A Subtle Periodic Table
—— an unsolved mystery of our Mother Nature

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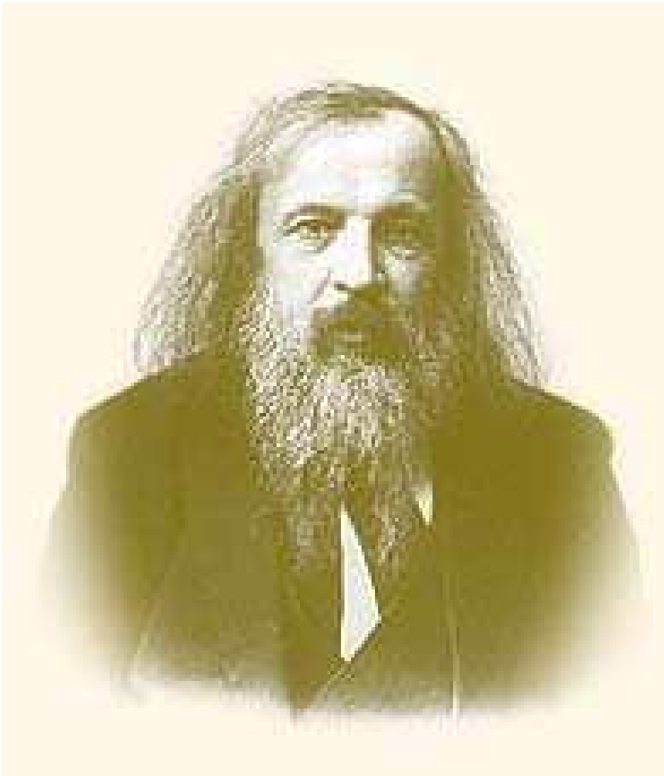
- A thousand years old question: What is our world made of?
- In ancient Greek, philosopher believed the building blocks are the "4 elements":

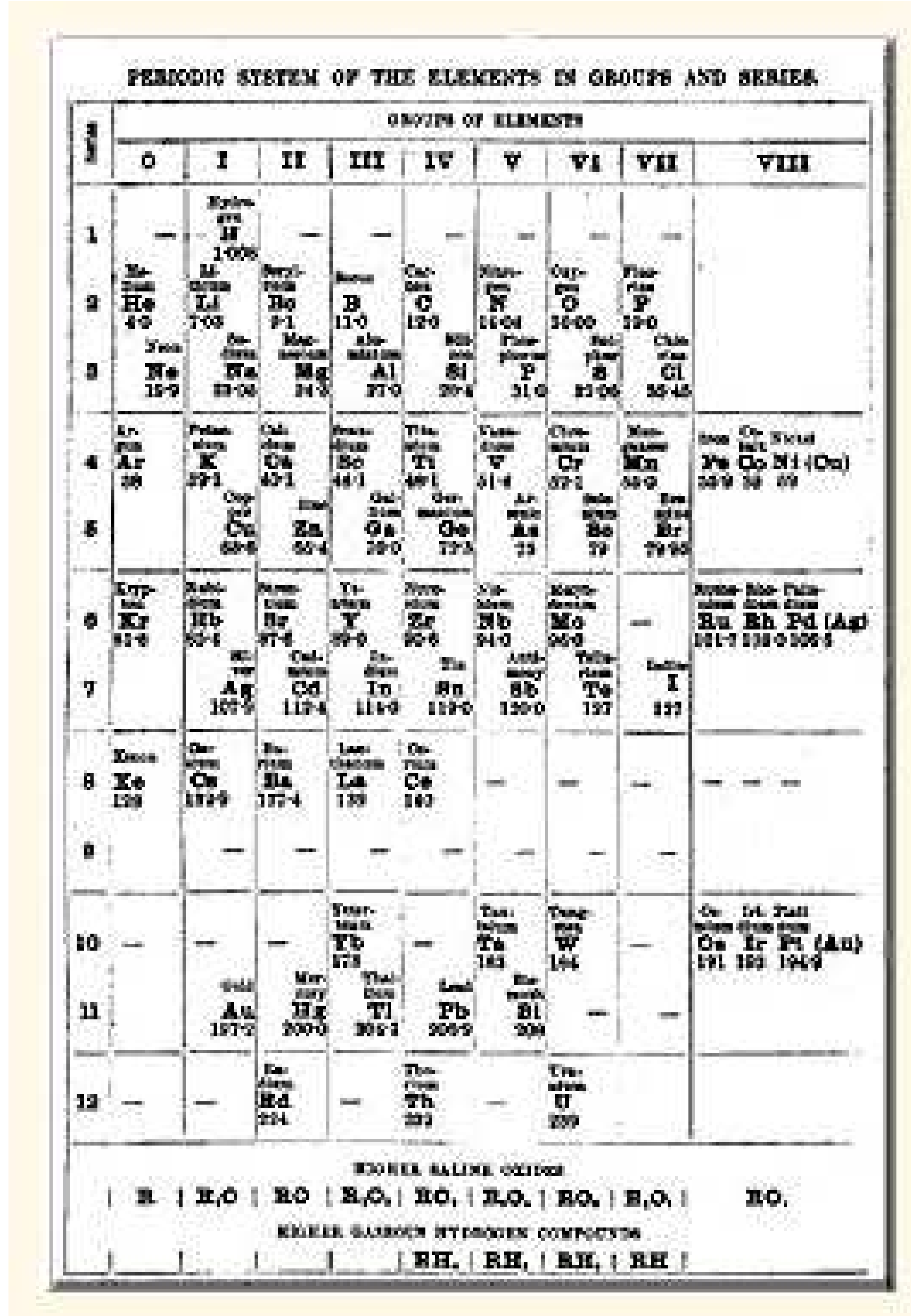
season	element	humour	body fluid	location
Spring	air	sanguine	blood	heart
Summer	fire	choleric	"yellow bile"	liver
Autumn	earth	melancholic	"black bile"	spleen
Winter	water	phlegmatic	phlegm	(various)

