Magnetism the Big picture

J. M. D. Coey

Trinity College Dublin

I. Science rules the Earth - OK?

II. The end of an aether

III. What the ancients knew

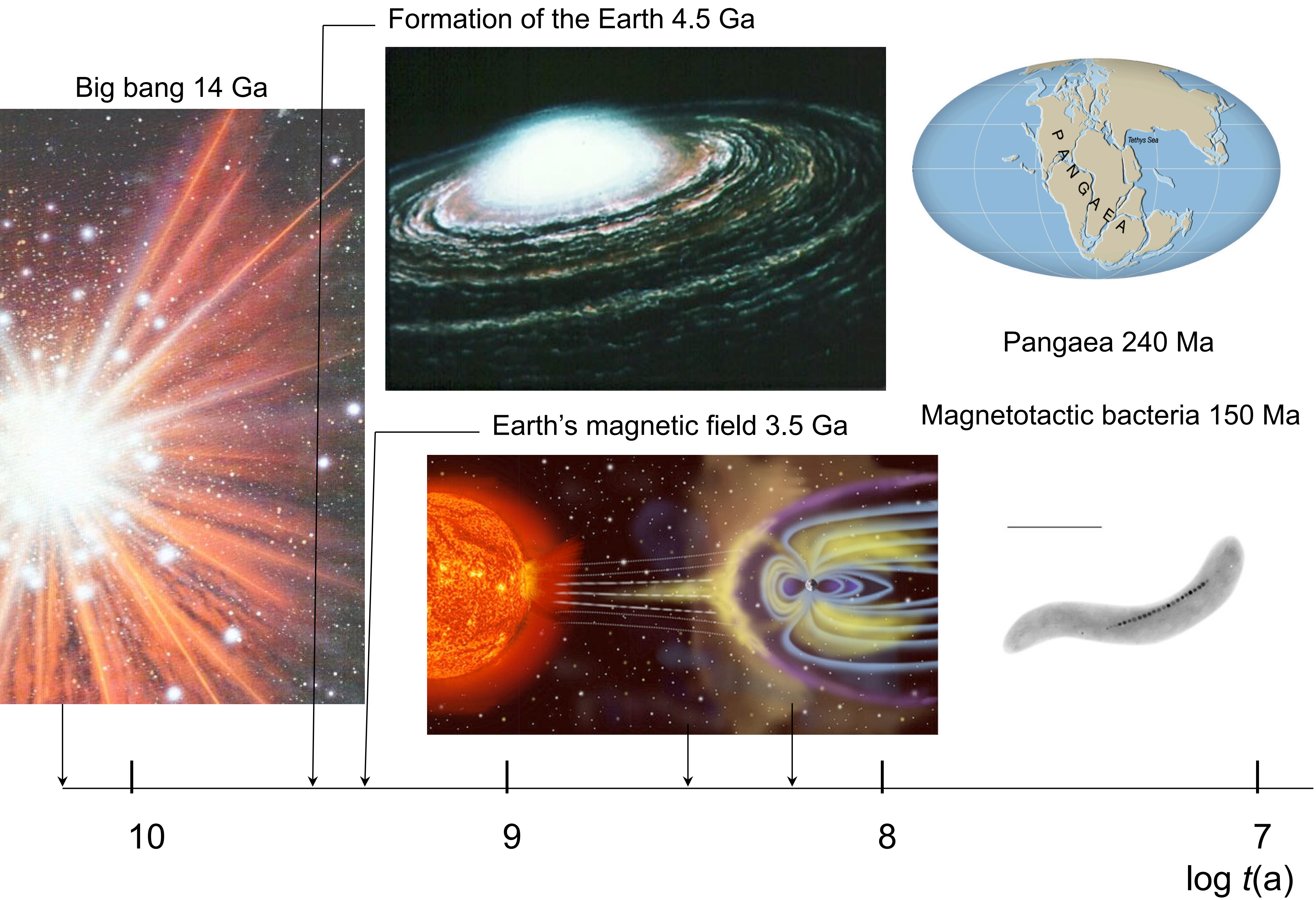
IV. Billions of magnets for billions of people

