Two Goals for Last Lecture

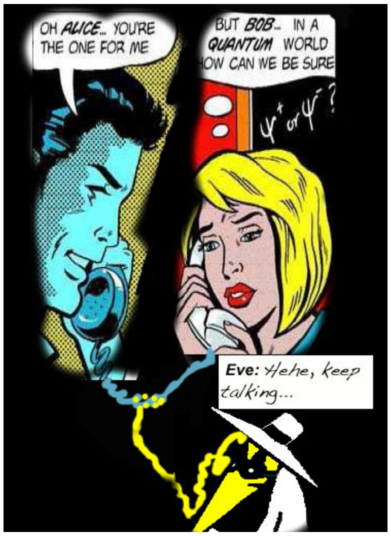
(1) A few words about *usefulness* of these strange features of QM (entanglement et cetera)

(2) Just so you don't feel cheated, a few words about the zoo of subatomic particles, antimatter, et cetera -- not so much "concepts" as "botany[1]"...

Reminder: office hrs tomorrow for review (could schedule another if demand indicates...)

[1] - (with apologies. Physicists can't help making fun of botany, which we like to misinterpret as "memorizing the names of flowers.")

Classical Cryptography



The only provably secure way to send secrets:

- the "one-time pad." Alice and Bob share a *random* "key", which is AS LONG AS THE ENTIRE MESSAGE.

They never reuse it. (Soviets made this mistake.)

Problem: How to be sure "Eve" didn't get a copy of the key?

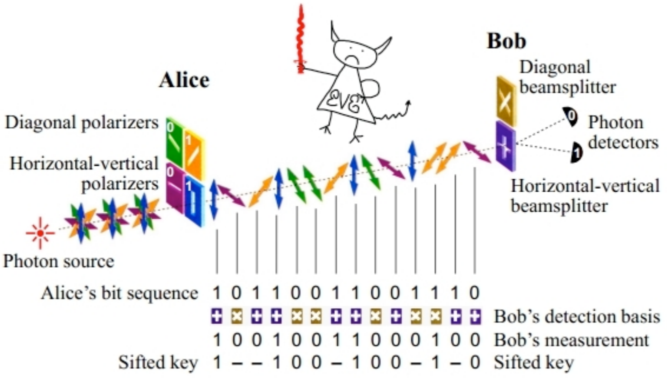
The Bennett-Brassard Protocol (1984)

Heisenberg to the rescue!

Photons have "polarisation

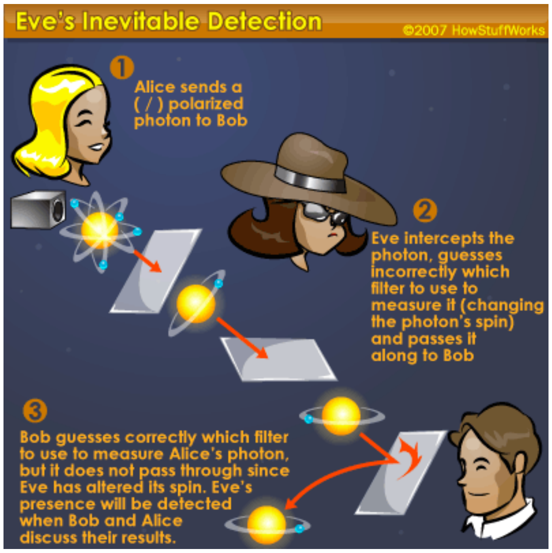
You can measure whether one is ↕ or ↔
OR you can measure whether it's ⤡ or ⤢

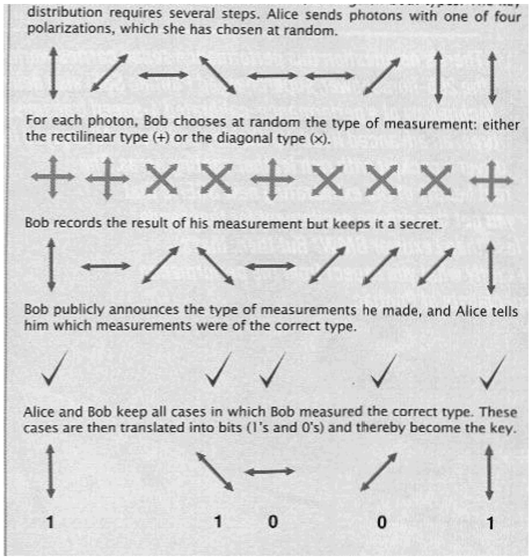
But if it's ⤡ and you measure HV, the result is random; and vice versa. ✛



Eve can't know in advance which axis to measure along... and if she guesses wrong, she destroys the correlations Alice & Bob test.

Quantum communications





distribution requires several steps. Alice sends photons with one of four polarizations, which she has chosen at random.

↕ ⤢ ↔ ⤡ ↔ ↔ ⤢ ↕ ↕

For each photon, Bob chooses at random the type of measurement: either the rectilinear type (+) or the diagonal type (×).

+ + × × + × × × +

Bob records the result of his measurement but keeps it a secret.

↕ ↔ ⤢ ⤡ ↔ ⤢ ⤢ ⤢ ↕

Bob publicly announces the type of measurements he made, and Alice tells him which measurements were of the correct type.

