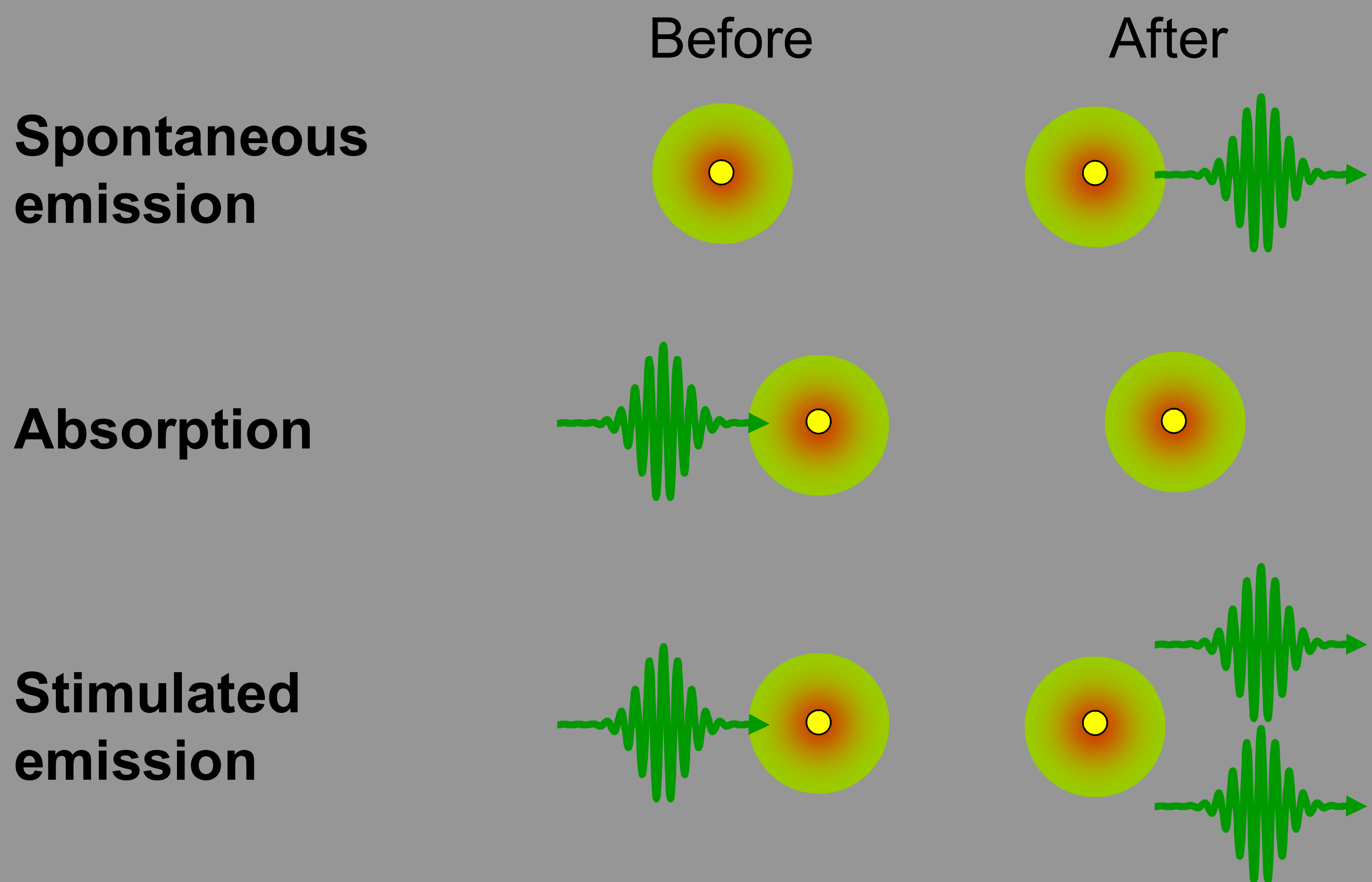
Rayleigh-Jeans Formula

$$\boxed{\mathscr{I}(\lambda,T) = \frac{2\pi ckT}{\lambda^4}}$$



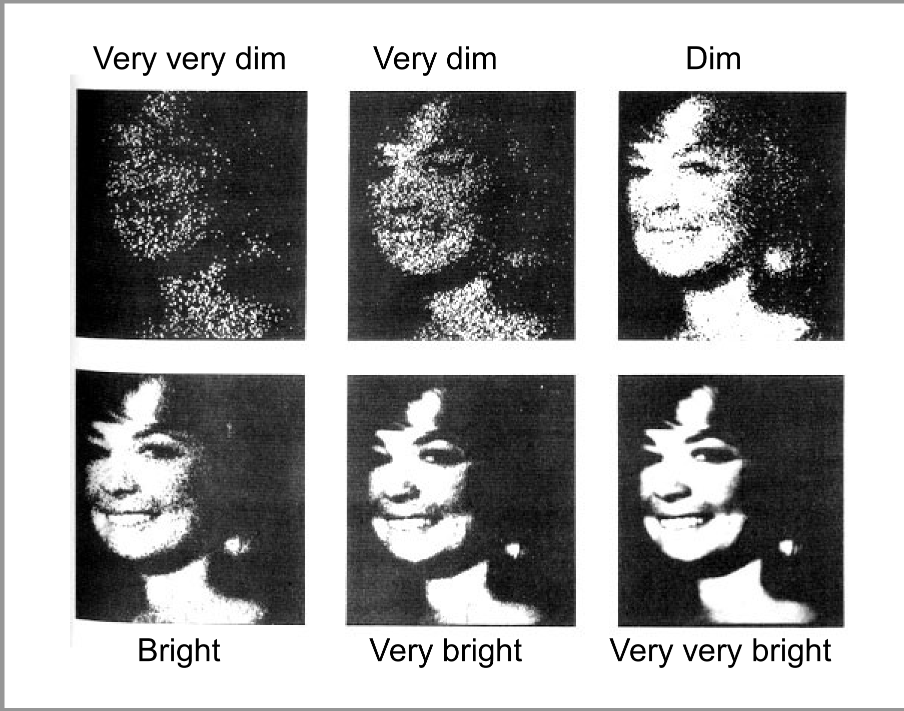
This worked at longer wavelengths but deviates badly at short ones. This problem became known as **the ultraviolet catastrophe** and was one of the many effects classical physics couldn't explain.

Einstein also showed that, if stimulated emission can also occur, then bye bye Ultraviolet Catastrophe.



Light is not only a wave, but also a particle.

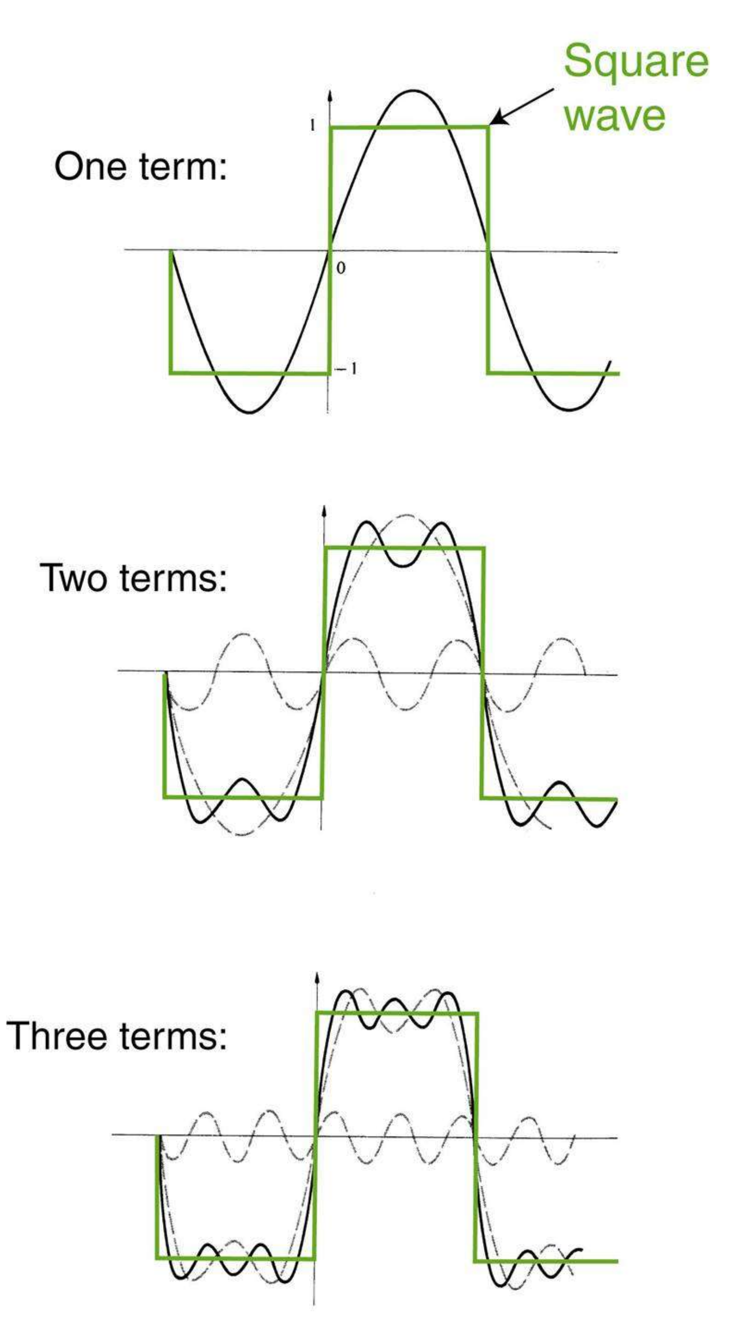
Photographs taken in dimmer light look grainier.



When we detect very weak light, we find that it's made up of particles. We call them photons.

Fourier decomposing functions plays a big role in physics.

Here, we write a square wave as a sum of sine waves of different frequency.



The Fourier transform is perhaps the most important equation in science.

It converts a function of time to one of frequency:

$$\tilde{E}(\omega) = \int_{-\infty}^{\infty} E(t) \exp(-i\omega t) \, dt$$

and converting back uses almost the same formula:

$$E(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{E}(\omega) \exp(+i\omega t) \, d\omega$$

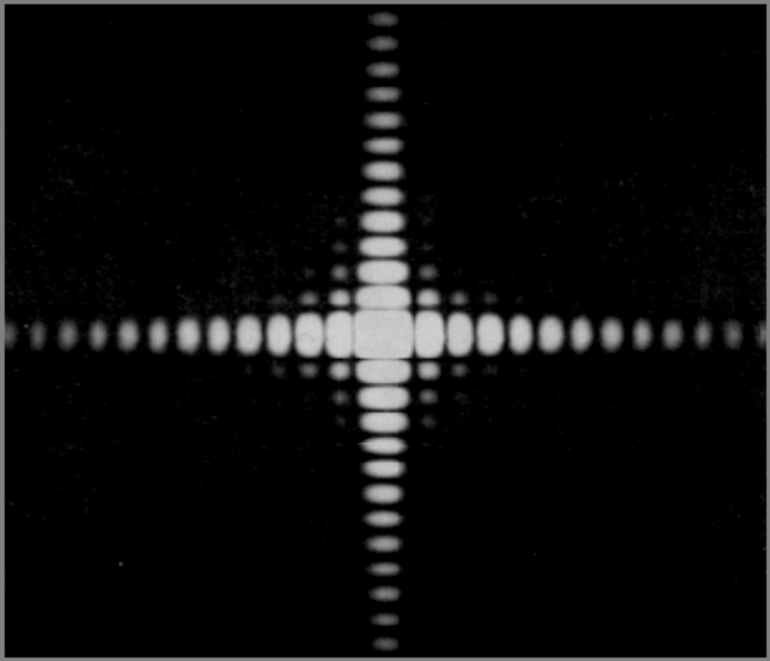
The **spectrum** of a wave will be given by: $\left|\tilde{E}(\omega)\right|^2$

And the Uncertainty Principle is a simple property of the Fourier transform!