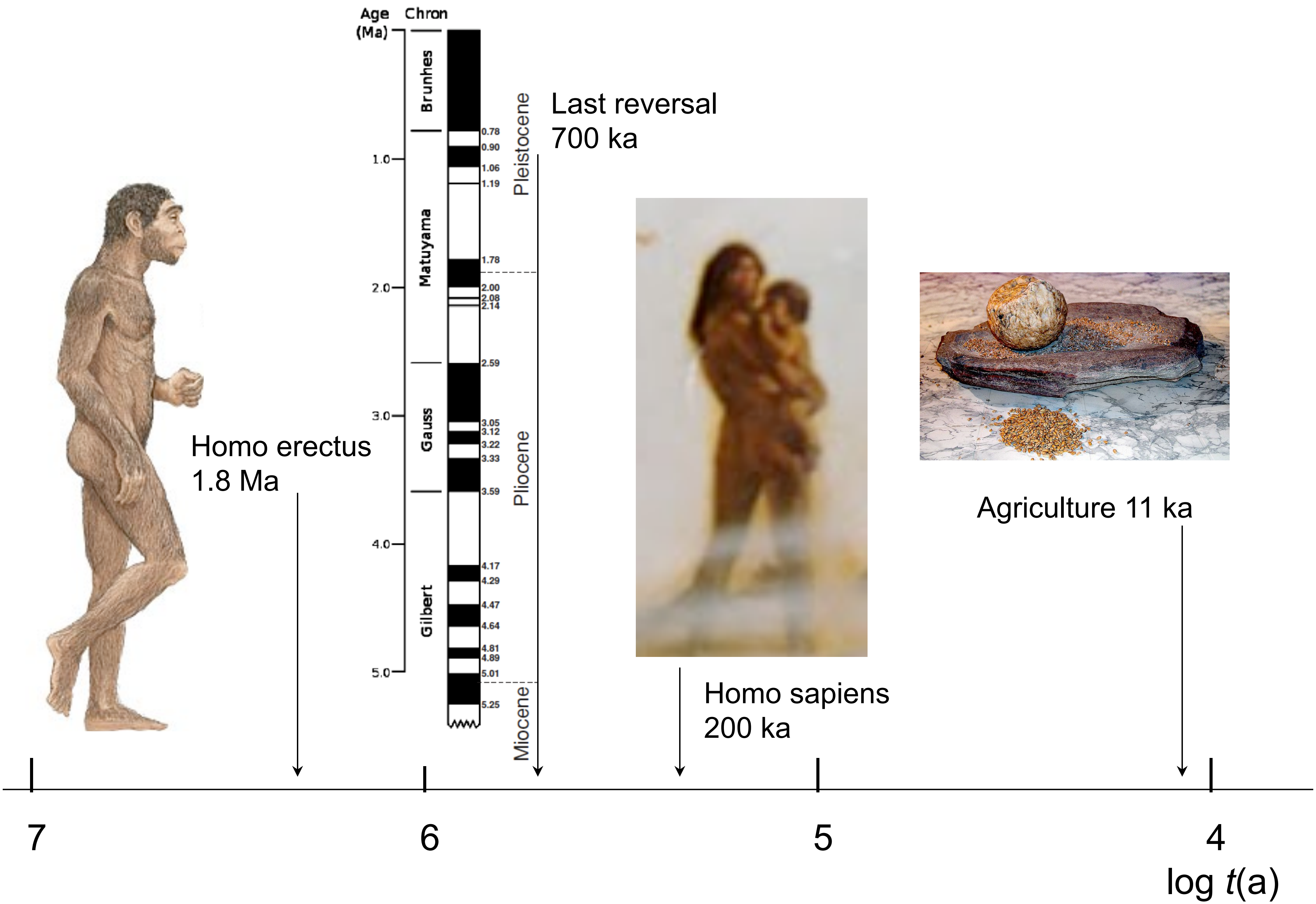
www.tcd.ie/Physics/Magnetism

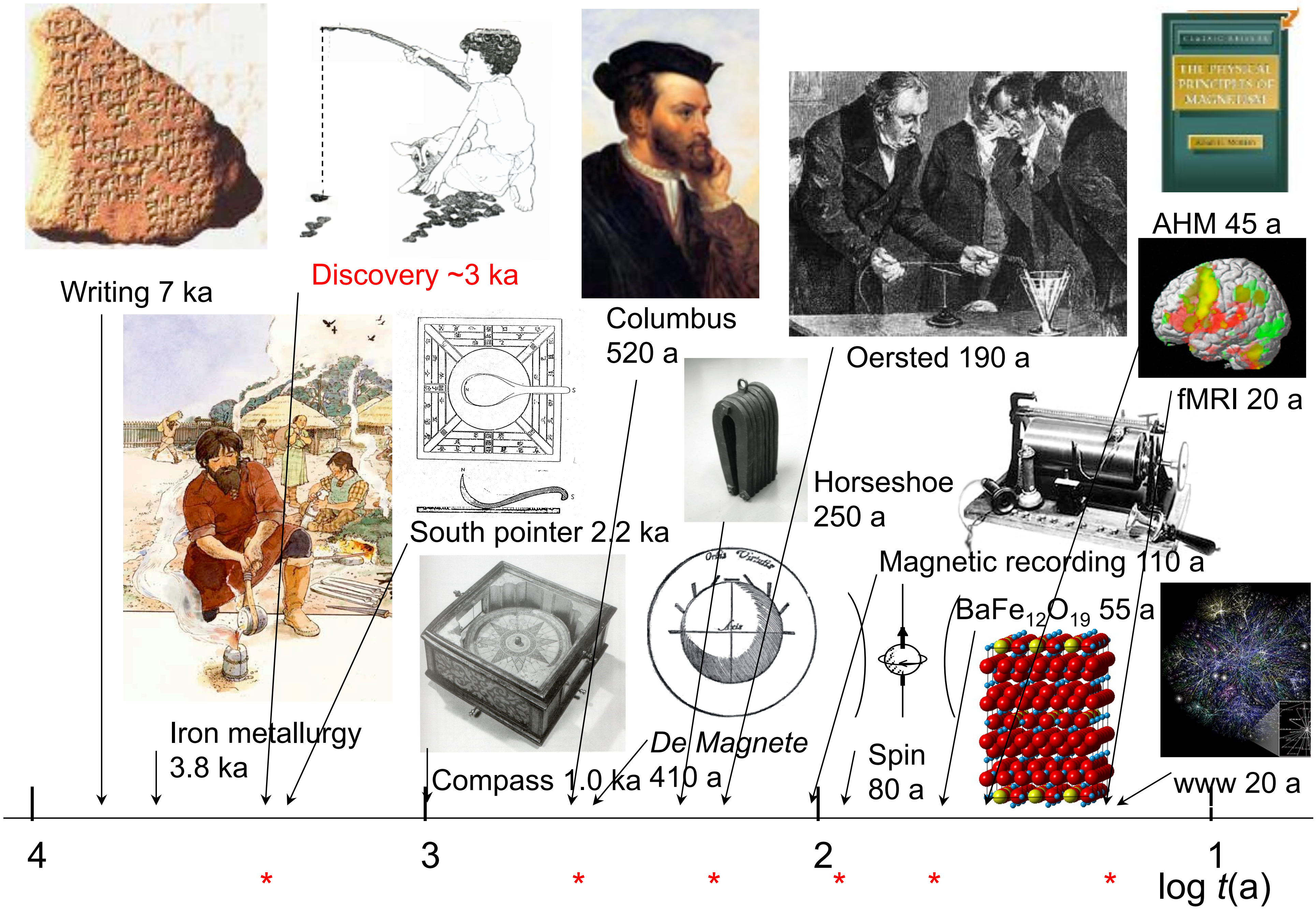
The first 3.5 Ga.