No, that’s not enough!



Mendeleev first trained as a teacher in the Pedagogic Institute of St. Petersbug before earing his MS in 1856.

Textbook written between 1868-1870



PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	0	I	II	III	IV	V	VI	VII	VIII
1	—	H 1·008	—	—	—	—	—	—	
2	He 4·0	Li 7·03	Be 9·1	B 11·0	C 12·0	N 14·04	O 16·00	F 19·0	
3	Ne 19·9	Na 23·05	Mg 24·3	Al 27·0	Si 28·4	P 31·0	S 32·06	Cl 35·45	
4	Ar 38	K 39·1	Ca 40·1	Sc 44·1	Ti 48·1	V 51·4	Cr 52·1	Mn 55·0	Fe Co Ni (Cu) 55·9 59 59
5		Cu 63·6	Zn 65·4	Ga 70·0	Ge 72·3	As 75	Se 79	Br 79·95	
6	Kr 81·8	Rb 85·4	Sr 87·6	Y 89·0	Zr 90·6	Nb 94·0	Mo 96·0	—	Ru Rh Pd (Ag) 101·7 103·0 106·5
7		Ag 107·9	Cd 112·4	In 114·0	Sn 119·0	Sb 120·0	Te 127	I 127	
8	Xe 128	Cs 132·9	Ba 137·4	La 139	Ce 140	—	—	—	— — —
9		—	—	—	—	—	—	—	
10	—	—	—	Yb 173	—	Ta 183	W 184	—	Os Ir Pt (Au) 191 193 194·9
11		Au 197·2	Hg 200·0	Tl 204·1	Pb 206·9	Bi 208	—	—	
12	—	—	Rd 224	—	Th 232	—	U 239		
HIGHER SALINE OXIDES	R	R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4
HIGHER GASEOUS HYDROGEN COMPOUNDS					RH_4	RH_3	RH_2	RH	

- At that time, the experimentally determined atomic masses were not always accurate. Mendeleev reordered elements despite their accepted masses.
For example, he changed the weight of Beryllium from 14 to 9.
In all, he found 17 elements had to be moved to new positions.
- Even so, there are many elements missing at some positions.
From the gap, he predicted the existence and properties of unknown elements.
- Gallium (by a French, Gallia is Latin for France), Scandium (by a Scandinavian), and Germanium (by a German) were found later to fit his prediction quite well.
- In all Medeleev predicted the existence of 10 new elements, of which seven were eventually discovered.
- After electron, proton, neutron and Quantum Mechanics were known, the periodic table can be easily understood.