Diffraction

Light bends around corners. This is called diffraction.

The light pattern emerging from a single small rectangular opening



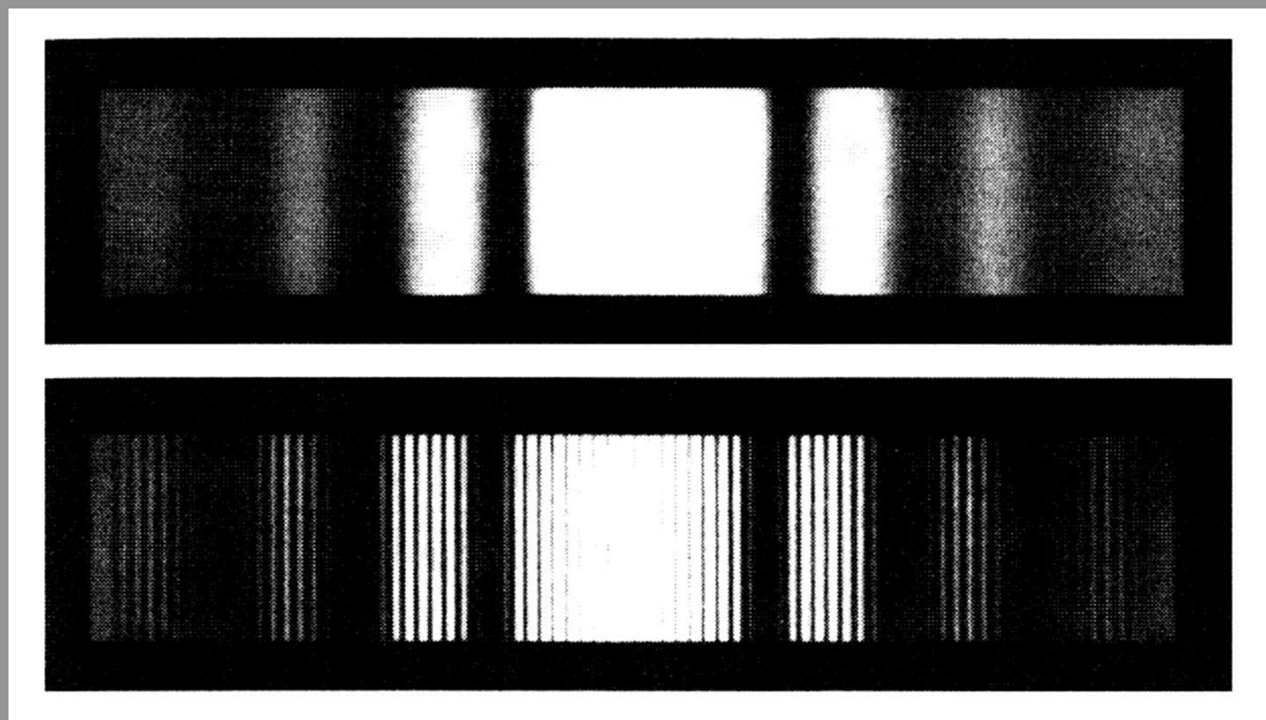
The diffraction pattern far away is the (2D) Fourier transform of the slit transmission vs. position!

Diffraction from one- and two-slit screens

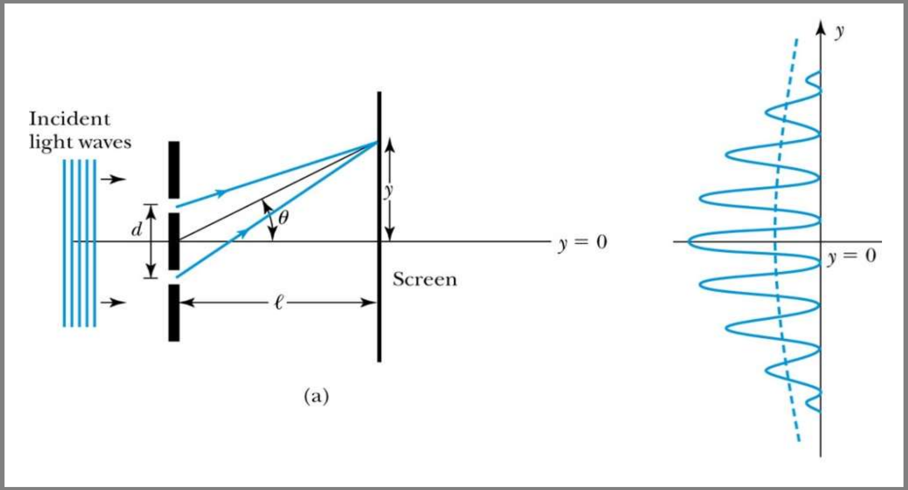
Diffraction patterns

One slit

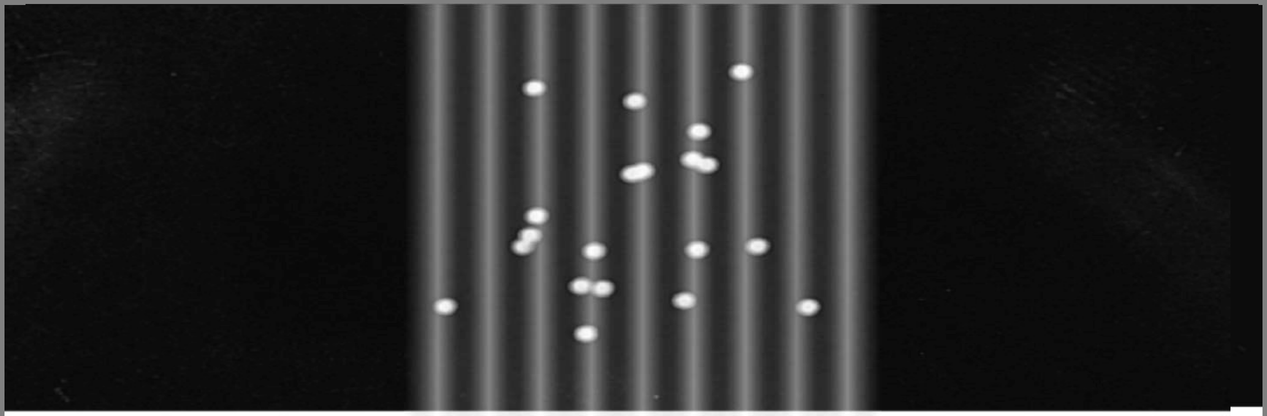
Two slits



Waves or Particles? It's even weirder…



Dimming the light in a two-slit experiment yields single photons at the screen. Since photons are particles, each can only go through one slit, so then their pattern should become the single-slit pattern.



(a) 20 counts

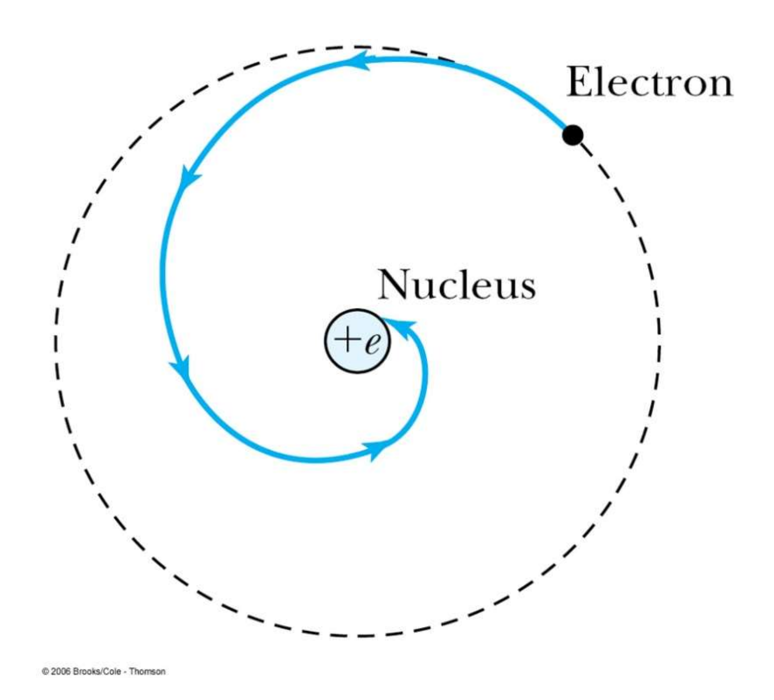
What is going on here?


Canon
HDV
Canon
HDV

The Planetary model for the atom was also a problem.

From classical E&M theory, an accelerated electric charge radiates energy (electromagnetic radiation), which means total energy must decrease.

And the radius r must decrease!



Why doesn’t the electron crash into the nucleus?

Bohr's Quantization Condition was a fix.

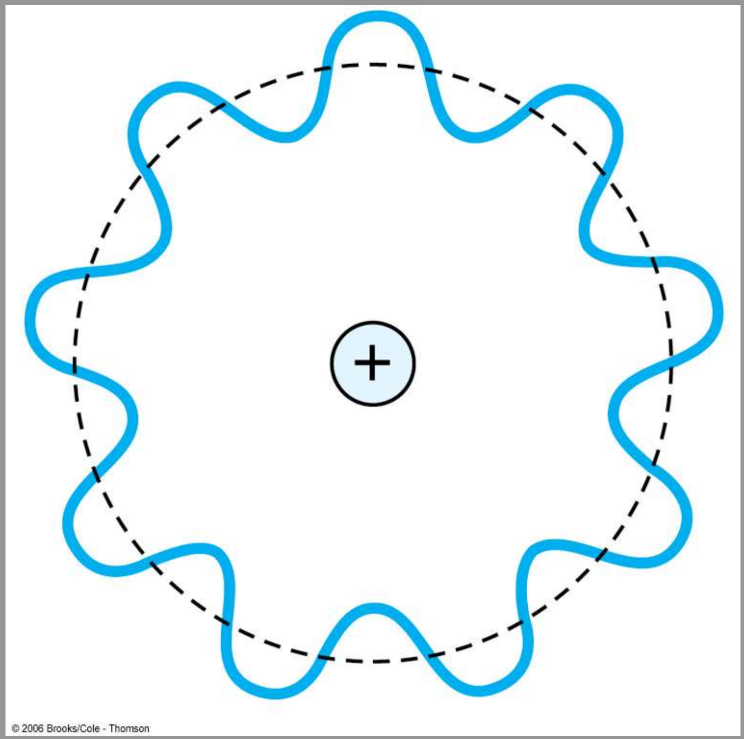
Bohr's hydrogen-atom model assumed that the angular momentum of the electron is an integral multiple of $\hbar = h/2\pi$.