✓ ✓ ✓ ✓ ✓

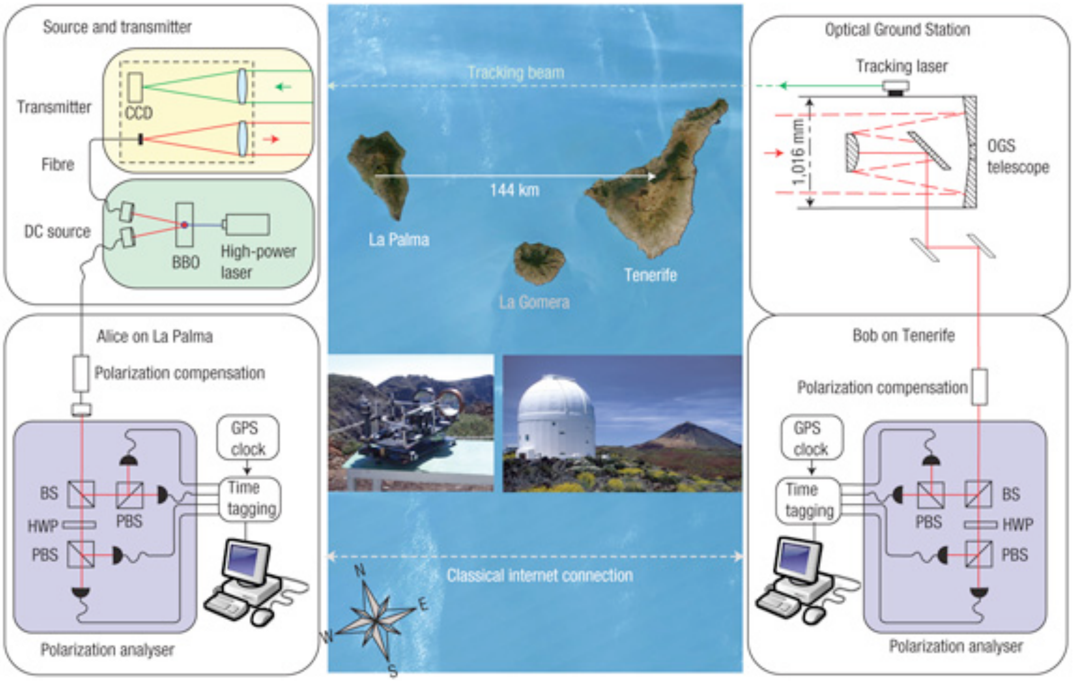
Alice and Bob keep all cases in which Bob measured the correct type. These cases are then translated into bits (1's and 0's) and thereby become the key.

↕ ⤡ ↔ ⤢ ↕

1 1 0 0 1

- Measurement disturbance -> if Eve measures the unknown quantity, there is a detectable effect
- Incompatible observables -> there is always at least one unknown quantity
- No-cloning -> she can't just make a second copy and wait to measure later

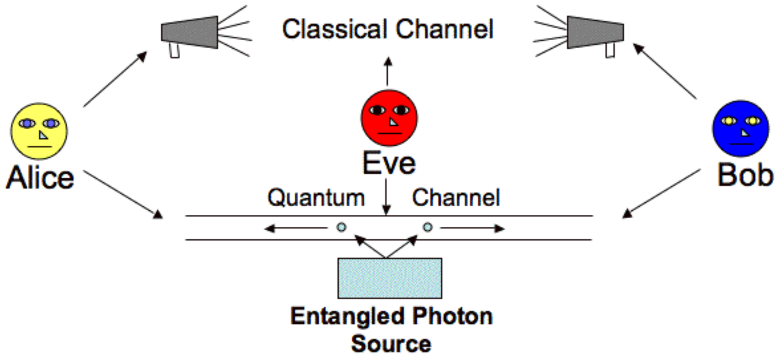
A good excuse for a junket!



One slight problem: “side channels”

the device that operated the switch in the first demonstration was so noisy that the system was only “secure against an eavesdropper who happened to be blind and deaf”

Solution: Ekert Protocol

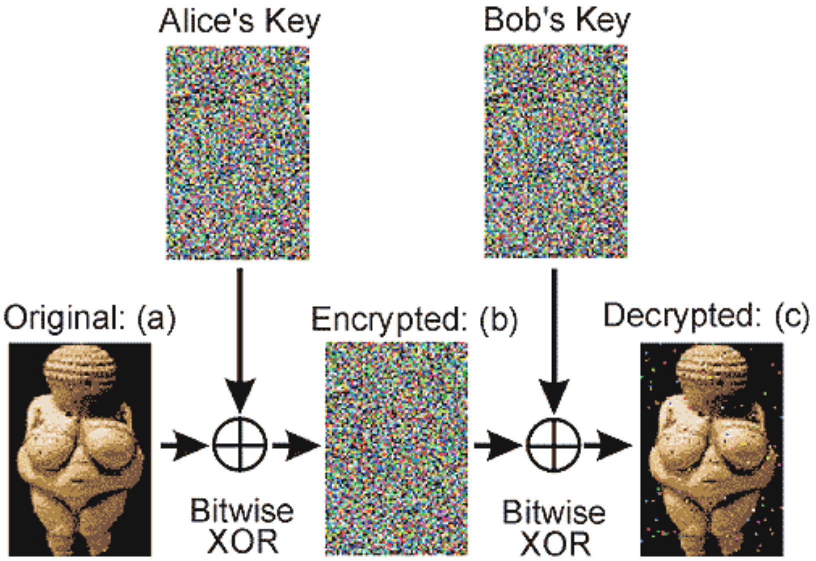


In any basis, Alice and Bob see correlated (opposite) results.
They can construct a key just as in the Bennett-Brassard ’84 protocol

They can use Bell Inequalities to test that their photons are entangled

Recall what BI’s really test: could you explain your results with local hidden variables?
Well, if Eve had measured the photons, each would have “collapsed” to the outcome of some measurement. Eve has the hidden variable.
If BI’s are violated, you **know** ***Eve has no information, side channels or not!***

This random string of bits can be used as a secret key...



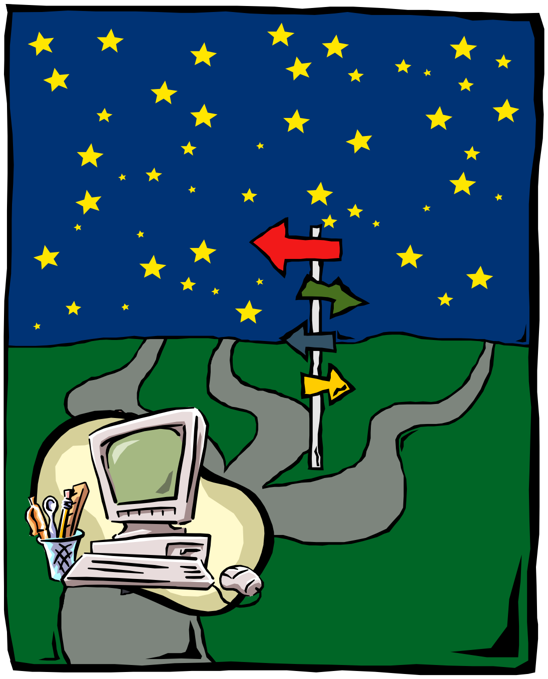
Quantum Cryptography

“We don’t need to worry about information security or message encryption. Most of our communications are impossible to understand in the first place.”

A few words about Quantum Computation...