1	1	one	x
10	10	ten	
10^2	100	hundred	
10^3	1000	thousand	kx kilo
10^4	10000	ten thousand	
10^5	100000	hundred thousand	
10^6	1000000	million	Mx mega
10^7	10000000	ten million	
10^8	100000000	hundred million	
10^9	1000000000	billion	Gx giga
10^{10}	10000000000	ten billion	

1	1	one	x
10^{-1}	0.1	tenth	
10^{-2}	0.01	hundredth	
10^{-3}	0.001	thousandth	mx milli
10^{-4}	0.0001	ten thousand	
10^{-5}	0.00001	hundred thousand	
10^{-6}	0.000001	millionth	μx micro
10^{-7}	0.0000001	ten millionth	
10^{-8}	0.00000001	hundred millionth	
10^{-9}	0.000000001	billionth	nx nano
10^{-10}	0.0000000001	ten billionth	


Formation of the Earth 4.5 Ga
Big bang 14 Ga
PANGAEA
Tethys Sea
Pangaea 240 Ma
Earth's magnetic field 3.5 Ga
Magnetotactic bacteria 150 Ma
10
9
8
7
log t(a)


Age (Ma)
Chron
Brunhes
Matuyama
Gauss
Gilbert
1.0
2.0
3.0
4.0
5.0
0.78
0.90
1.06
1.19
1.78
2.00
2.08
2.14
2.59
3.05
3.12
3.22
3.33
3.59
4.17
4.29
4.47
4.64
4.81
4.89
5.01
5.25
Pleistocene
Pliocene
Miocene
Last reversal
700 ka
Homo erectus
1.8 Ma
Homo sapiens
200 ka
Agriculture 11 ka
7
6
5
4
log t(a)



Writing 7 ka
Discovery ~3 ka
Columbus
520 a
Oersted 190 a
AHM 45 a
fMRI 20 a
Iron metallurgy
3.8 ka
South pointer 2.2 ka
Horseshoe
250 a
Magnetic recording 110 a
$BaFe_{12}O_{19}$ 55 a
Compass 1.0 ka
De Magnete
410 a
Spin
80 a
www 20 a
4
3
2
1
*
*
*
*
*
*
log t(a)

3. The end of an aether

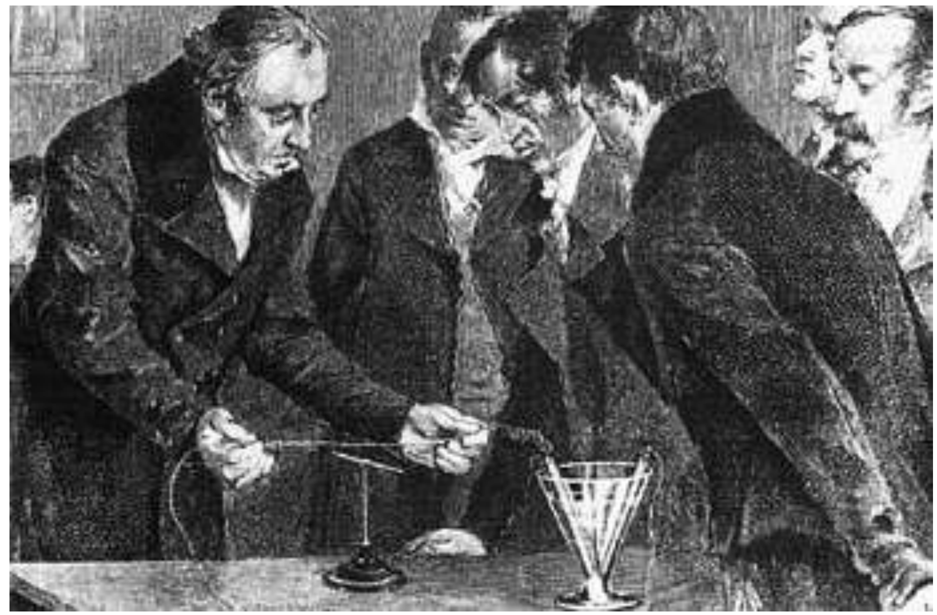
- *De Magnete* The first scientific text
- The Earth's magnetic field
- Gauss's *Magnetverein*
- Chaos - It reverses !
- The Earth moves.