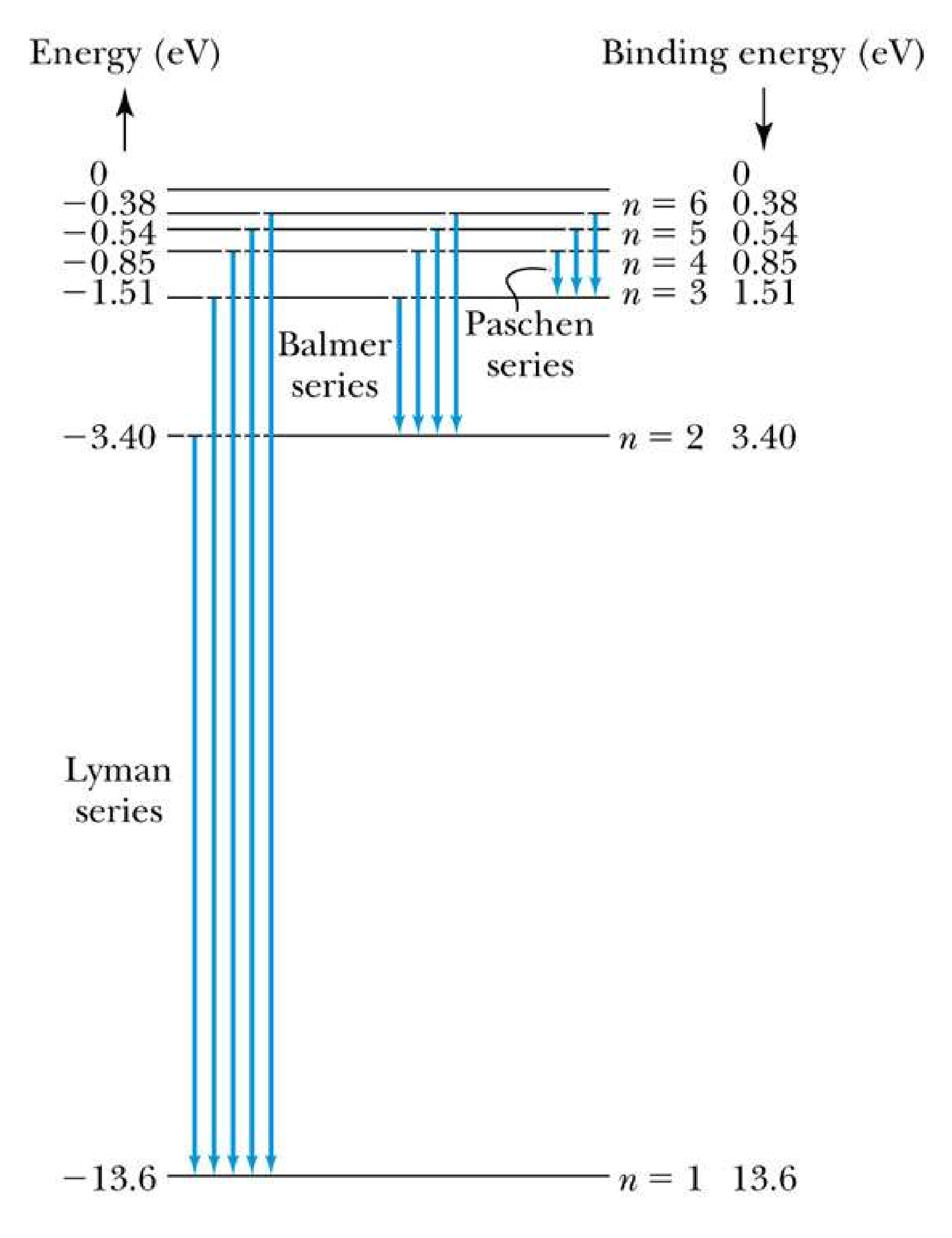
The electron is a standing wave in an orbit around the proton. This standing wave will have nodes and be an integral number of wavelengths.

$$\boxed{2\pi r = n\lambda = n\frac{h}{p}}$$

The angular momentum becomes:

$$\boxed{L = rp = \frac{nh}{2\pi} = n\hbar}$$





Bohr's model worked for the Hydrogen atom.

It explained Hydrogen's emission and absorption spectra.

But it didn't work for other atoms.


Canon
HDV
Canon
HDV

The Schrödinger Equation

Bohr's model failed for more complex systems. The Schrödinger Equation is the correct answer. In its time-dependent form for a particle of energy E moving in a potential V in one dimension, it's:

$$i\hbar \frac{\partial \Psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi(x,t)}{\partial x^2} + V\Psi(x,t)$$

Its extension to three dimensions is

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \left(\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} \right) + V\Psi(x,y,z,t)$$

where: $i = \sqrt{-1}$

And ψ is called the wave function.

What on earth is Ψ?

The probability $P(x)\,dx$ of a particle being between x and $x + dx$ is given in the equation

$$\boxed{P(x)\,dx = \Psi^*(x,t)\Psi(x,t)\,dx}$$

The probability of the particle being between x_1 and x_2 is given by

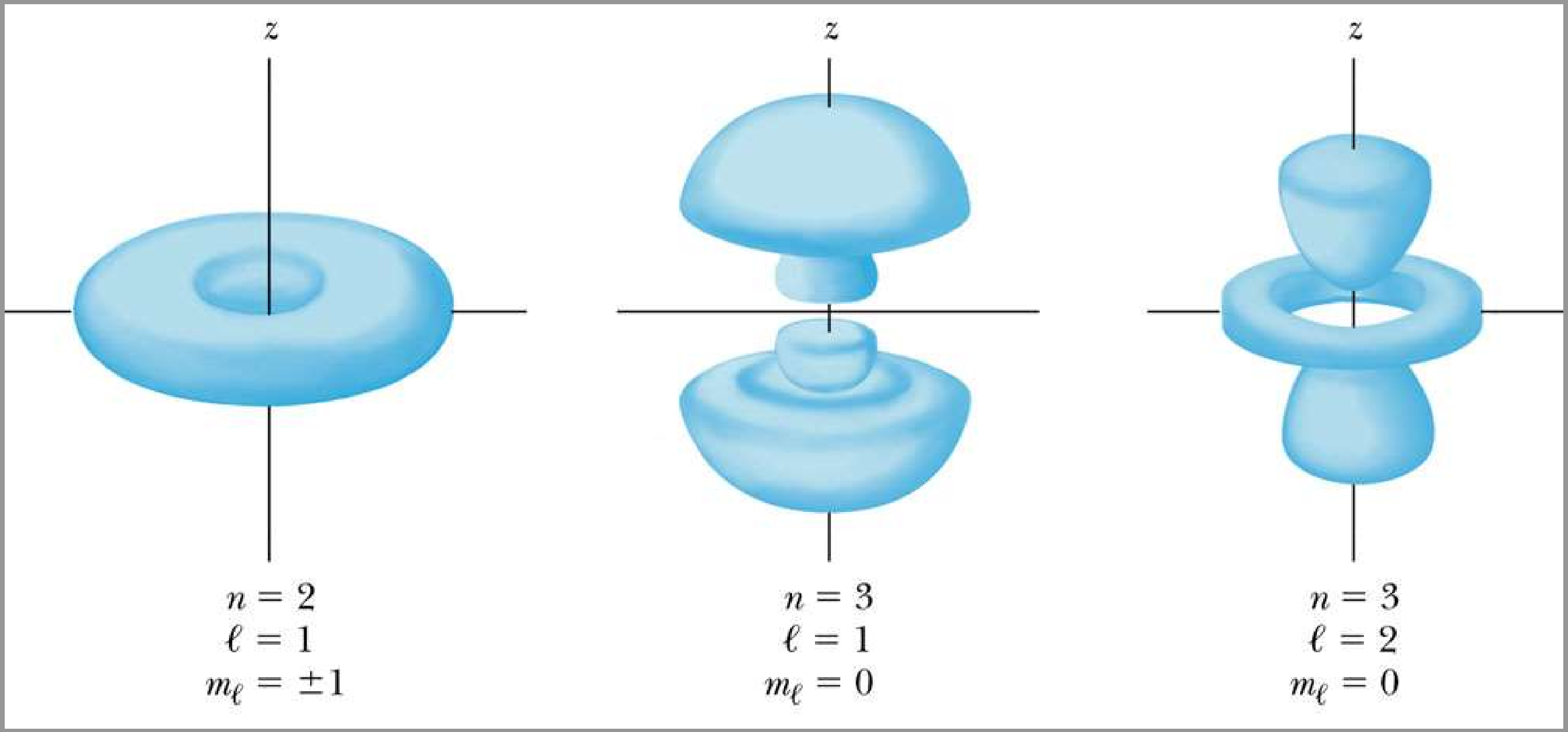
$$\boxed{P = \int_{x_1}^{x_2} \Psi^*\Psi\,dx}$$

The wave function must also be normalized so that the probability of the particle being somewhere on the x axis is 1.

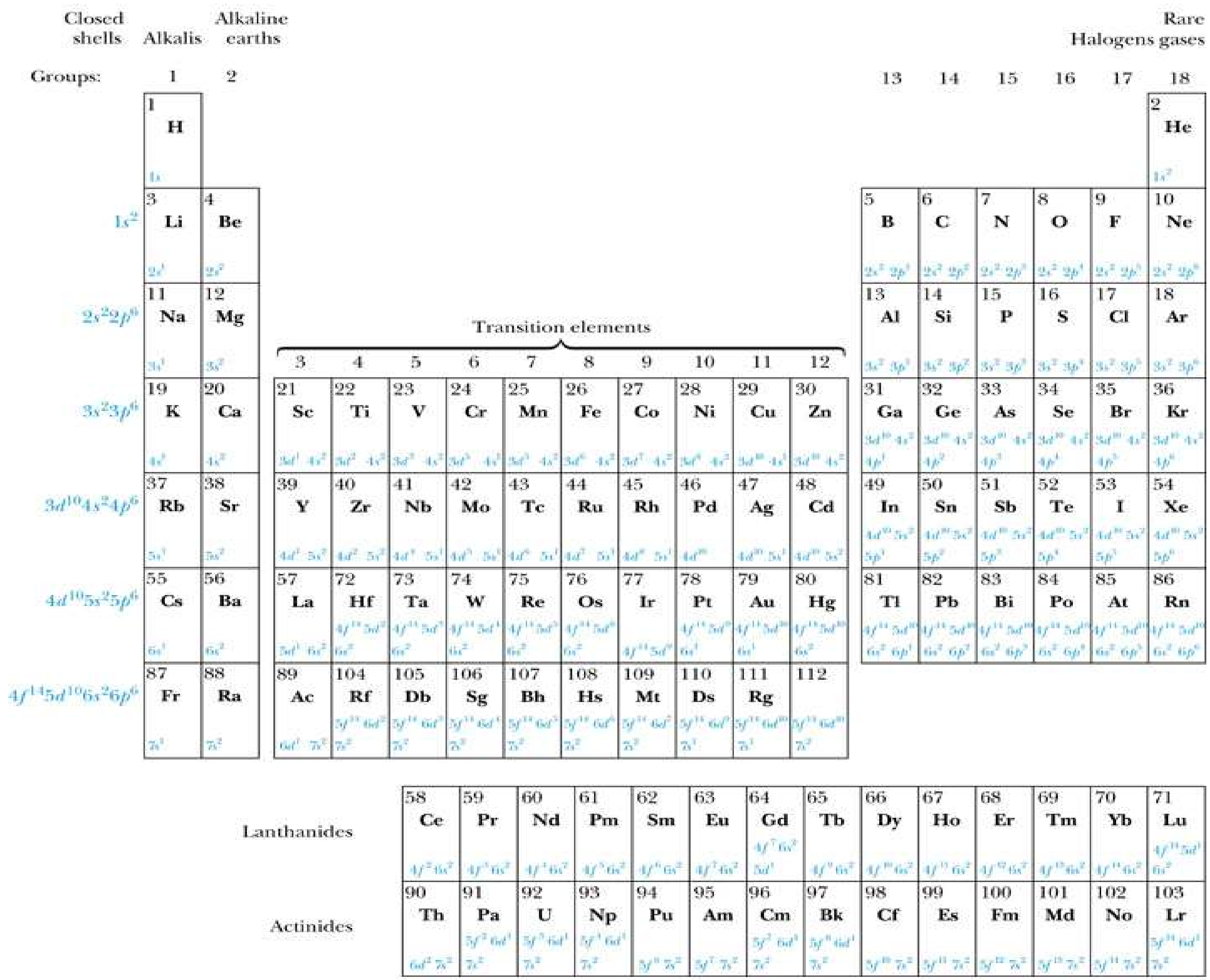
$$\boxed{\int_{-\infty}^{\infty} \Psi^*(x,t)\Psi(x,t)\,dx = 1}$$

Probability Distribution Functions

The probability density for the hydrogen atom for three different electron states.