People like Richard Feynman and David Deutsch realized that the "uncertain" state of a quantum computer could actually be useful...
If it doesn't know what state it's in, maybe it can be in all of them at the same time... and then solve many possible problems all at once?!

(Yes and no, but Deutsch – and later Shor – showed there were at least some clever things to do.)



Quantum Computation?

Some problems (like factoring large numbers) are "exponentially hard" on classical computers [as far as we know] – this means that every time you make the number one digit longer, the problem takes twice [for example] as long for a computer to solve.

This is why your credit card # is (maybe) secure when you send it over the internet!

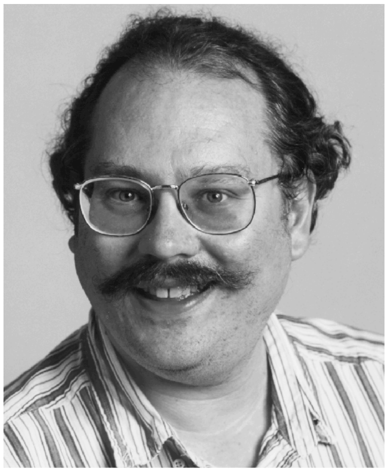
But there are countless examples throughout history of people who thought their codes were secure, but learned otherwise (see Simon Singh's "The Code Book").

Feynman noticed that figuring out what a quantum system is going to do is also exponentially hard... does that mean that (unlike classical computers), the quantum system is "powerful" enough to "simulate" these other hard problems?

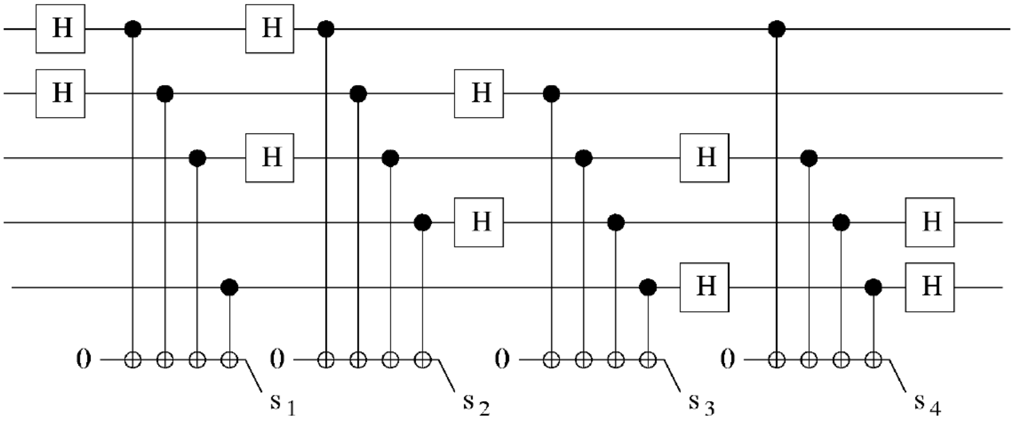
Quantum Larceny?

Peter Shor showed about eighteen years ago that if a computer were in a *quantum* state (completely uncertain), it could break the classical code ("RSA") based on factoring products of primes.

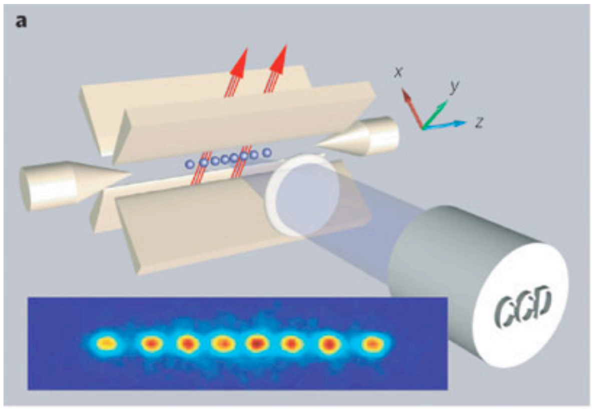
No solution but quantum cryptography!



Quantum computing so far...



This is a small fragment of the "quantum logic circuit" which was used a few years back to prove 15 = 3 (±1) • 5 (±1) !

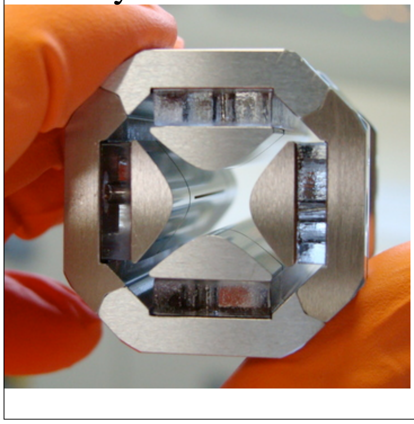


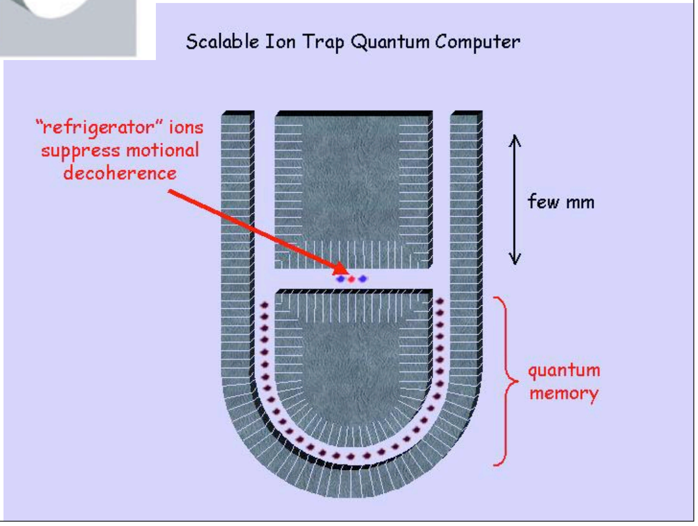
Wineland’s ion-trap quantum computers

(Note: entanglement is the key)