3. *The end of an aether.*

The modern world began in 1820, when Hans-Christian Oersted stumbled on the connection between electricity and magnetism. The news spread like wildfire across Europe as electromagnetism spawned motors and generators, electric trains and mains power, telegraphs, radio and magnetic recording — all before 1900. If Maxwell's equations were the greatest intellectual achievement of the century, the origin of magnetism was one of its greatest puzzles — a puzzle that could only be understood with relativity, quantum mechanics and Dirac's electrons with spin.

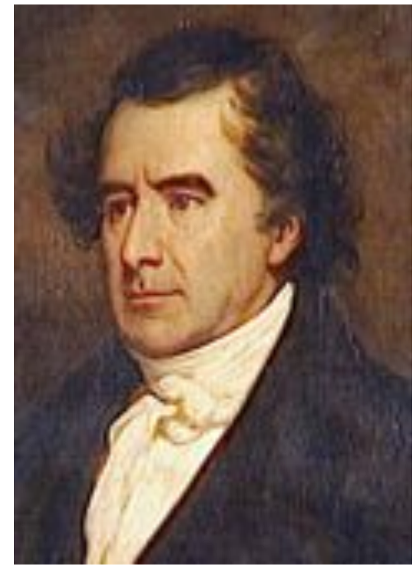
3. Electricity and magnetism united

The electromagnetic revolution; 1820 to 1905

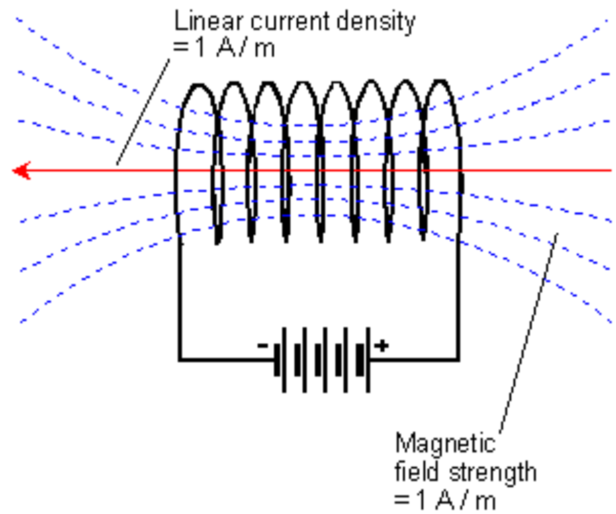


Oersted's famous experiment showed that a current-carrying conductor created a field everywhere *perpendicular* to the wire

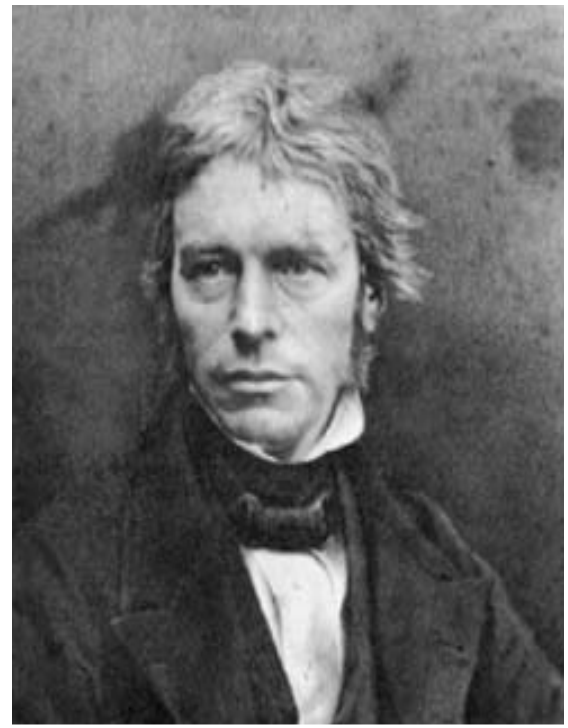
Within a week of the news reaching Paris, Ampère and Arago showed that a current acts as a magnet, especially when wound into a solenoid. Ampère measured the force between conductors, and proposed that huge internal electric currents were responsible for the magnetism of iron.



Laplace
Poisson
Fresnel
Fourier
Biot
Savart



It was a field day for experimentalists. The most intuitive and talented of all was Michael Faraday, who made a simple motor, discovered electromagnetic induction in 1831 and found a connection between magnetism and light.



Faraday’s electromagnet

1820 Oersted discovers the magnetic effect of electric currents
1821 Ampere attributes the magnetism of matter to ‘molecular’ currents
1821 Faraday builds a primitive electric motor
1825 Sturgeon invents the first pracical electromagnet
1831 Faraday discovers electromagnetic induction
1833 Gauss and Weber build a telegraph more than 1 km long, with a galvanometer as the receiver
1845 Faraday discovers paramagnetism and diamagnetism
1847 Helmholtz states the conservation of energy in a general form
1858 The first transatlantic telegraph cable
1864-73 Maxwell formulates the theory of electromagnetism
1869 Gramme invents a practical dynamo
1879 Swan invents a practical incandescent bulb
1881 First public electric railway in Berlin
1882 First hydroelectric power station
1887 Hertz generates and detects radio waves
1887 Michelson and Morely fail to detect the motion of the aether
1888 Tesla invents a practical AC motor
1890 Ewing describes hysteresis
1895 Curie describes the temperature variation of paramagnetic susceptibility
1896 Marconi patents the radio; transmits radio signals across the Atlantic in 1901
1898 Valdemar Poulson invents magnetic recording

Maxwell's equations

$$\boxed{\begin{aligned} \nabla \cdot \boldsymbol{H} &= 0 \\ \varepsilon_0 \nabla \cdot \boldsymbol{E} &= \rho \\ \nabla \times \boldsymbol{H} &= \boldsymbol{j} + \varepsilon_0 \partial \boldsymbol{E}/\partial t \\ \nabla \times \boldsymbol{E} &= - \mu_0 \partial \boldsymbol{H}/\partial t \end{aligned}}$$

From a long view of the history of mankind, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. Richard Feynmann

Written in terms of two fields $\boldsymbol{H}$ (A m^{-1}) and $\boldsymbol{E}$ (V m^{-1}), they are valid in free space.