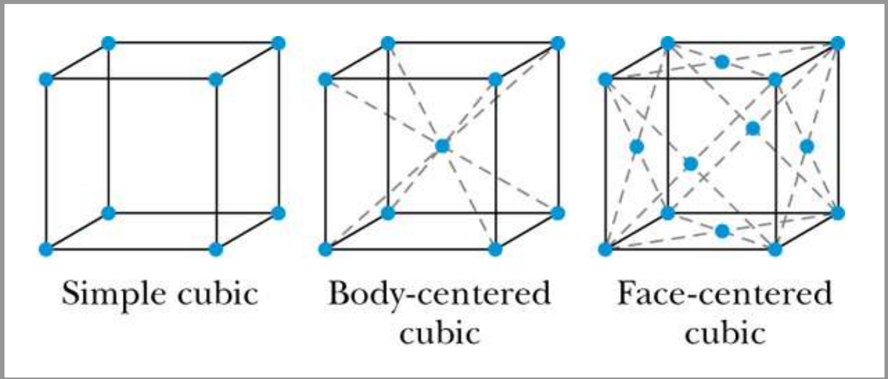
Quantum theory explains the Periodic Table.

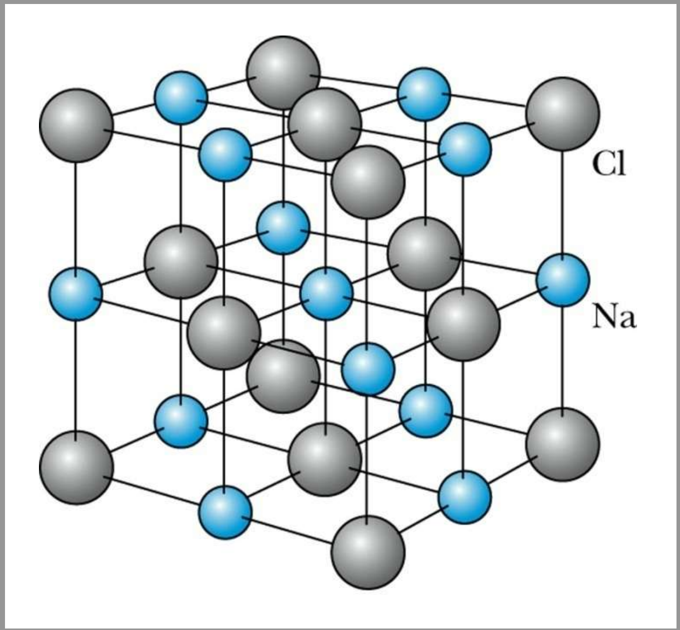


Molecules and solids

It’s far too difficult to solve the Schrodinger Equation for molecules and solids, so approximation methods must be used.

Fortunately, some general ideas have emerged.



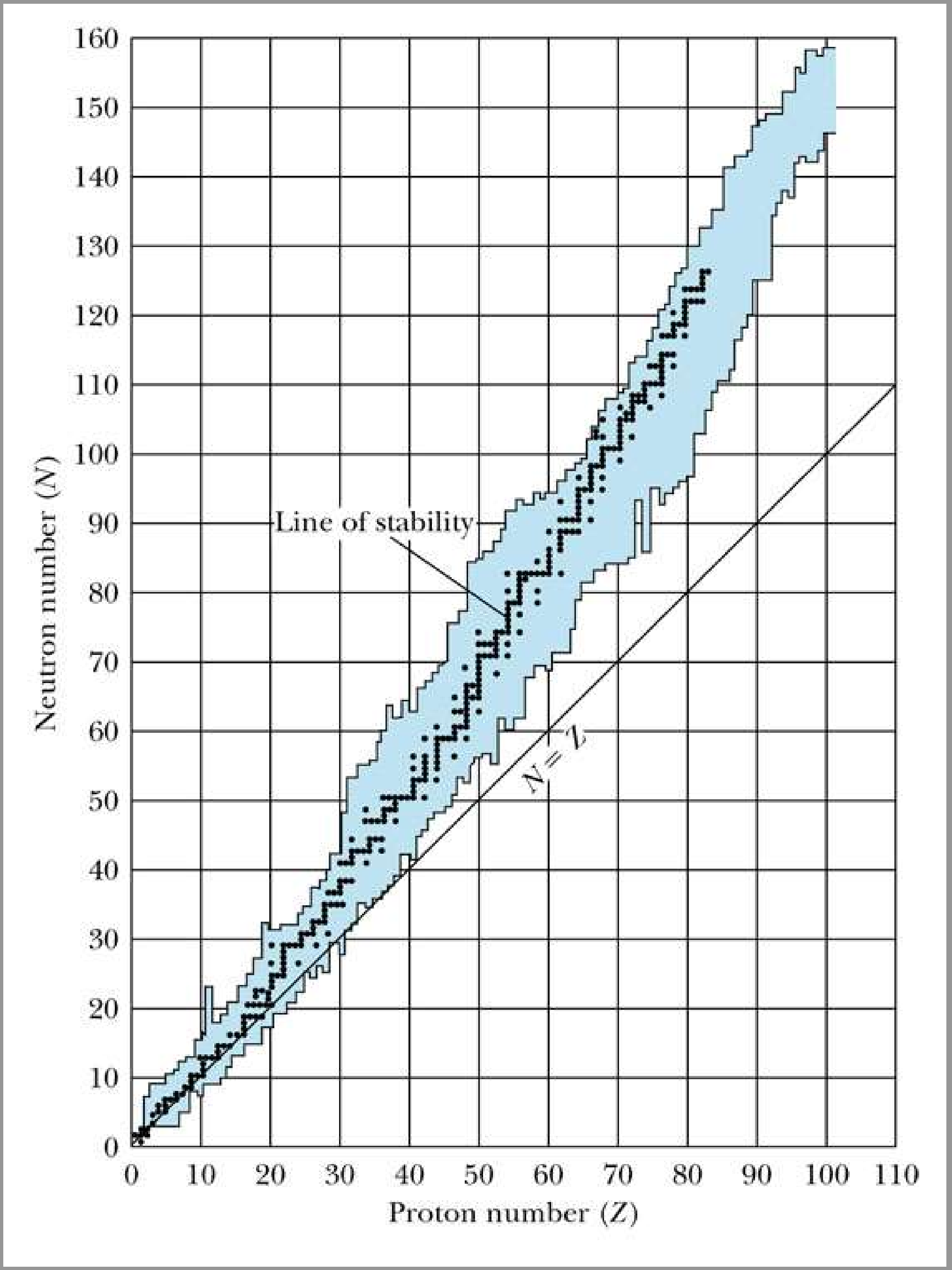


Nuclear Physics

The nucleus of an atom is made up of positively charged protons and electrically neutral neutrons. So there's no negative charge!

How can a nucleus hold together?

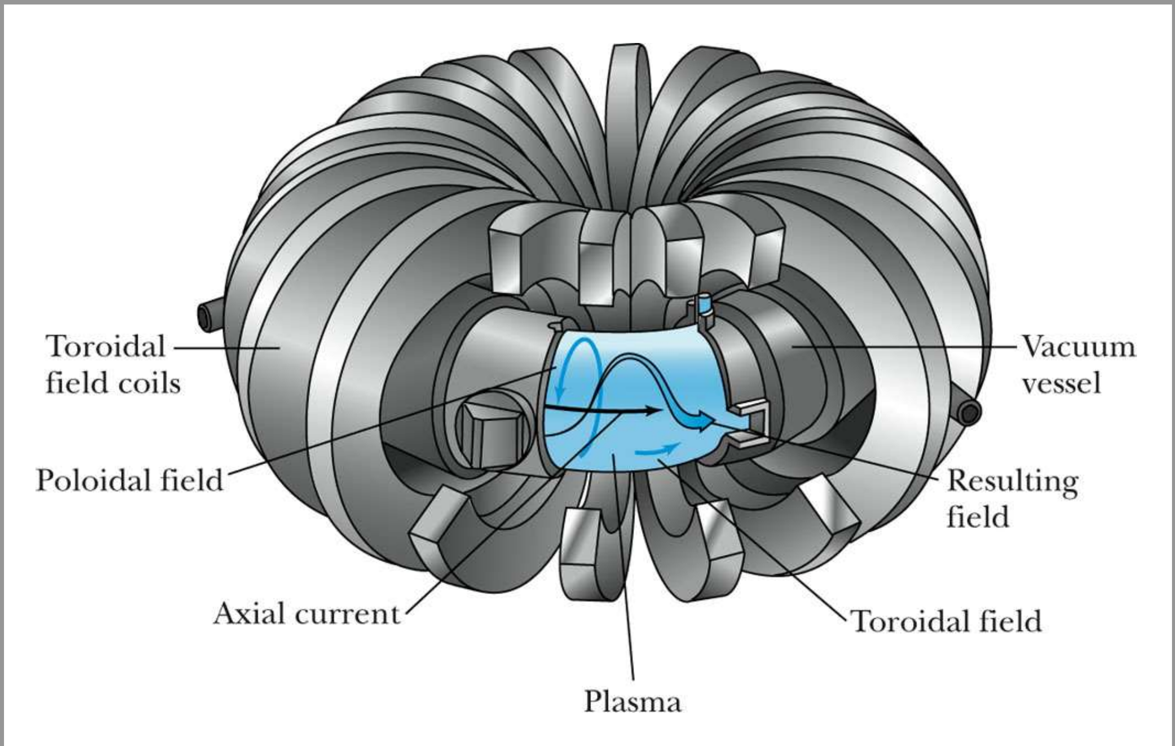
The strong force!