Modern Periodic Table

Table 4.1. Revised 2004 by C.G. Wohl (LBNL). Adapted from the Commission of Atomic Weights and Isotopic Abundances, "Atomic Weights of the Elements 1995," Pure and Applied Chemistry **68**, 2339 (1996), and G. Audi and A.H. Wapstra, "The 1993 Mass Evaluation," Nucl. Phys. **A565**, 1 (1993). The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. For a new determination of atomic masses, not weighted by abundances, see G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003). Atomic masses are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. However, although Th, Pa, and U have no stable isotopes, they do have characteristic terrestrial compositions, and meaningful weighted masses can be given. For elements 110 and 111, the numbers of nucleons A of confirmed isotopes are given.

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 Ds Darmstadt. [269,271]	111 [272]							

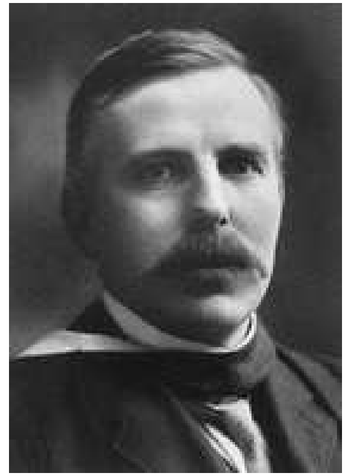
Lanthanide series

57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967

Actinide series

89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

J Thomson
electron, 1906



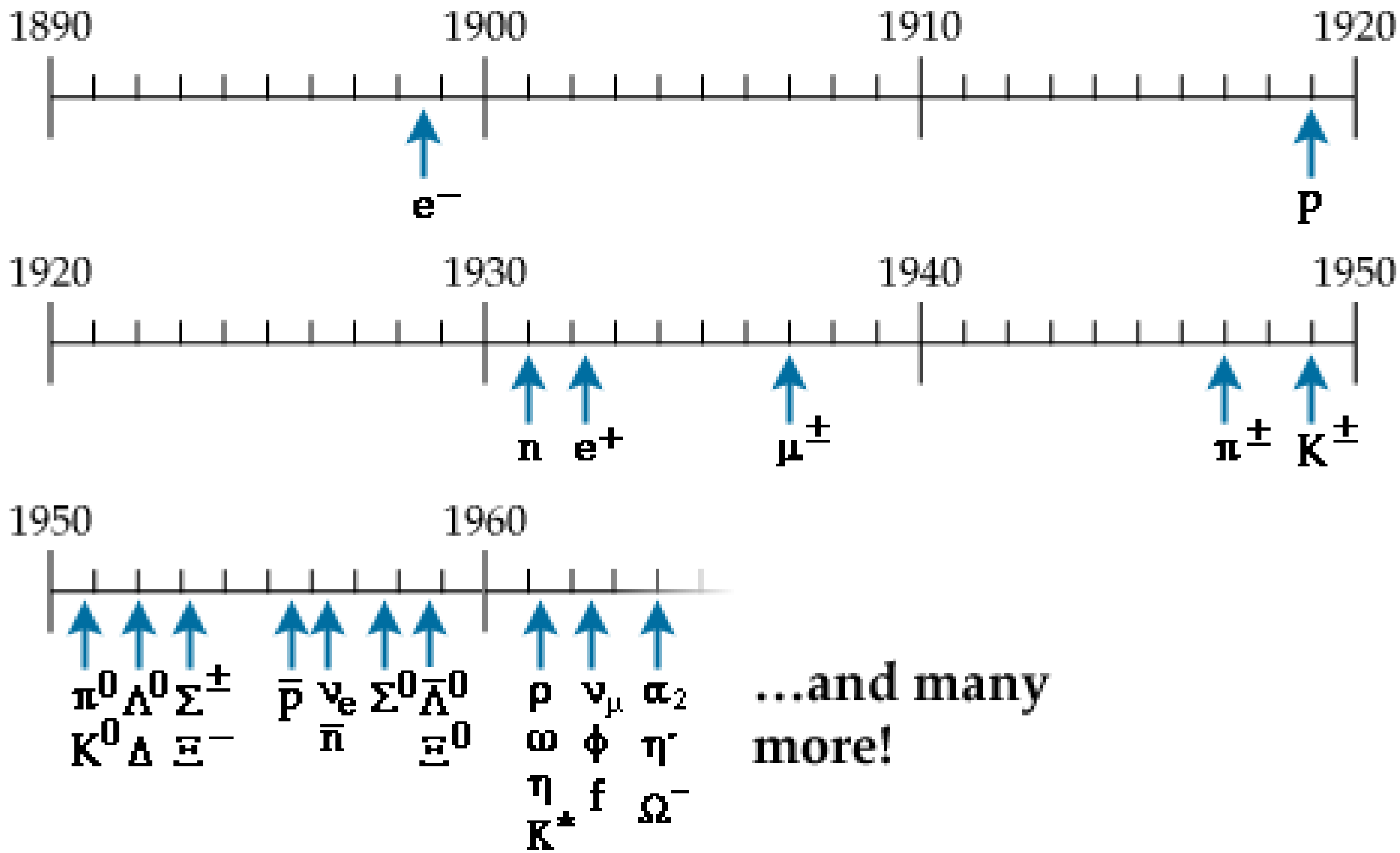
Rutherford
proton, 1908 (chem)