They relate these fields to the charge density ρ (C m^{-3}) and the current density $\boldsymbol{j}$ (A m^{-2}) at a point.

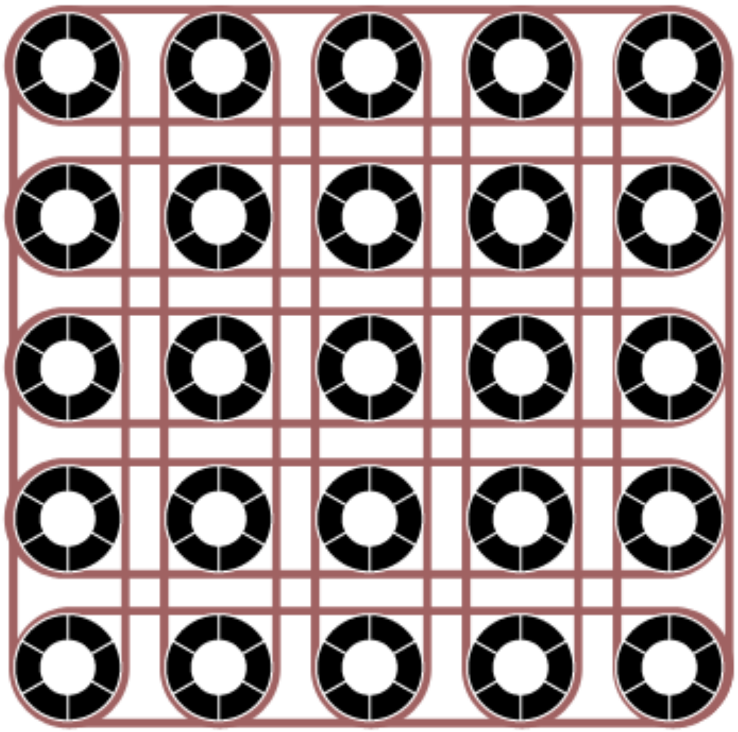
$c = \boxed{(\varepsilon_0 \mu_0)^{1/2}}$ $\quad$ $c = 2.998\ 10^8$ m s^{-1} $\quad$ $c = \lambda\nu$

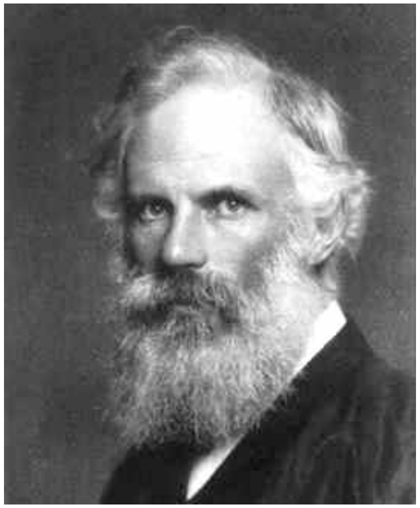
Also, the force on a moving charge q, velocity **v**

$$\boldsymbol{F} = \boxed{q(\boldsymbol{E} + \mu_0 \boldsymbol{v} \times \boldsymbol{H})}$$

In the 19th century, everyone was convinced that electromagnetic waves traveled in the aether, at the speed of light.

Mechanical models were built, to demonstrate how the equations actually worked, for specific cases.