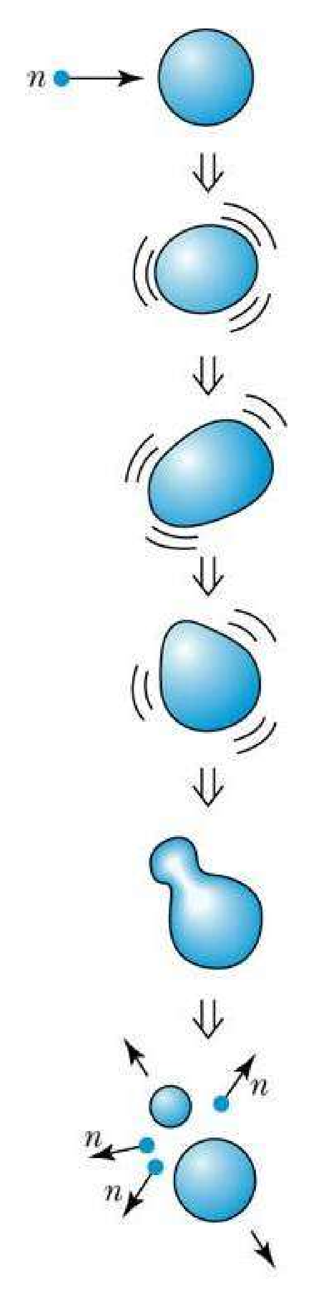


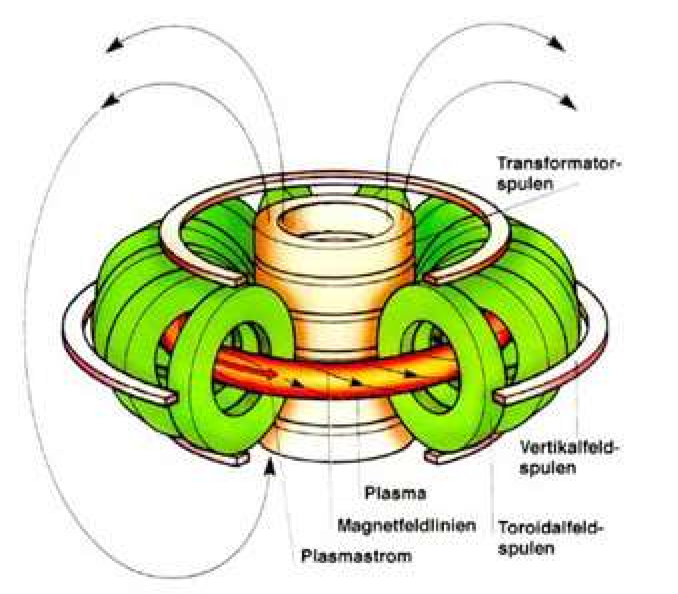
Nuclear Reactions

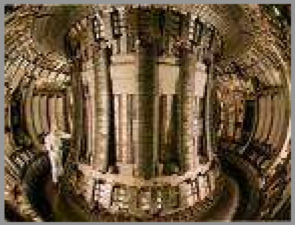
Nuclear fission is the breaking apart of a heavy nucleus, which releases much energy.

Nuclear fusion is the combining together of two light nuclei, which also releases much energy.






Transformator-
spulen
Vertikalfeld-
spulen
Plasma
Magnetfeldlinien
Toroidalfeld-
spulen
Plasmastrom

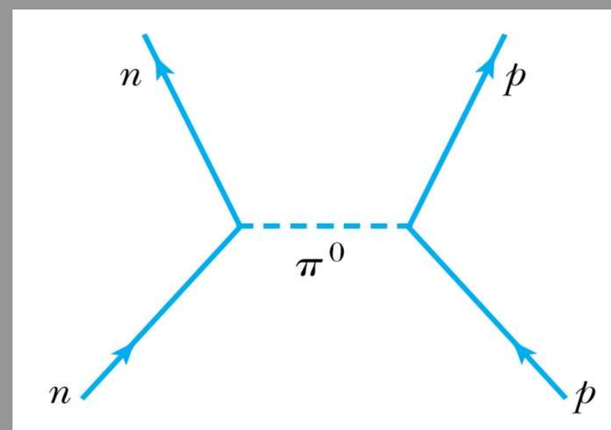


Elementary Particle Physics

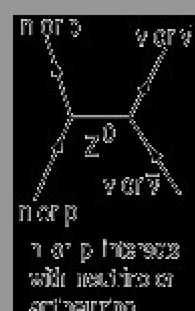
But, if nuclei are made up of protons and neutrons, what are protons and neutrons made of?

Physicists have discovered a zoo of elementary particles, including quarks of 1/3 the charge of a proton.

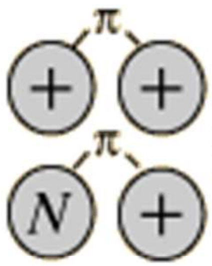
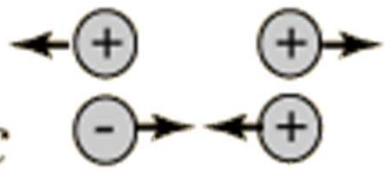
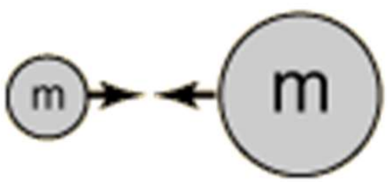
A Feynman diagram indicating the exchange of a pion (Yukawa's meson) between a neutron and a proton. (Strong force)



Feynman Diagrams for Weak Force



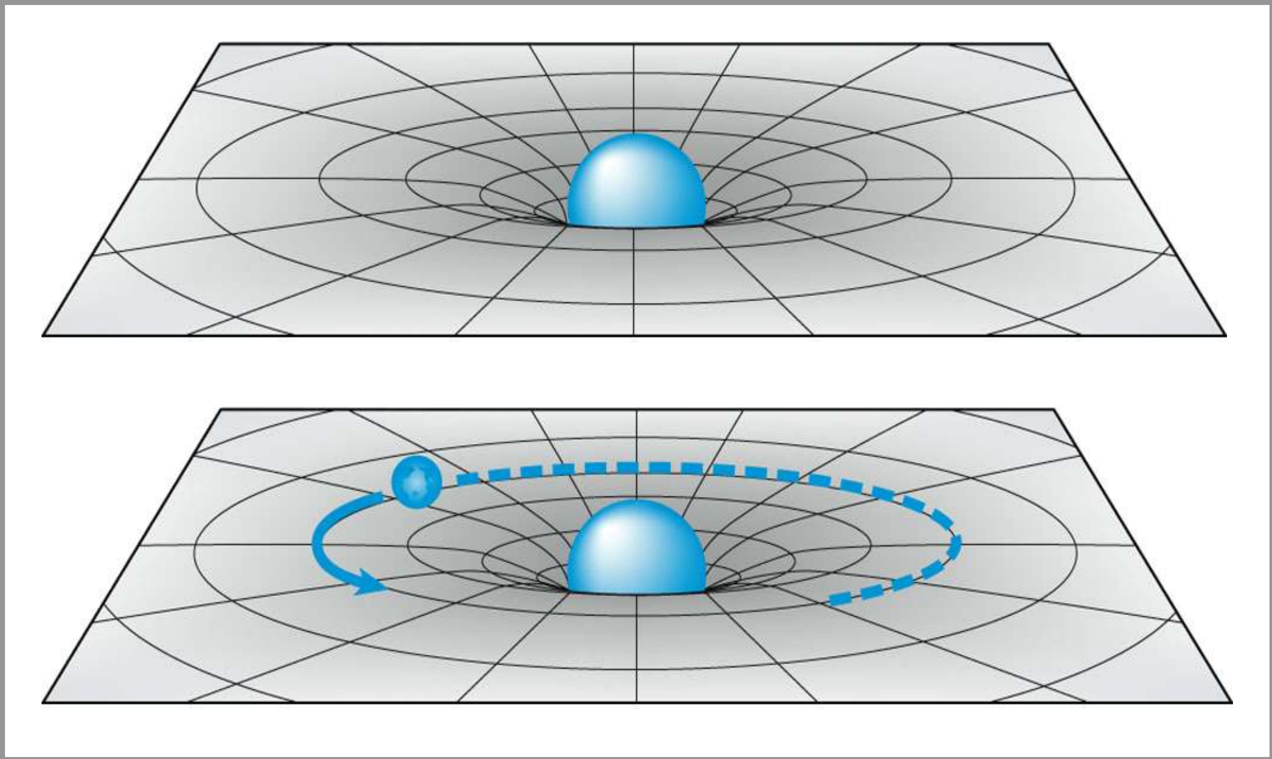
Fundamental Forces

Force	Illustration	Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons) **Spin = 1** **Mass = 0**
Electro-magnetic		$\frac{1}{137}$	Infinite	photon, mass = 0, spin = 1
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV, spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0, spin = 2

General Relativity and the Curvature of Space

Between ~1910 and ~1920, Einstein lost interest in the quantum-mechanical revolution that he started and decided to consider the possibility that the effect of mass (i.e., gravity) was to curve space. No one thought that this was a good idea at the time.

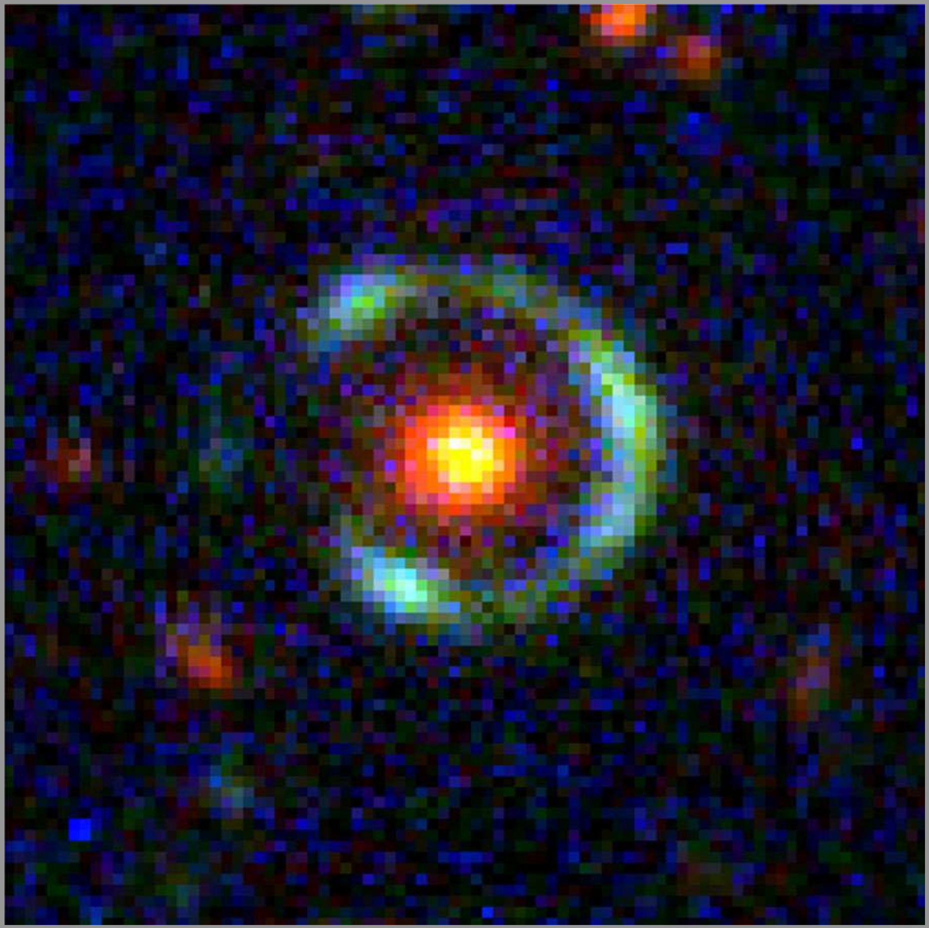
So if space-time is not flat, then the straight line path of light will appear curved.



Gravitational Lensing

A quasi-stellar radio source ("quasar") is a very energetic and distant active galactic nucleus. Quasars are the most luminous objects in the universe.