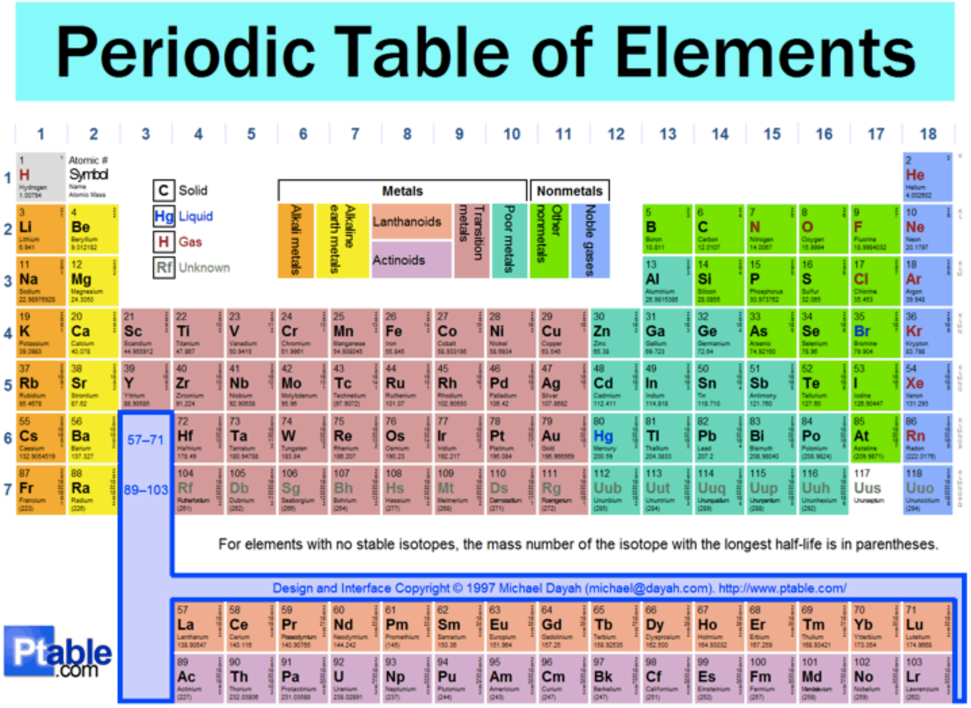
In a few more years?

Today





The “standard model” (mostly)



Periodic Table of Elements

Atomic # Symbol Name Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals

Nonmetals: Other nonmetals, Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57–71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89–103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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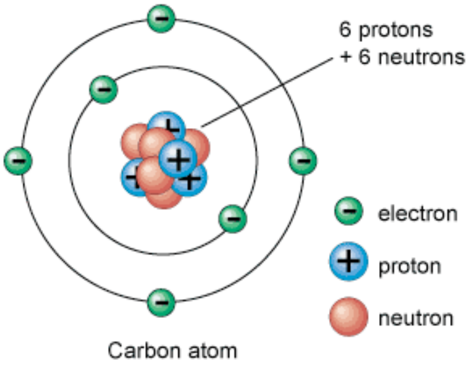
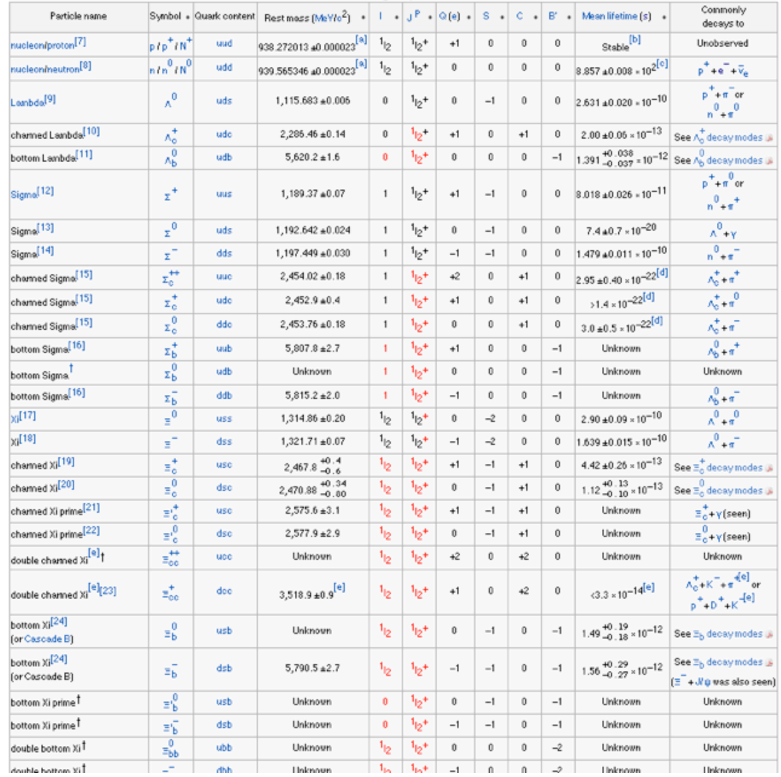
The “standard model” (mostly)



The “standard model” (mostly)