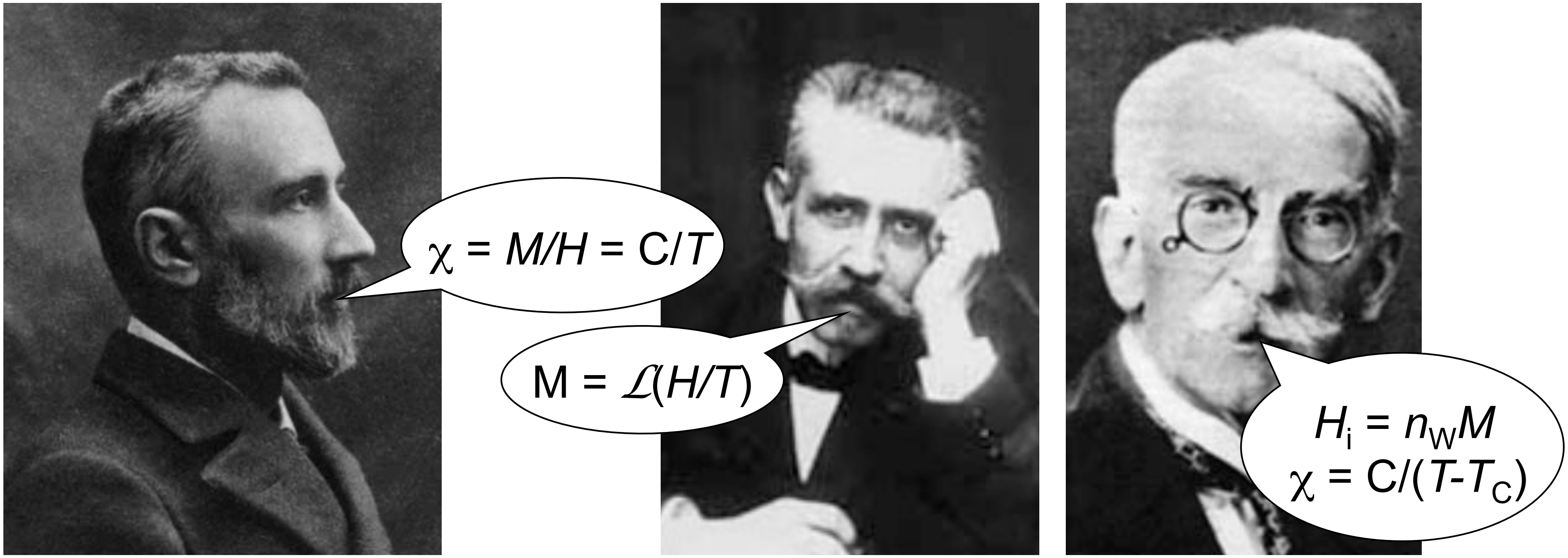




George FitzGerald’s model represented a magnetic field by vortices

Belief in the aether was shaken by the failure of the Michelson-Morley experiment in 1887 to detect the movement of the earth through the luminiferous ether.


Tylers
BOOTS



Pierre Curie

Paul Langevin

Pierre Weiss

The magnetization of iron is 1.7 MA m^{-1}
Why does it not melt ?

The Curie temperature of iron is 1044 K so H_i must be ≈ 1000 MA m^{-1} but $\nabla.\boldsymbol{B} = 0$ means that $B_\perp$ is continuous at the surface. H_{out} ≈ 1 MA m^{-1}

By 1900, the focus in physics had shifted to the structure of matter. The idea that electricity is carried by tiny negatively charged particles, the *electrons*, was firmly established following the work of Jean Perrin and J J Thompson.

A planetary model of the atom – mostly empty space – was emerging. It was natural to associate magnetism with circulating electron currents.

G F Fitzgerald had even suggested in 1890 that magnetism could be associated with angular momentum of electrons

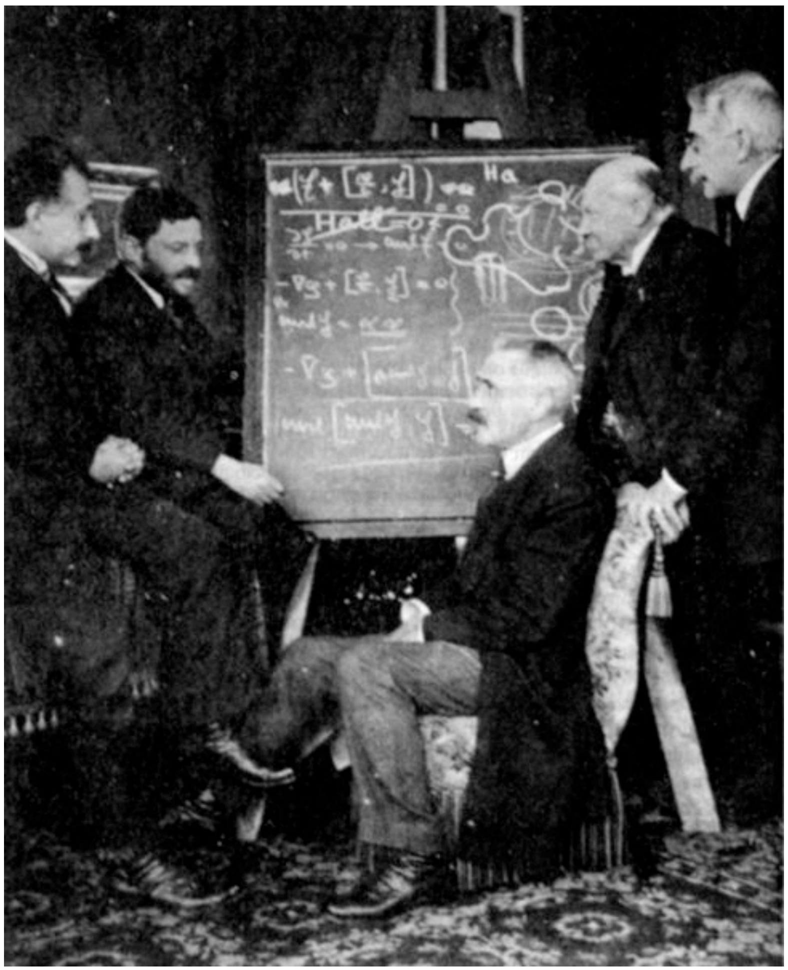
BUT

Bohr and van Leeuwen proved a theorem in classical statistical mechanics which states that *at any finite temperature and in all finite electric or magnetic fields, the net magnetization of a collection of electrons in thermal equilibrium vanishes identically*. Every sort of magnetism is impossible for electrons in classical physics!