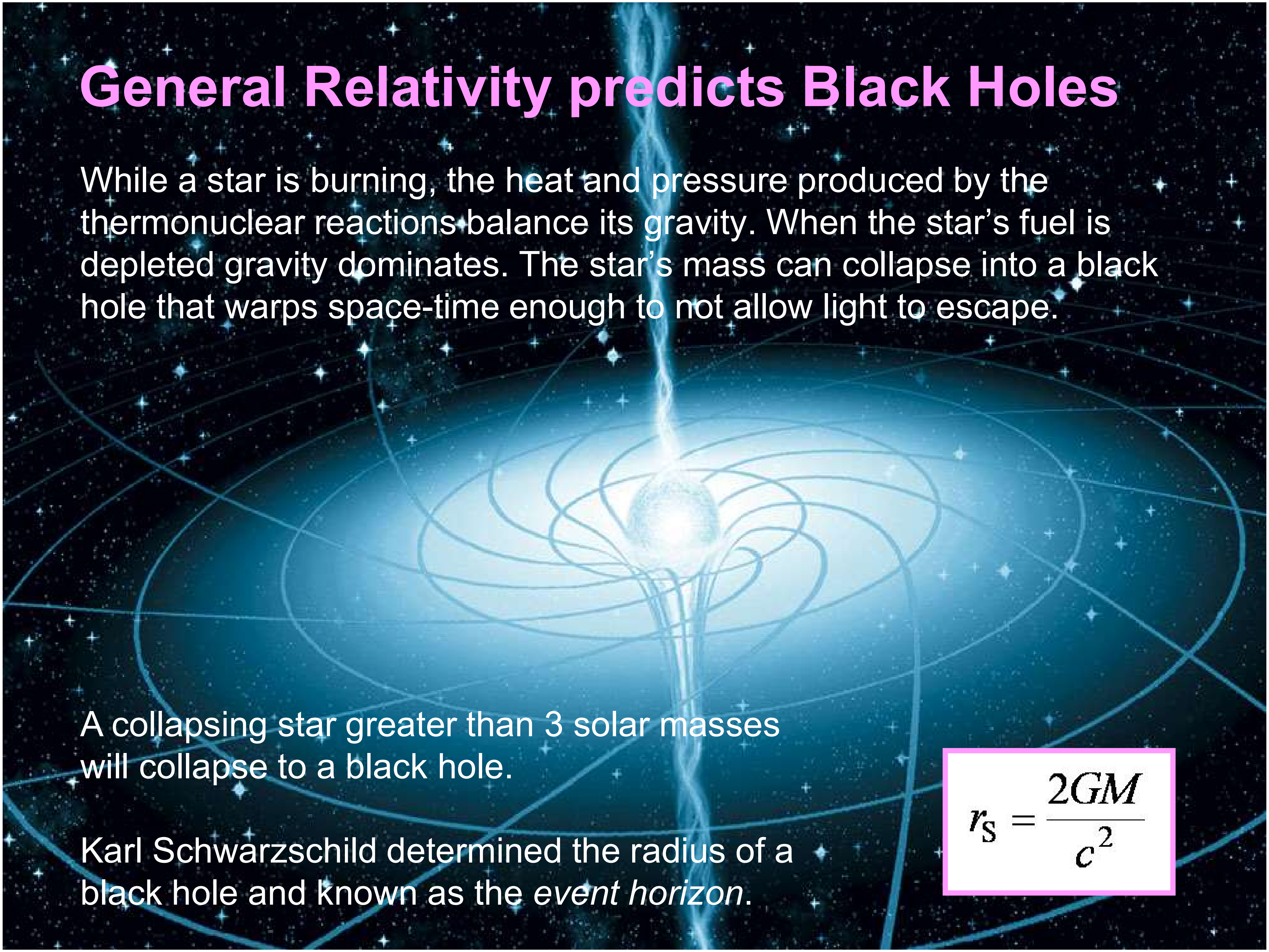
When light from a distant object like a quasar passes by a nearby galaxy on its way to us on Earth, the light can be bent multiple times as it passes in different directions around the galaxy.



The Cosmic Horseshoe

General Relativity predicts Black Holes

While a star is burning, the heat and pressure produced by the thermonuclear reactions balance its gravity. When the star's fuel is depleted gravity dominates. The star's mass can collapse into a black hole that warps space-time enough to not allow light to escape.



A collapsing star greater than 3 solar masses will collapse to a black hole.

Karl Schwarzschild determined the radius of a black hole and known as the *event horizon*.

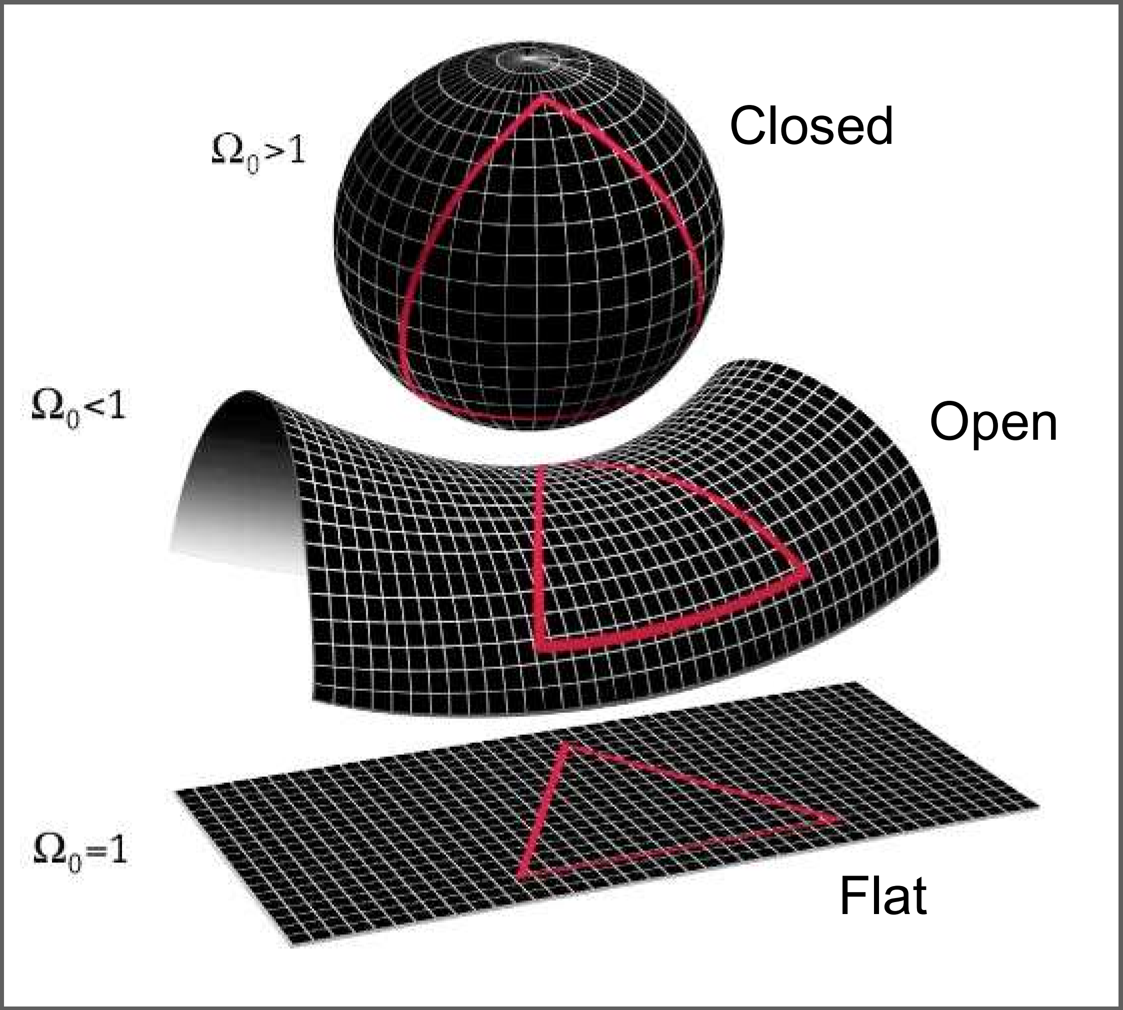
$$r_S = \frac{2GM}{c^2}$$

Possible geometries of the universe

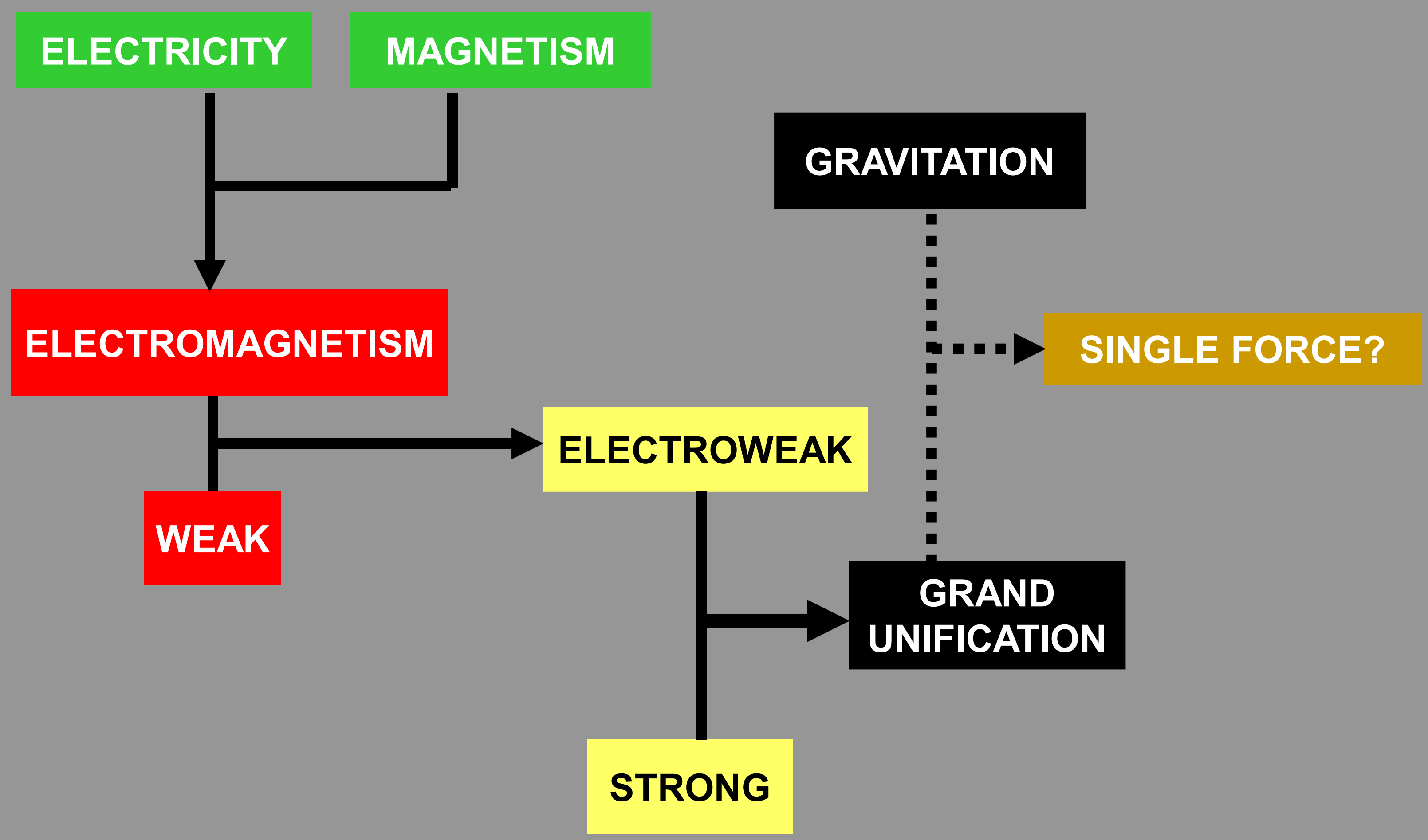
The density, ρ, of matter in the universe determines which shape it has.

$$\Omega_0 \equiv \rho / \rho_{crit}$$

where ρ_{crit} = is the critical density for which the universe is flat.