$J^P = \frac{1}{2}^+$ baryons

Particle name	Symbol	Quark content	Rest mass (MeV/c^2)	I	J^P	Q (e)	S	C	B′	Mean lifetime (s)	Commonly decays to
nucleon/proton[7]	p / p^+ / N^+	uud	938.272013 ± 0.000023[a]	½	½+	+1	0	0	0	Stable[b]	Unobserved
nucleon/neutron[8]	n / n^0 / N^0	udd	939.565346 ± 0.000023[a]	½	½+	0	0	0	0	$8.857 \pm 0.008 \times 10^{2}$[c]	$p^+ + e^- + \bar{\nu}_e$
Lambda[9]	Λ^0	uds	$1{,}115.683 \pm 0.006$	0	½+	0	−1	0	0	$2.631 \pm 0.020 \times 10^{-10}$	$p^+ + \pi^-$ or $n^0 + \pi^0$
charmed Lambda[10]	Λ_c^+	udc	$2{,}286.46 \pm 0.14$	0	½+	+1	0	+1	0	$2.00 \pm 0.06 \times 10^{-13}$	See Λ_c^+ decay modes
bottom Lambda[11]	Λ_b^0	udb	$5{,}620.2 \pm 1.6$	0	½+	0	0	0	−1	$1.391^{+0.038}_{-0.037} \times 10^{-12}$	See Λ_b^0 decay modes
Sigma[12]	Σ^+	uus	$1{,}189.37 \pm 0.07$	1	½+	+1	−1	0	0	$8.018 \pm 0.026 \times 10^{-11}$	$p^+ + \pi^0$ or $n^0 + \pi^+$
Sigma[13]	Σ^0	uds	$1{,}192.642 \pm 0.024$	1	½+	0	−1	0	0	$7.4 \pm 0.7 \times 10^{-20}$	$\Lambda^0 + \gamma$
Sigma[14]	Σ^-	dds	$1{,}197.449 \pm 0.030$	1	½+	−1	−1	0	0	$1.479 \pm 0.011 \times 10^{-10}$	$n^0 + \pi^-$
charmed Sigma[15]	Σ_c^{++}	uuc	$2{,}454.02 \pm 0.18$	1	½+	+2	0	+1	0	$2.95 \pm 0.40 \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^+$
charmed Sigma[15]	Σ_c^+	udc	$2{,}452.9 \pm 0.4$	1	½+	+1	0	+1	0	$>1.4 \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^0$
charmed Sigma[15]	Σ_c^0	ddc	$2{,}453.76 \pm 0.18$	1	½+	0	0	+1	0	$3.0 \pm 0.5 \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^-$
bottom Sigma[16]	Σ_b^+	uub	$5{,}807.8 \pm 2.7$	1	½+	+1	0	0	−1	Unknown	$\Lambda_b^0 + \pi^+$
bottom Sigma†	Σ_b^0	udb	Unknown	1	½+	0	0	0	−1	Unknown	Unknown
bottom Sigma[16]	Σ_b^-	ddb	$5{,}815.2 \pm 2.0$	1	½+	−1	0	0	−1	Unknown	$\Lambda_b^0 + \pi^-$
Xi[17]	Ξ^0	uss	$1{,}314.86 \pm 0.20$	½	½+	0	−2	0	0	$2.90 \pm 0.09 \times 10^{-10}$	$\Lambda^0 + \pi^0$
Xi[18]	Ξ^-	dss	$1{,}321.71 \pm 0.07$	½	½+	−1	−2	0	0	$1.639 \pm 0.015 \times 10^{-10}$	$\Lambda^0 + \pi^-$
charmed Xi[19]	Ξ_c^+	usc	$2{,}467.8^{+0.4}_{-0.6}$	½	½+	+1	−1	+1	0	$4.42 \pm 0.26 \times 10^{-13}$	See Ξ_c^+ decay modes
charmed Xi[20]	Ξ_c^0	dsc	$2{,}470.88^{+0.34}_{-0.80}$	½	½+	0	−1	+1	0	$1.12^{+0.13}_{-0.10} \times 10^{-13}$	See Ξ_c^0 decay modes
charmed Xi prime[21]	Ξ'^+_c	usc	$2{,}575.6 \pm 3.1$	½	½+	+1	−1	+1	0	Unknown	$\Xi_c^+ + \gamma$ (seen)
charmed Xi prime[22]	Ξ'^0_c	dsc	$2{,}577.9 \pm 2.9$	½	½+	0	−1	+1	0	Unknown	$\Xi_c^0 + \gamma$ (seen)
double charmed Xi[e]†	Ξ_{cc}^{++}	ucc	Unknown	½	½+	+2	0	+2	0	Unknown	Unknown
double charmed Xi[e][23]	Ξ_{cc}^+	dcc	$3{,}518.9 \pm 0.9$[e]	½	½+	+1	0	+2	0	$<3.3 \times 10^{-14}$[e]	$\Lambda_c^+ + K^- + \pi^+$[e] or $p^+ + D^+ + K^-$[e]
bottom Xi[24] (or Cascade B)	Ξ_b^0	usb	Unknown	½	½+	0	−1	0	−1	$1.49^{+0.19}_{-0.18} \times 10^{-12}$	See Ξ_b decay modes
bottom Xi[24] (or Cascade B)	Ξ_b^-	dsb	$5{,}790.5 \pm 2.7$	½	½+	−1	−1	0	−1	$1.56^{+0.29}_{-0.27} \times 10^{-12}$	See Ξ_b decay modes ($\Xi^- + J/\psi$ was also seen)
bottom Xi prime†	Ξ'^0_b	usb	Unknown	0	½+	0	−1	0	−1	Unknown	Unknown
bottom Xi prime†	Ξ'^-_b	dsb	Unknown	0	½+	−1	−1	0	−1	Unknown	Unknown
double bottom Xi†	Ξ_{bb}^0	ubb	Unknown	½	½+	0	0	0	−2	Unknown	Unknown
double bottom Xi†	Ξ_{bb}^-	dbb	Unknown	½	½+	−1	0	0	−2	Unknown	Unknown

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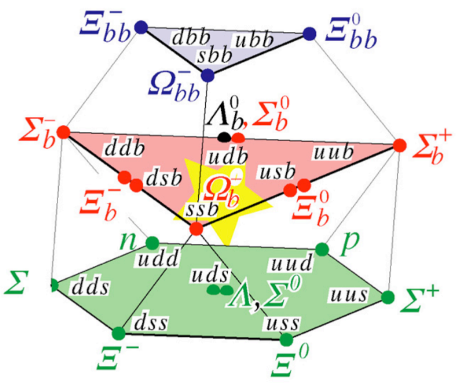
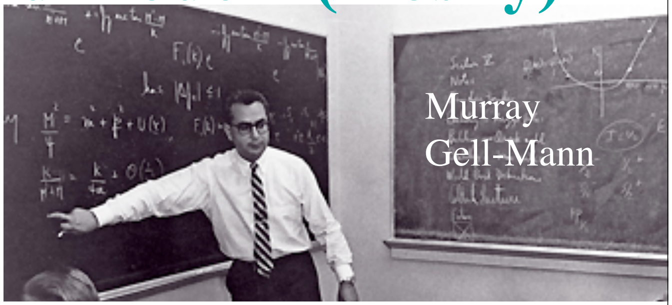
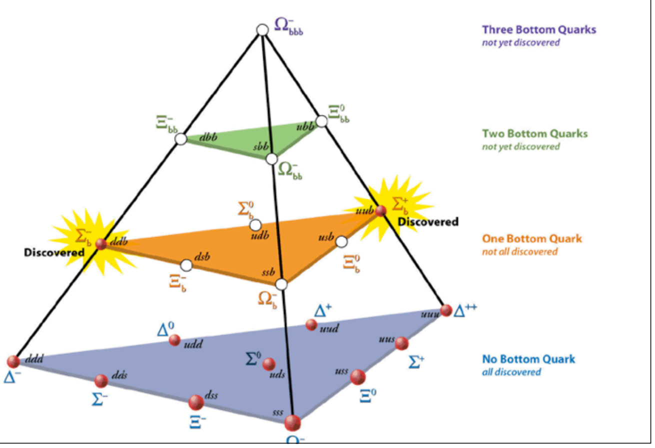
The “standard model” (mostly)