J. Chadwick
neutron, 1935

C Anderson
positron, 1936

Yukawa
pion theory, 1949

C. Powell
pion, 1950

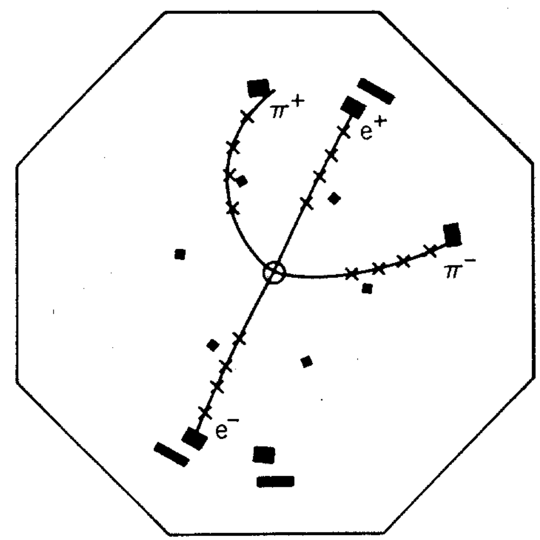


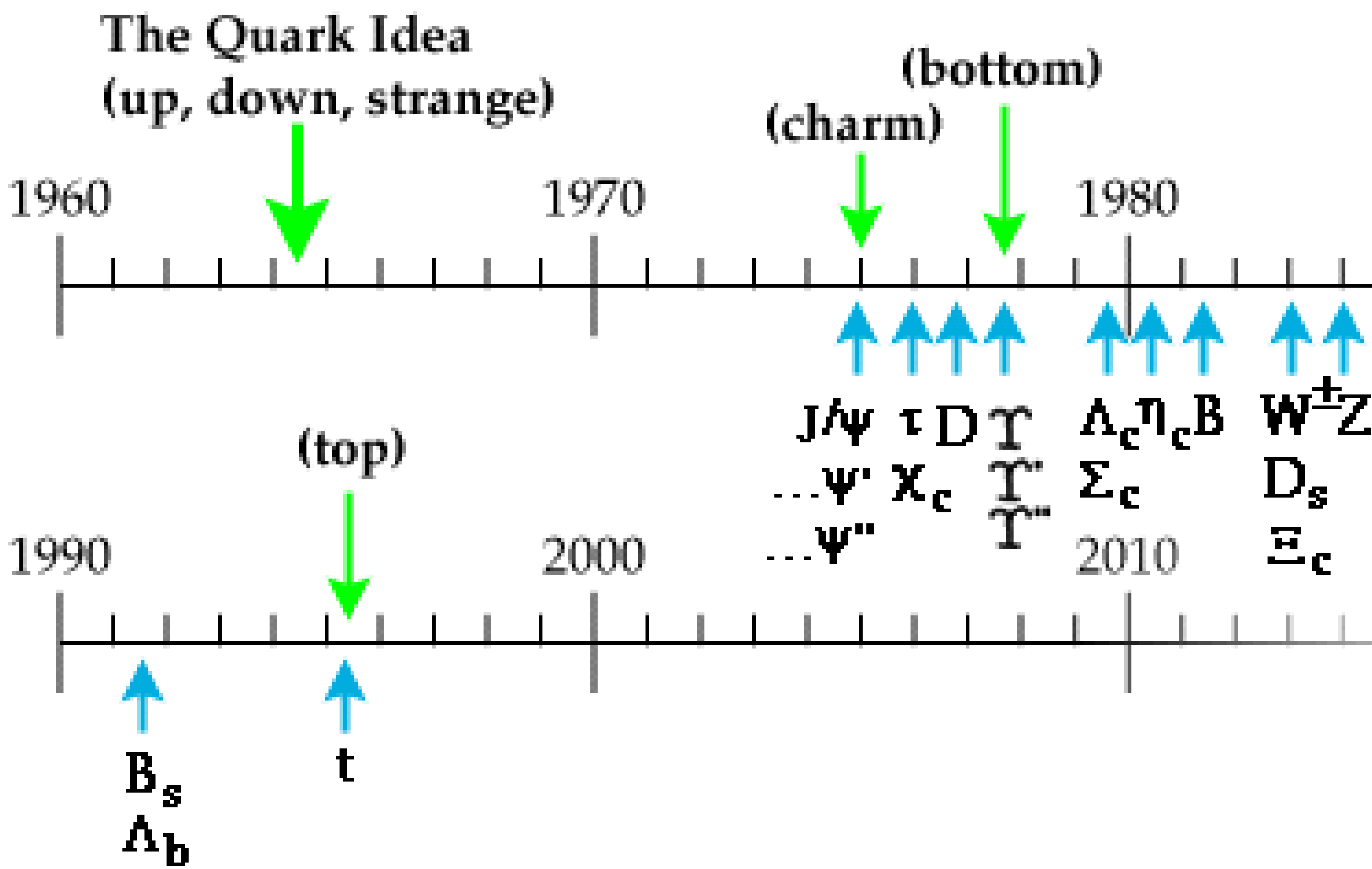
1890
1900
1910
1920
e⁻
p
1920
1930
1940
1950
n
e⁺
μ±
π±
K±
1950
1960
π⁰ Λ⁰ Σ±
K⁰ Δ Ξ⁻
p̄ νe Σ⁰ Λ̄⁰
n̄ Ξ⁰
ρ νμ α₂
ω φ η'
η f Ω⁻
K*
...and many more!

In 1964, Murray Gell-Mann and George Zweig tentatively put forth the idea of quarks. They suggested that mesons and baryons are composites of three quarks or antiquarks, called up, down, or strange (u, d, s) with spin 1/2 and electric charges 2/3, -1/3, -1/3, respectively (it turns out that this theory is not completely accurate). Since the charges had never been observed, the introduction of quarks was treated more as a mathematical explanation of flavor patterns of particle masses than