The Ultimate Goal of Physics: Unification of All Forces into a Single Force



The revolutions in physics inspired revolutions in other fields, too.

Fields like chemistry, engineering, and biology necessarily also underwent revolutions because physics is their basis.

And mathematics also began to see flaws in its fundamental foundations.

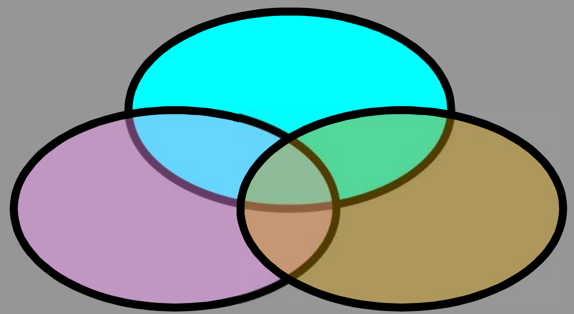
And the revolutions in physics spurred revolutions in art, music, architecture, and psychology and even changed the way the average person saw the world.

Bertrand Russell

(1872-1970)

http://en.wikipedia.org/wiki/Bertrand_Russell

Weirdness in mathematics: Russell's Paradox (1901)



Consider a set that contains itself.

Example: { {}, { {}, {{}} }, … }

Next consider the set of all sets that contain themselves.

Now consider **the set of all sets that don't contain themselves**.

Does this last set contain itself?

If it doesn't, then it does. But if it does, then it doesn't.

Because set theory is the basis of all mathematics (and numbers!), this fundamental paradox is a serious crack in the foundations of mathematics.

More weirdness in Mathematics: Gödel's Incompleteness Theorem (1931)

In 1931, Kurt Gödel proved that there are **theorems that can neither be proven nor disproven**.

This solved the second of David Hilbert's famous list of the 23 most important unsolved math problems.

And Hilbert's first problem turned out to be one of Gödel's unprovable theorems ("the continuum hypothesis"—whether there's an infinity between the number of integers, $\aleph_0$, and the number of real numbers, $\aleph_1$)!

Kurt Gödel (1906 – 1972)

Weirdness in social theory: Arrow's Impossibility Theorem (1951)

Try to design a system for **voting** (ordering people's preferences for candidates). It should have these properties:

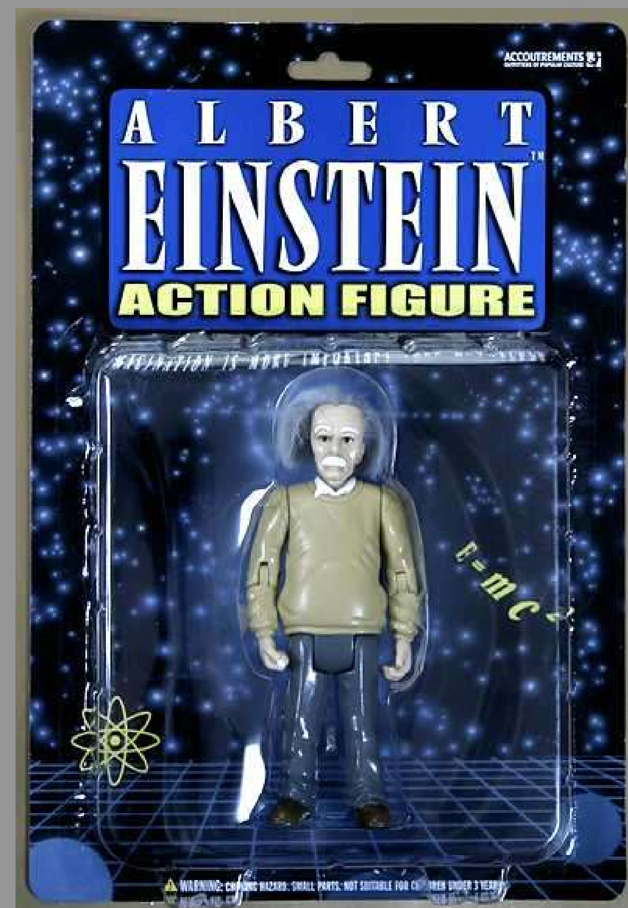
1. **Non-dictatorship** (one voter shouldn't have all the say)
2. **Repeatability** (the same ranking should occur again if the votes are the same)
3. **Relevance** (changes in choices involving A and B shouldn't change the resulting order of C and D)
4. **Monotonicity** (ranking an option higher should not hurt it)
5. **Efficiency** (if everyone prefers A over B, A should beat B)

Kenneth Arrow (1921 -)

Arrow's Impossibility Theorem says this is impossible!

While these strange ideas in physics, mathematics, and social theory are real, not all weird ideas that have emerged are justified.

As a result of these exciting revolutions, physicists were the stars of the early 20th century.



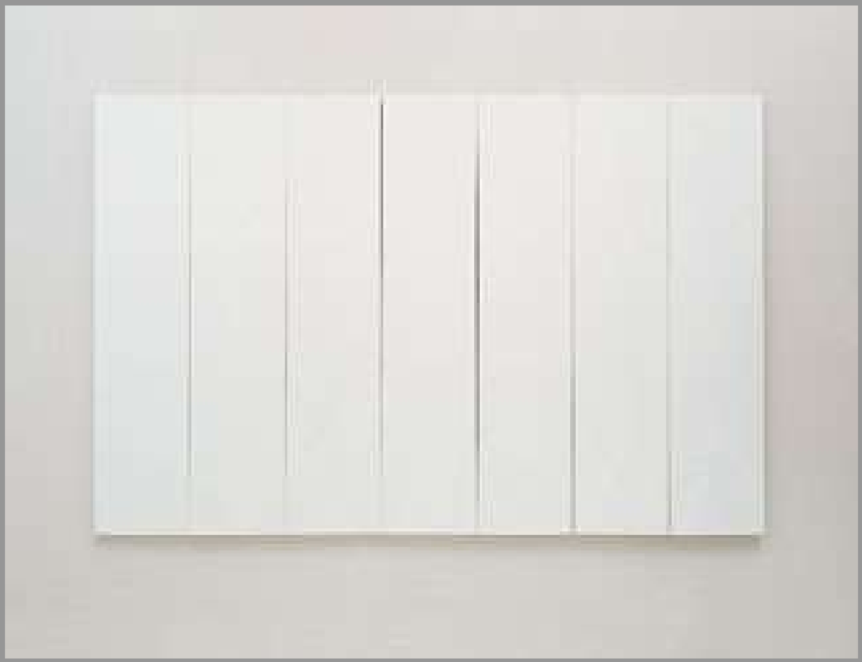
Weirdness in Art

Whereas pre-20th-century art was very literal, modern art has become very abstract and unintuitive.

Pre-1905 art

The Death of Socrates (1787)
Jacques-Louis David

Post-1905 art



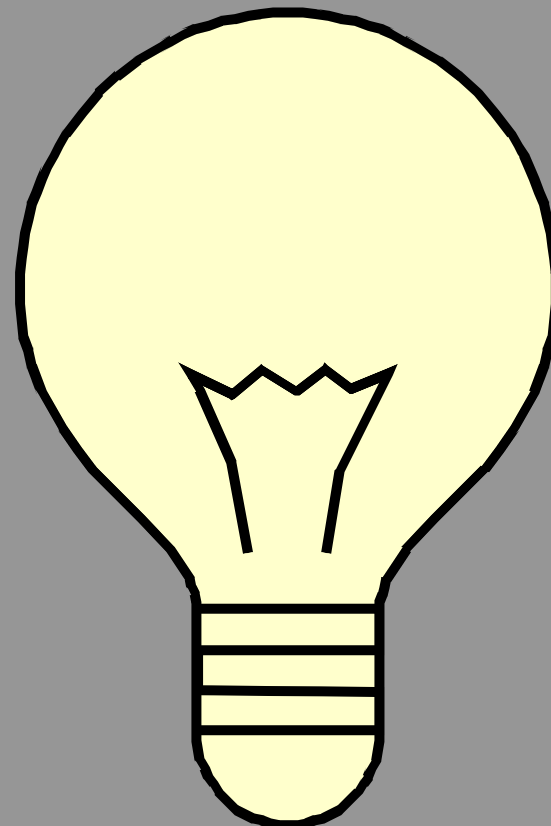
White Painting (1951)
Robert Rauschenberg

Interestingly, most "great" works of modern art have only required a few minutes of effort to create.

Modern art is getting weirder and weirder.

"Light in [an empty] room turning on and off" won the top British art prize (The Turner Prize, £20,000) in 2001.

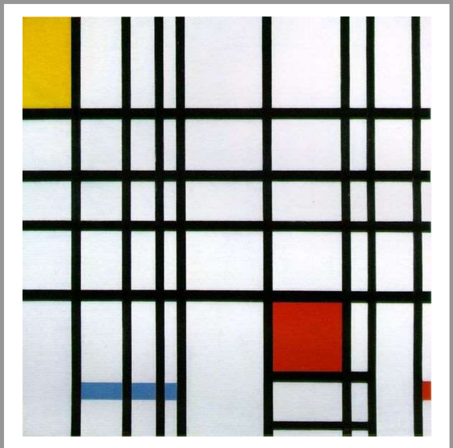
Martin Creed
Winner of prize

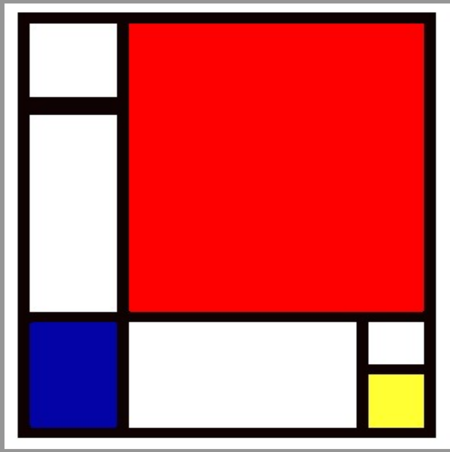


And this is one of the least objectionable and ridiculous winners of this prize.

Weirdness in Art Appreciation

Pieter
Mondrian
1872 - 1944





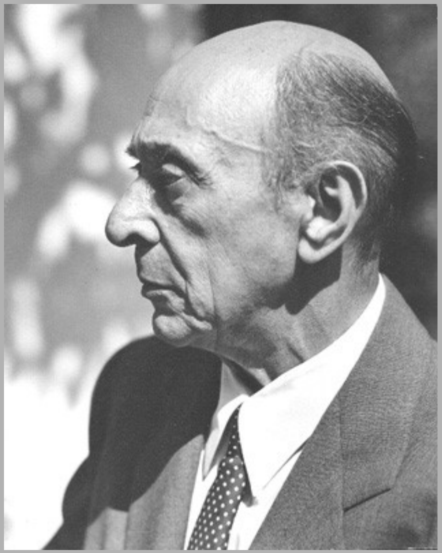
Mondrian's art “was, in the end, to be so fine that, having induced a radiant harmony and balance throughout society, the need for painting itself would no longer be necessary.”

Bennett Schiff, *Smithsonian* 1995

Mondrian died in 1944, a time of complete radiant harmony and balance throughout society...