$J = 1/2$ b Baryons

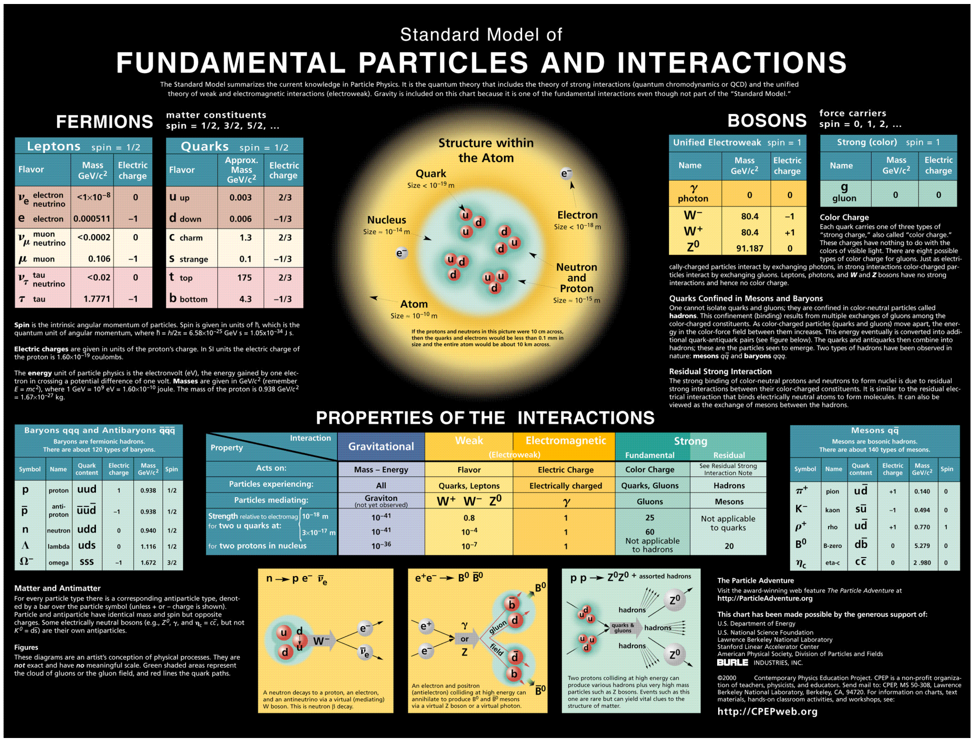




Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin ($J = 3/2$)



The “standard model” (mostly)



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the “Standard Model.”

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton’s charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of “strong charge,” also called “color charge.” These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist’s conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

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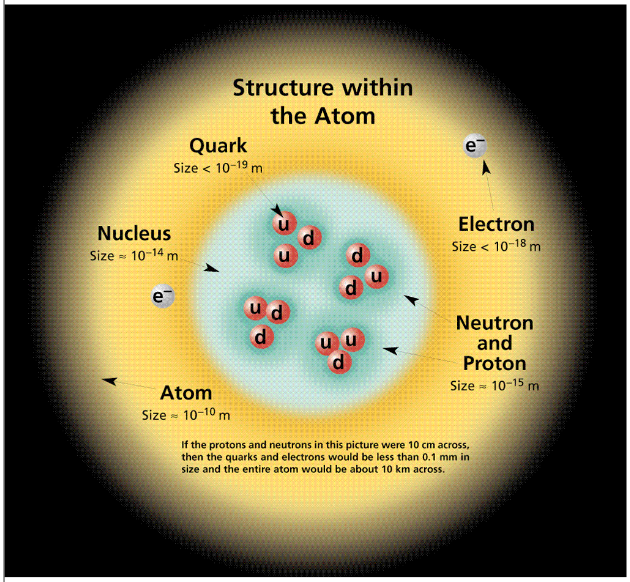
Why does “high-energy physics” = “particle physics” ?



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

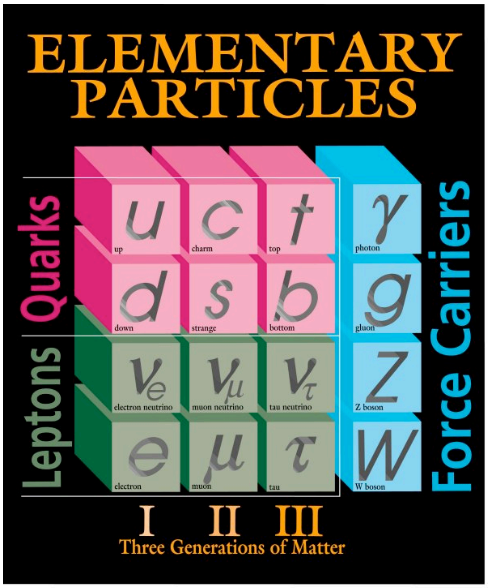
Uncertainty principle: things confined to small regions may have very large momenta -> high energies.

It takes a lot of energy to build a good “microscope.”