as a postulate of actual physical object. Later theoretical and experimental developments allow us to now regard the quarks as real physical objects, even though they cannot be isolated.

November Revolution in Physics

The world of physics was dazzled in November 1974 when two separate experiments at SLAC and at Brookhaven independently discovered the first of a new set of particle states, the J/Psi particle.
Burton Richter of the SLAC collaboration, and Sam Ting, of the Brookhaven group, received the 1976 Nobel Prize in Physics
"for their pioneering work in the discovery of a heavy elementary particle of a new kind."





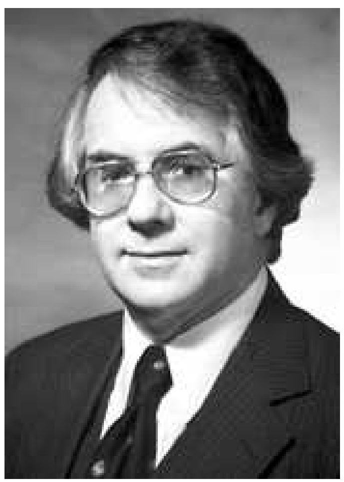
The Quark Idea
(up, down, strange)
(charm)
(bottom)
1960
1970
1980
1990
J/ψ
...ψ'
...ψ''
τ
D
χc
ϒ
ϒ'
ϒ''
Λc
ηc
B
Σc
W±Z
Ds
Ξc
(top)
1990
2000
2010
Bs
Λb
t