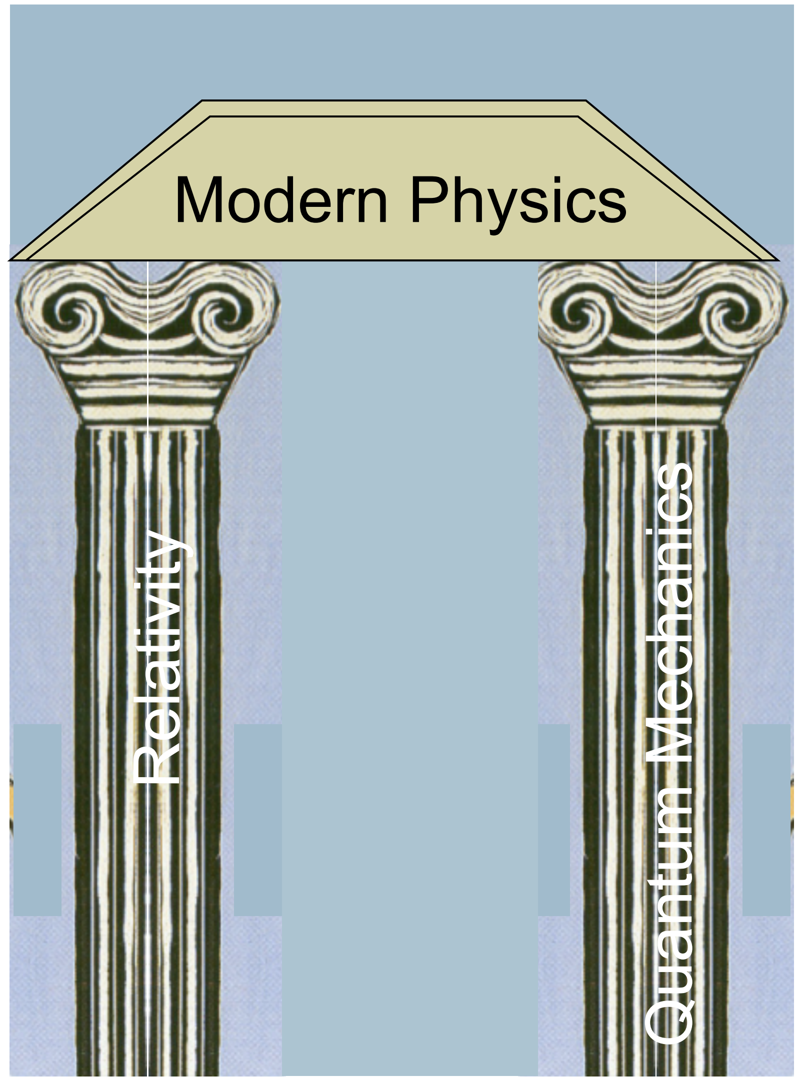
IMPASSE

4. Magnetism understood !

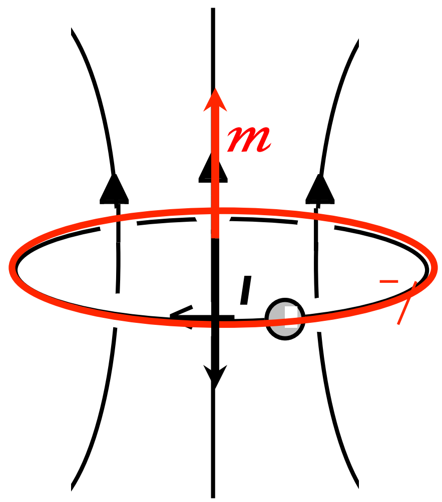
The revolution of 1905 to 1935



Einstein Ehrenfest Langevin Onnes Weiss



According to the quantum theory of Bohr, the orbital angular momentum of the electron is *quantized* in a set of stationary states.



Orbital moment

Ampère: $\boldsymbol{m} = I\mathcal{A} = (ev/2\pi r)\,\pi r^2 = evr/2$

Bohr: $m_e vr = \ell\hbar$

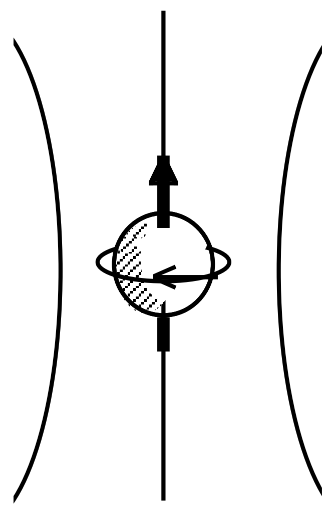
Planck's constant

quantum number

$$\boxed{\boldsymbol{m} = \ell(e\hbar/2m_e)}$$

Bohr magneton μ_B

Goudschmidt and Uhlenbeck discovered in 192x that the electron possesses an *intrinsic* angular momentum of $\hbar/2$, its spin, s.
It has an intrinsic magnetic moment of one Bohr magneton.