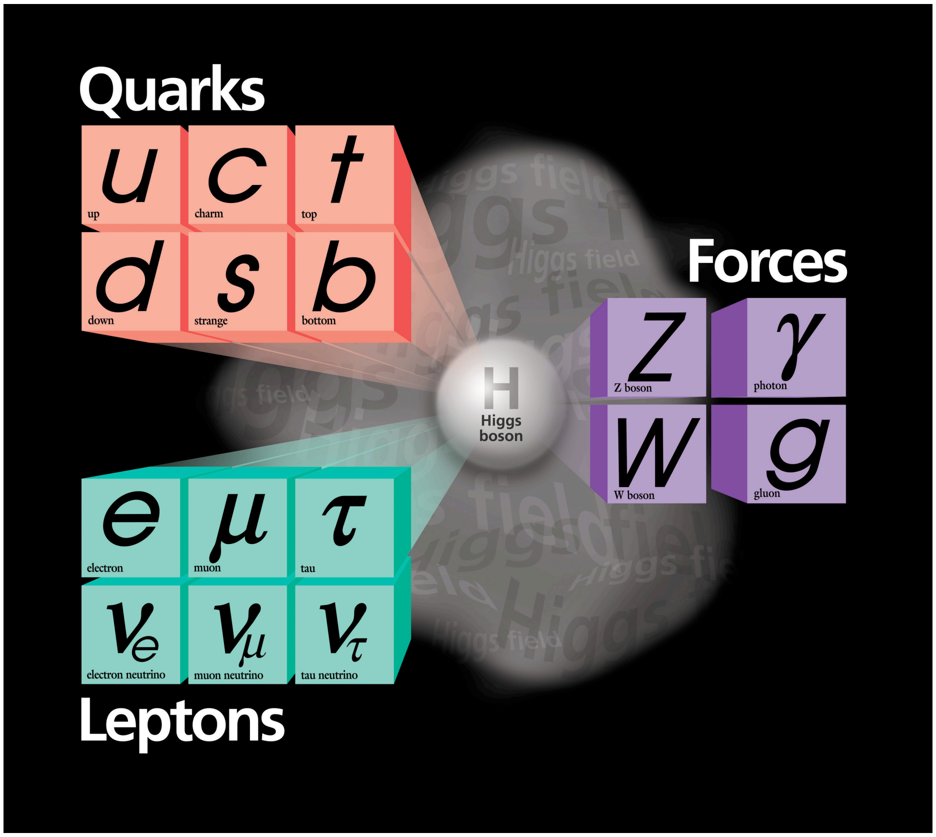
Matter is electrons + protons (quarks) + neutrons (quarks).

1936: studying cosmic rays, people found particles which behaved just like electrons, but hundreds of times heavier: “muons.”

1937: atomic physicist I. I. Rabi asks “who ordered that?”



Fermilab 95-759



How to do QM *and* relativity?

Wait a minute:

in relativity, space & time are like two aspects of one thing; they need to be treated "symmetrically."

But QM said "there is some $\Psi(x)$ given at t=0; find it for other t."

Not symmetric.

Schrödinger found a symmetric equation, but it gave the wrong answers (turns out to be correct for "pions," not for electrons, I think).

1928 - Dirac finds one that works.

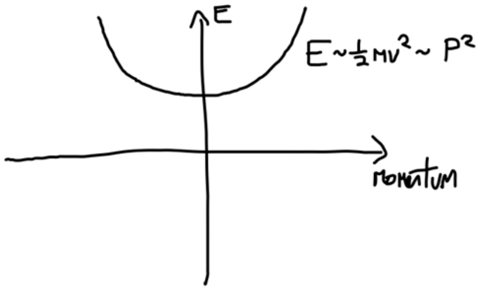
But a problem...

Symmetry of x & t

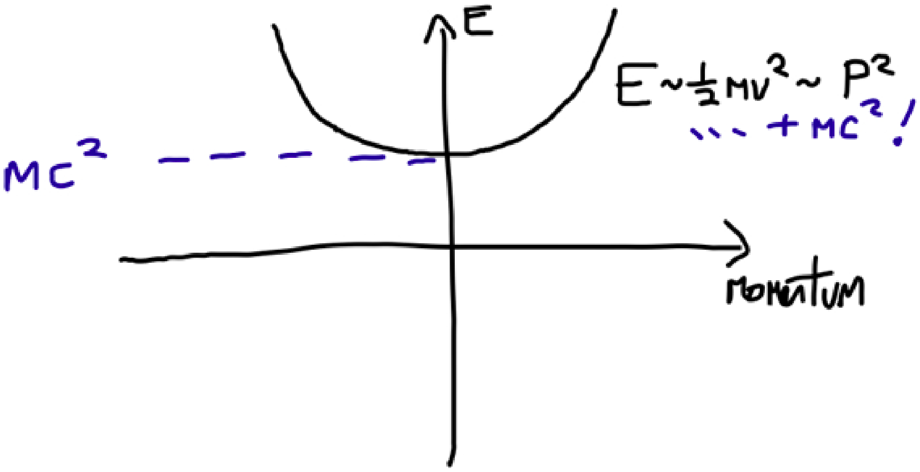
The Schrödinger equation starts from the idea that the energy depends on momentum squared (kinetic energy goes up by 4 if velocity doubles)

It turns out that Energy has to do with time (the frequency of the wave) and Momentum has to do with space (the wave*length*).

To by symmetric, the equation should either relate E^2 and P^2 or
E and P, but certainly not E and P^2 !



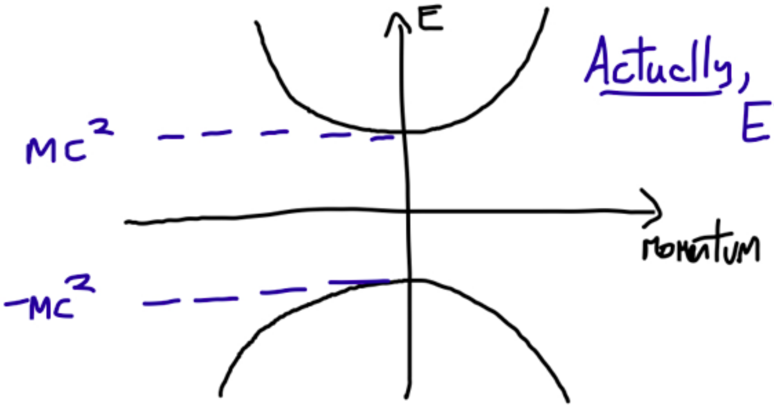
Remember relativity...



$E \sim \frac{1}{2}Mv^2 \sim P^2$

$\cdots + Mc^2$!