Standard Model

- Standard Model(SM) is the most successful theoretical understanding of the Mother Nature in human history (with only 19 free parameters.)

$$SM = \text{Quantum Mechanics} + \text{Special Relativity} + \text{Field theory}$$
$$+\text{Gauge Symmetry}\,[\equiv SU(3)_c \times SU(2)_L \times U(1)]$$
$$+ \text{Matter Content}\,[quarks,\ leptons] + \text{Higgs Mechanism.}$$

- Predicts that weak interaction is mediated by exchange of $W^{\pm}$ and Z^0 bosons.



S. Glashow

Abdus Salam

Steven Weinberg

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–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

These are a few of the many 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	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

The subtle periodic table in the modern particle physics:

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

Leptons spin =1/2

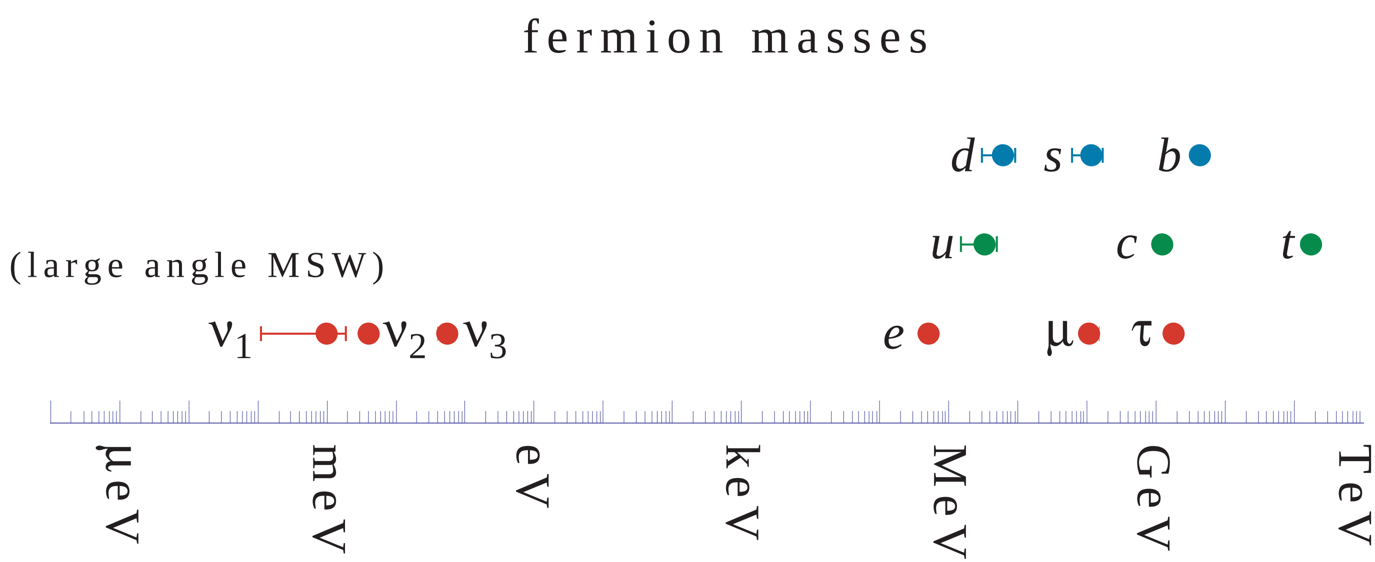
Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

Fermion masses

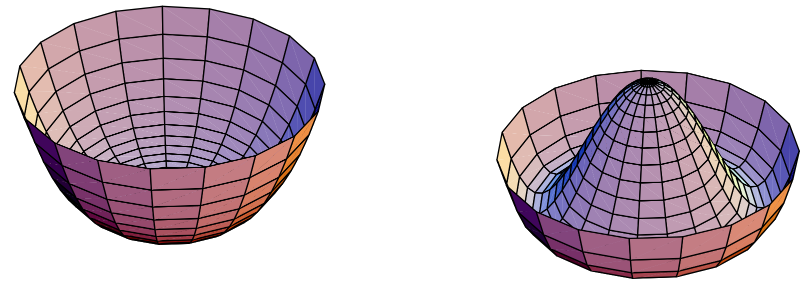
- Fermion masses in log scale



- Where comes the mass?