Weirdness in Music

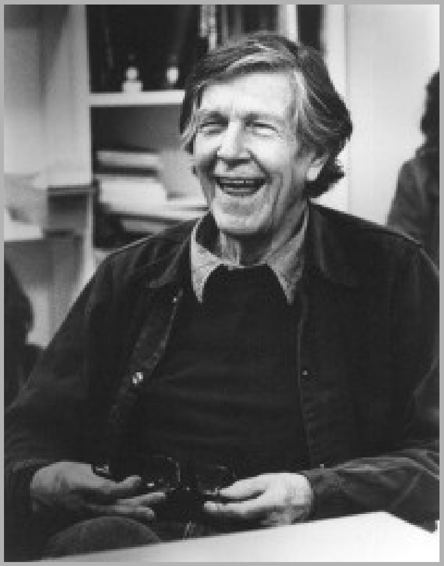
In 1907 Schoenberg, who stated publicly that he wanted to do for music what Einstein did for physics, introduced **atonal music**, which violated all known principles of what constituted good music and, for the most part, sounds like noise.



Arnold Schoenberg (1874 - 1951)

Stephen Reich (1936 -)

John Cage (1912 - 1992)



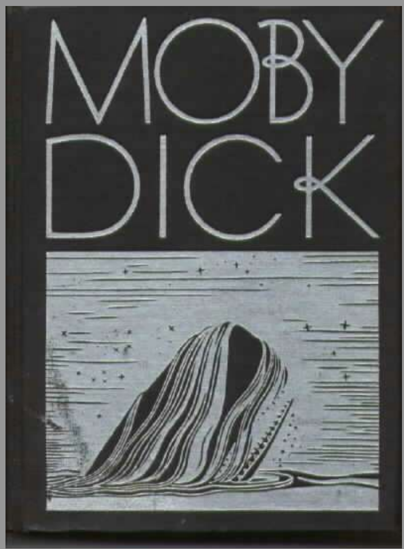
John Cage is best known for his 1952 composition, *4'33"*, whose three movements are each composed entirely of silence.

Weirdness in Literature

19th century literature:

"Call me Ishmael…"

Herman Melville's *Moby Dick* (1851) was first and foremost a simple whaling story, but it was also a superb study of human obsession and taught us about human nature.



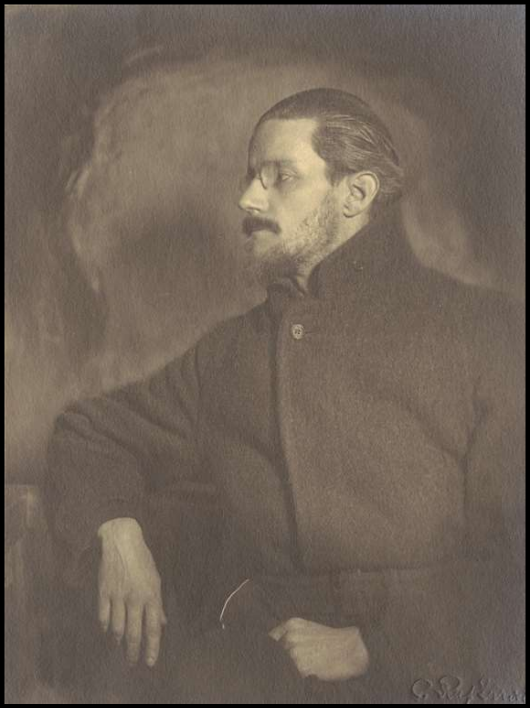
20th century literature:

"…Throgmoggle Fordful
mantly overgoo
bog manty gong goppling
rill cum nack throgginds.
Choomin:
Chillchinchar Engestchin
chanty chopcharchill
chorey chopcharchill chooley
chingle choon chingley
choodle.
Throgmoggle Fordful?
Chillchincar Engestchin?
Fulford mog-gle throg
Throggins…"

Colleen Thibaudeau's
From Throgmoggle & Engestchin: A relationship
(1991)

20th Century Literature

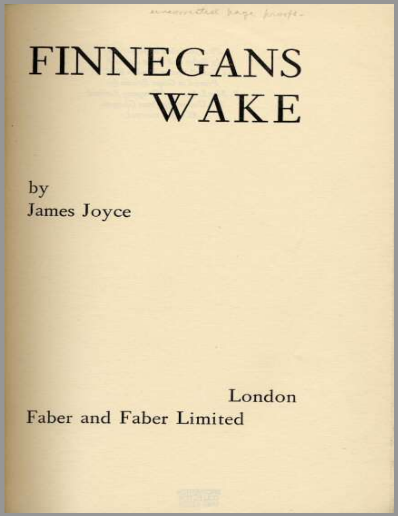
John Bishop, in his introduction to James Joyce's *Finnegans Wake* in 1999, wrote these less-than-encouraging words: "There is no agreement as to what *Finnegans Wake* is about, whether or not it is 'about' anything, or even whether it is, in any ordinary sense of the word, 'readable.' Since Joyce's sentences are packed with obscure allusions, often written in dozens of different languages, it remains impossible to compile a definite synopsis of *Finnegans Wake*."



James Joyce
1882 - 1941

Literary critic Fritz Senn said of the currently available summaries: "We have some traditional summaries, some by Joyce himself. I find them most unsatisfactory and unhelpful…"

Excerpt from *Finnegans Wake*



You're probably thinking that I'm exaggerating.

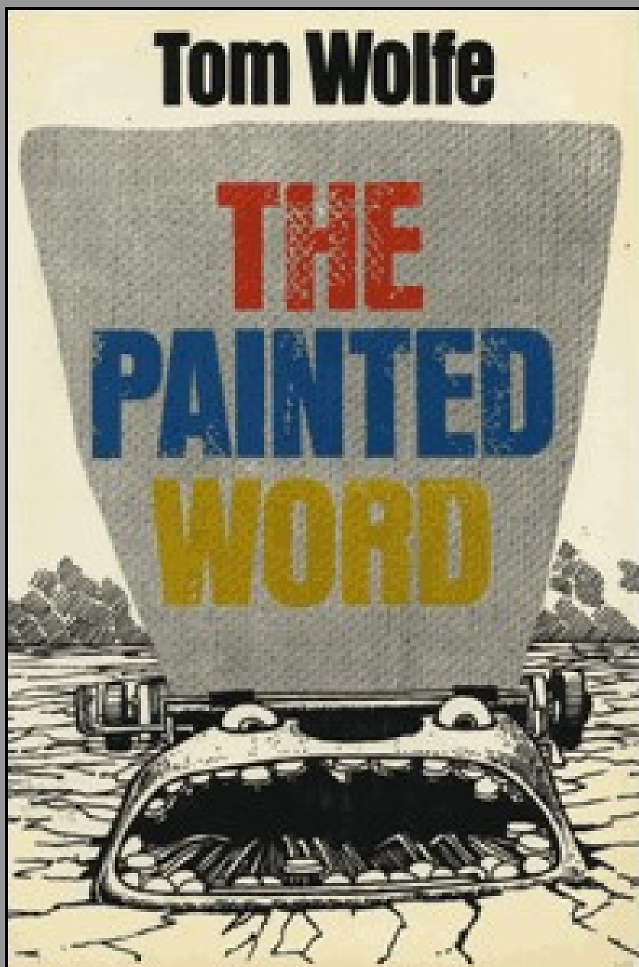
Here's an excerpt (chosen at random) from this "classic" of modern literature:

"…The fall (bababadalgharaghtakamminarronnkonnbronntonner-ronntuonnthunntrovarrhounawnskawntoohoohoordenenthur-nuk!) of a once wallstrait oldparr is retaled early in bed and later on life down through all christian minstrelsy. The great fall of the offwall entailed at such short notice the pftjschute of Finnegan, erse solid man, that the humptyhillhead of humself prumptly sends an unquiring one well to the west in quest of his tumptytumtoes: and their upturnpikepointandplace is at the knock out in the park where oranges have been laid to rust upon the green since dev-linsfirst loved livvy. …"

Weirdness in Sculpture, and Architecture

The architect himself says his $300 million new computer science and artificial intelligence building at M.I.T. "looks like a party of drunken robots got together."

To read more about weirdness in modern art and architecture…



Artists and architects
hate these two books…

Weirdness in Psychology

Sigmund Freud
(1856 – 1939)

Sigmund Freud (and others) developed a bizarre and complex theory of human behavior—psychoanalysis—based mostly on sexual desire.

Psychoanalysis is **unfalsifiable**. If you deny your Oedipal complex, then you're repressing it!

Richard Webster called psychoanalysis "one of the great follies of Western civilization."

H. J. Eysenck says that Freud "set psychiatry back 100 years," consistently misdiagnosed his patients, fraudulently misrepresented case histories, and that "what is true in Freud is not new, and what is new in Freud is not true."

J. von Scheidt speculated that Freud's theories were due to his cocaine use, which increases sexual interest and obsessive thinking.

In any case, Freud was clearly **subconsciously** influenced by physics!

A field of “Postmodern Thought” emerged.

A post-modern journal

Postmodern thinkers:

Use scientific or pseudoscientific terminology and concepts without knowing what these words mean.

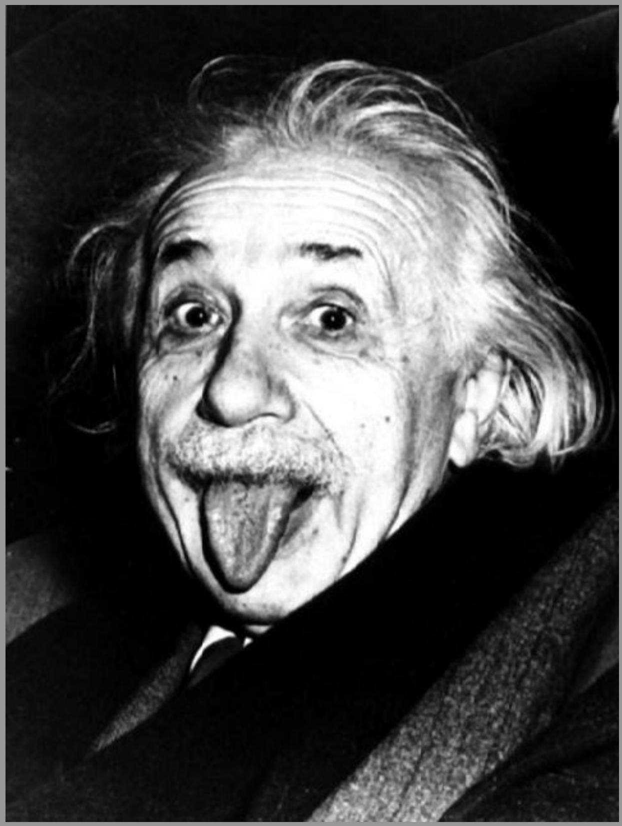
Display superficial erudition by shamelessly throwing around technical terms where they are irrelevant, presumably to impress and intimidate the non-specialist reader.

Manipulating words and phrases that are, in fact, meaningless to appear to knowledgeable.

Genuine vs. Artificial Revolutions

The revolutions in physics were the result of new **experiments** and **observations** and so were **forced** upon us by the world around us.

That they involved weird ideas that average people couldn't understand is due to the fact that the universe is, in fact, weird.



The "revolutions" in art, literature, psychology, and music were the result of simple arrogance of the practitioners and their desire to have their own unintuitive ideas that only they could "understand"—what I like to call **Physics Envy**. But they nicely illustrate the dramatic effects on others of the genuine revolutions that occurred in physics.

Physicists have responded in entertaining ways.

In 1995, physicist Allan Sokal successfully published a fake paper of complete gibberish in the postmodern journal “Social Text.” In it, he “concludes,” among other things, that physical reality is only an illusion.

Allan Sokal

Jeremy Stribling, one of the MIT students who submitted the paper. Photo from his home page.

In 2005, MIT graduate students wrote a computer program to generate bogus research papers with completely nonsensical text, charts, and diagrams and got a paper accepted at the World Multiconference on Systemics, Cybernetics and Informatics.