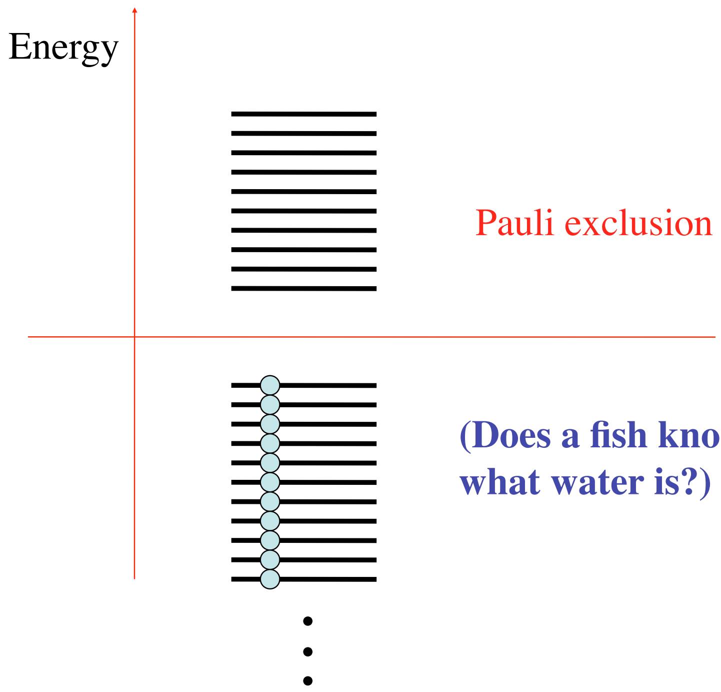
The “symmetric” solution



Actuclly, Einstein said $E^2 \sim m^2 + p^2$

But wait a second: things always flow to lower-energy states. If there are *negative* energy states, with E all the way down to –infinity, then why doesn’t everything run off to infinity??

Dirac sea?



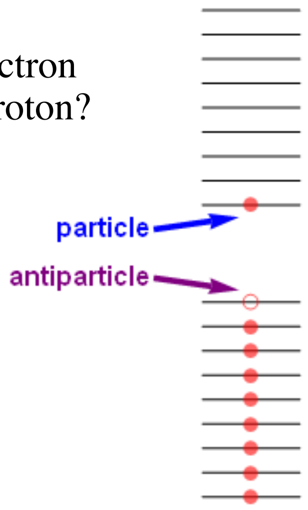
Pauli exclusion principle

(Does a fish know what water is?)

Only when it's missing!

electron
& proton?

NO!

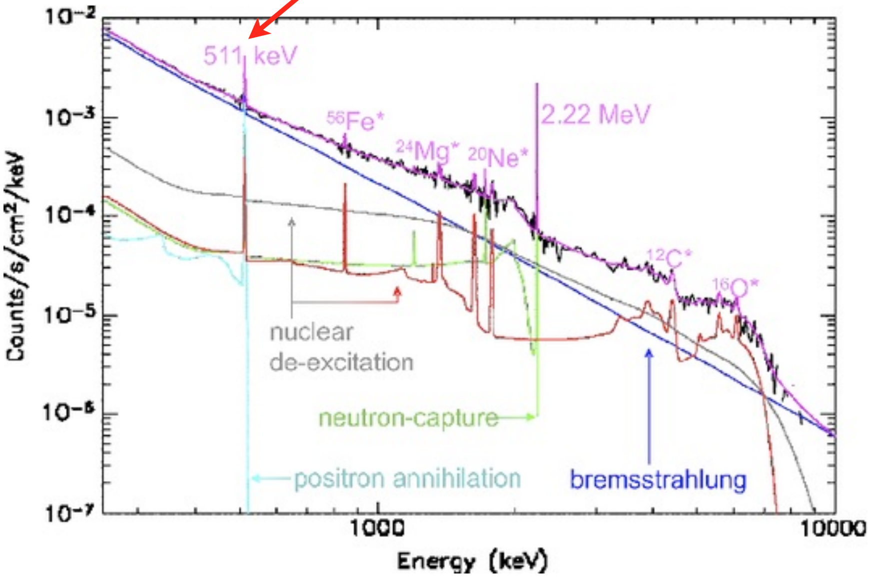


Two photons (energy) generate matter (electron+positron)

An electron and its antiparticle *annihilate* (turn into pure energy, a pair of photons)

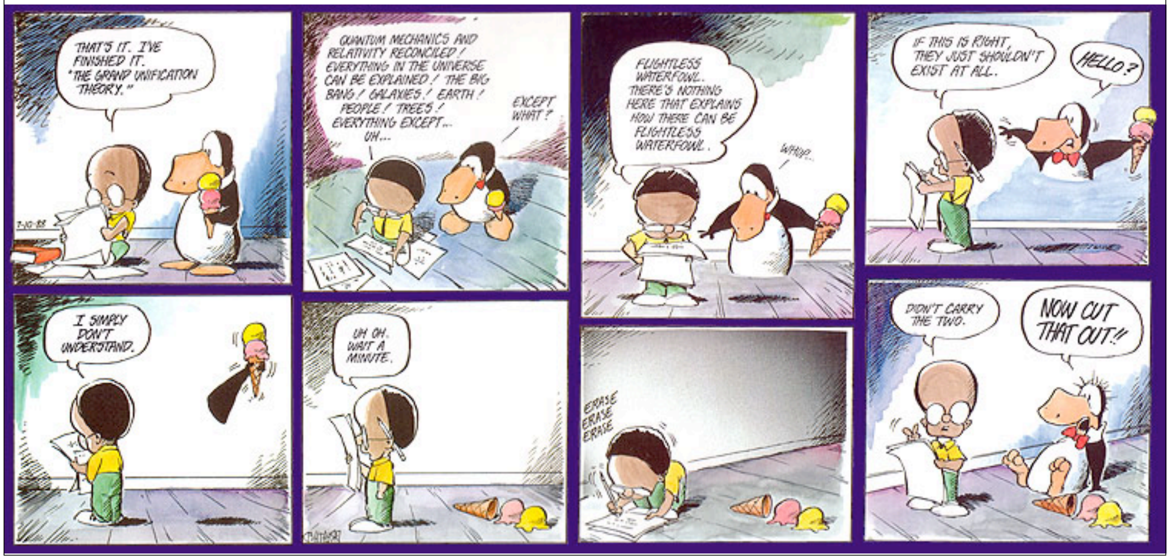
Gamma rays observed from solar flares

511 keV = the electron mass divided by c^2!



Problems...

Mass (Higgs?)
Gravity (string theory? loop quantum gravity?)
Symmetries (why these tiny violations of symmetry)?
Why these particular particles, masses, charges,...?
And, of course, flightless waterfowl:



Summary

“There is more on Heaven and Earth, Horatio, than is dreamt of in your philosophy.”

But that’s not a reason to try to learn as much as we can about it and, whenever possible, to make sense of it.

This (not “calculating things,” let alone building things) is the project of physics. (Though we’re kind of chuffed if what we find out also turns out to be useful, naturally!)