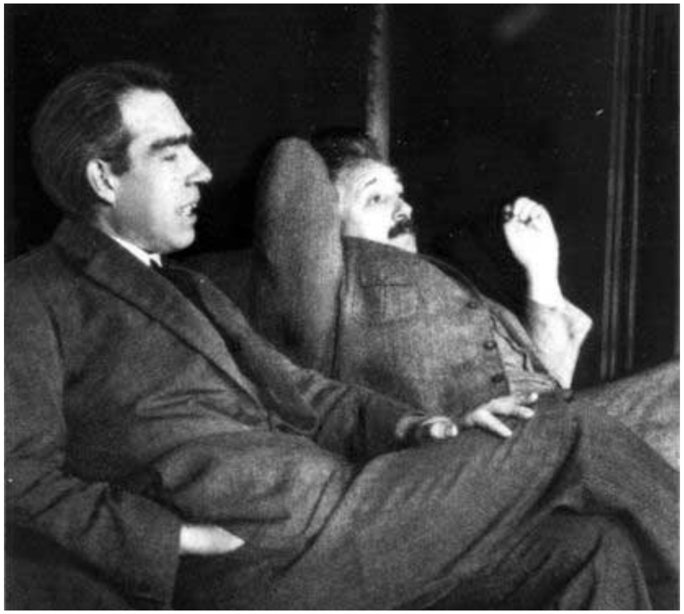


Spin

In a theoretical tour de force in 1927, Dirac deduced the spin of the electron, and its magnetic moment from a relativistically-invariant formulation of Schrodinger's equation $\mathscr{H}\psi = E\psi$

Heisenberg showed that the interaction between electron spins which is responsible for ferromagnetism, represented by the Weiss field, was just due to the Coulomb repulsion between electrons, subject to the quantum-mechanical constraints of the Pauli principle.

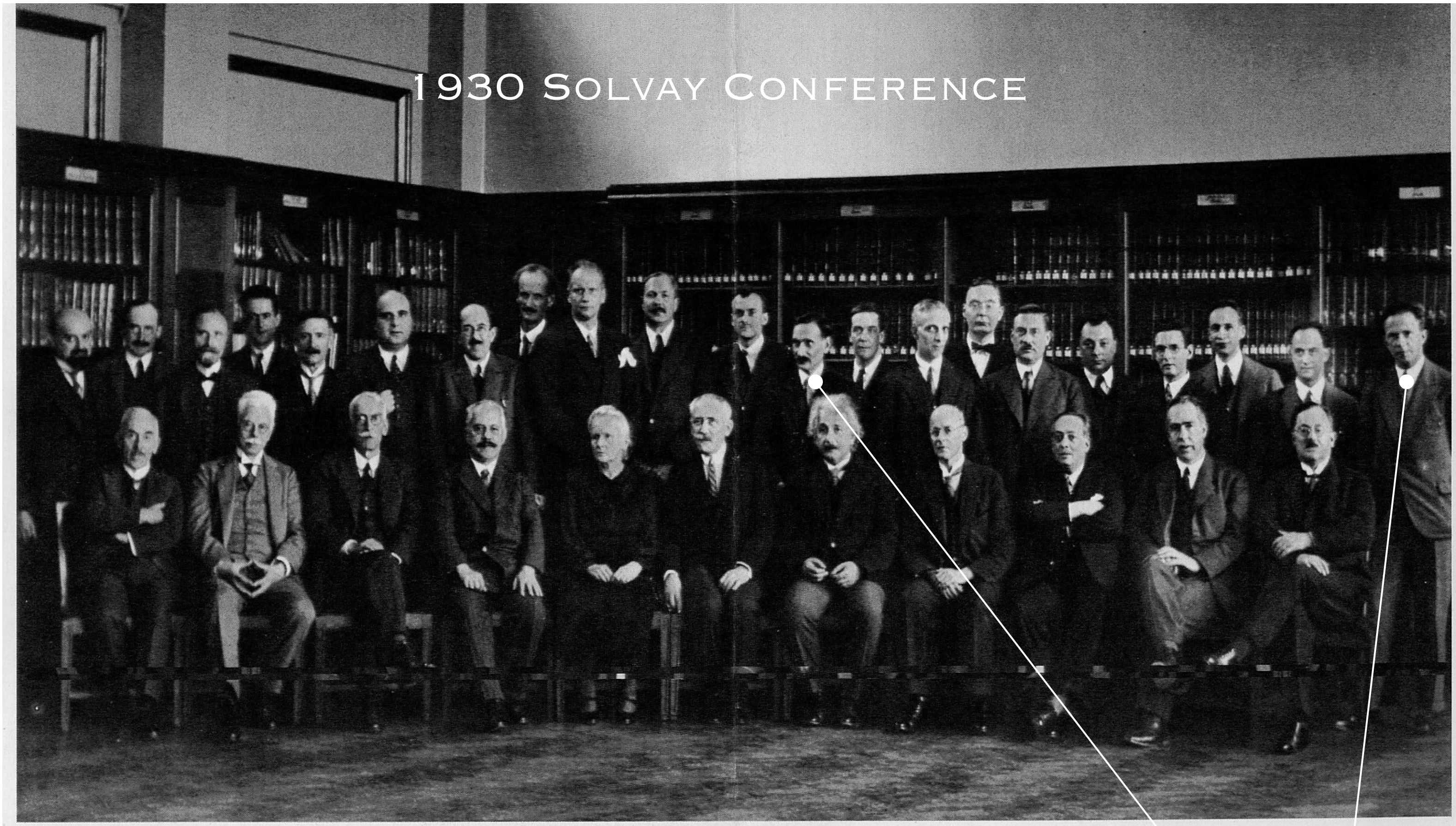
$$\mathscr{H} = -2J\mathbf{s}_i\mathbf{s}_j$$



Bohr
Einstein

Heissenberg
Dirac

The 1930 Solvay conference consecrated our physical understanding of magnetism in terms of quantum mechanics (exchange) and relativity (spin)



Dirac Heisenberg

At this point it seems that the whole of chemistry and much of physics is understood in principle. The problem is that the equations are much to difficult to solve….. P.A. M. Dirac