Masses and the Higgs field

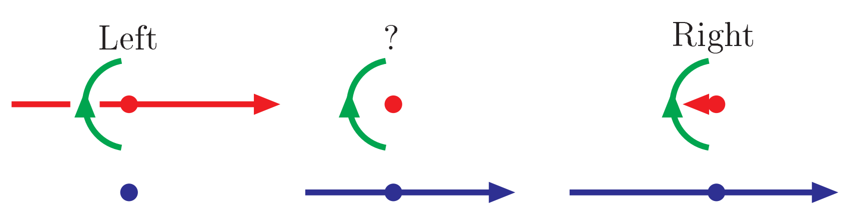
- The left-handed and right-handed fermions are coupled by Higgs boson and get their mass through nonzero VEV.



- Mathematically, the fermion mass term can be expressed as

$$\mathcal{L}_{Yukawa} = f_{ij}\overline{\psi_{Li}}\psi_{Rj}H + H.c.$$

- A thought experiment:
  If a left-handed fermion has mass, we can move fast enough to pass and find a right-handed partner.
  Since we observe no right-handed neutrino $\Rightarrow$ neutrinos are massless in Standard Model.



Fermion Mixing

- We have learnt that:
the mixing among neutrinos are "Bi-LARGE" and only few mass matrix patterns can explain the data.

$$U_{MNS} = \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta+i\phi_2} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12} \sim 33^\circ$,$\theta_{23} \sim 45^\circ$, $\theta_{13} < 13^\circ$; δ, ϕ_1, ϕ_2 are still unknown.

- Compared to the SM quark sector:

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12} \sim 13^\circ$, $\theta_{23} \sim 2^\circ$, $\theta_{13} \sim 0.2^\circ$; $\delta \sim 65^\circ$.

- Puzzles!!

Let's look back.

- Too many elements
  $\Longrightarrow$ Periodic Table
  $\Longrightarrow$ Atoms consist of electrons and nuclei
- Too many isotopes
  $\Longrightarrow$ nuclei is made of protons and neutrons
- Too many hadrons
  $\Longrightarrow$ quarks and $SU(3)_c$
- Too many redundant generations
  $\Longrightarrow$ Preon and Hypercolor??

Preon doesn't work!

In the 1980s, the preon was a very popular research topic. But it doesn't look promising anymore:

- No direct experimental evidence or hints of the existence of substructure of quarks or lepton.
  Contact interaction search at LEP

$$\Longrightarrow \Lambda_p > \text{TeV}$$

- The theory is difficult.
  - Must be another Yang-Mills:
    Which group? Which representation? How to calculate?
  - Why are quarks and leptons so light?
    Natural expectation is mass$\sim \Lambda_p >$ TeV.
    Chiral symmetry is the only known symmetry to protect large mass, no one knows how to make it work here.
  - How to get the SM quantum number?
  - Some generic bad predictions:
    exotic boson, quarks, and leptons..

Other tries.

- Bigger symmetry group?

$$SU(5) \to SU(8)\,,\ SO(10) \to SO(10+4k)\,,\ E6 \to E8$$

  However, familon problem, predicts $K^+ \to pi^+ + f$

- Symmetry, or extra quantum number in the Yukawa sector:
  Structure Zeros, Froggatt-Nielsen, or the hybrid.

- Statistics:
  Anarchy, Landscape..

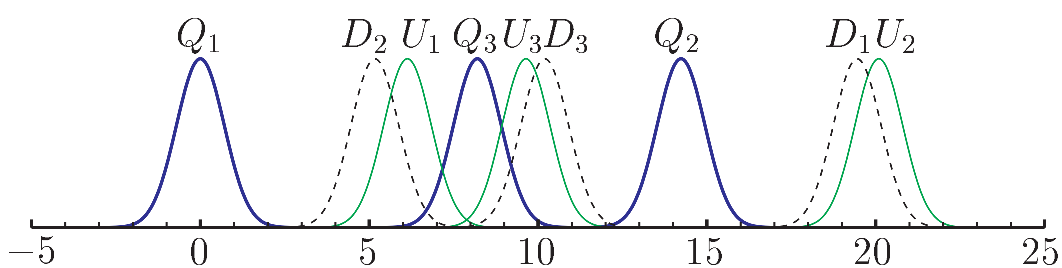
Geometry in extra Dimension?

- 5D fermion localizes at different position, z_i, in extra dimension $y \in [-\pi R, \pi R]$, $\psi_i(x,y) = g(z_i, y)\psi(x)$,

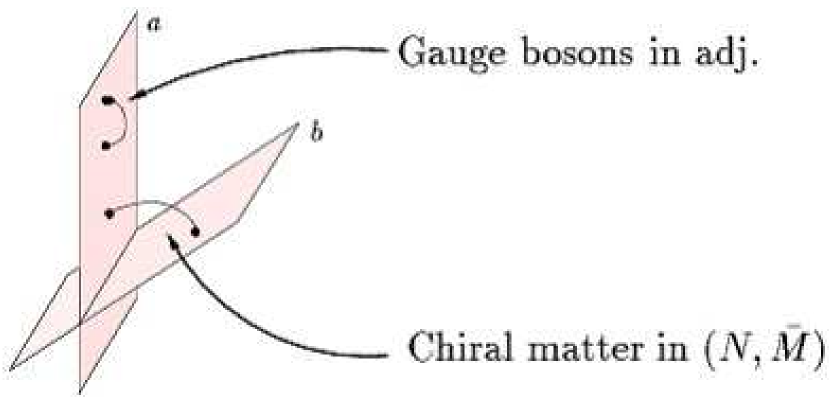
$$g(z_i, y) = \frac{1}{(\pi\sigma^2)^{1/4}} \exp\left[-\frac{(y-z_i)^2}{2\sigma^2}\right]$$

$$g(z_1, y)g(z_2, y) = \exp\left[-\frac{(z_1-z_2)^2}{4\sigma^2}\right] g\left(\frac{z_1+z_2}{2}, y\right)$$

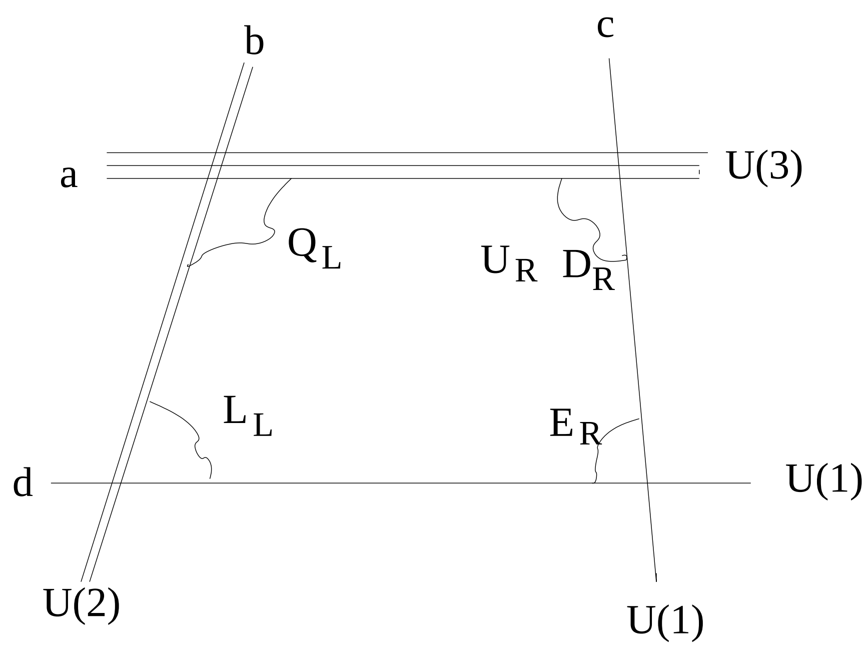
- Exponential Yukawa hierarchy becomes linear displacement between left-handed and right-handed fermions in the fifth dimension.
- The following map can reproduce all quarks' masses and CKM mixings



Intersecting brane?



It may provide a topological reason why we have 3 generations.




NO ADULTS
ALLOWED UNLESS
ACCOMPANIED
BY CHILDREN
CPC 653G