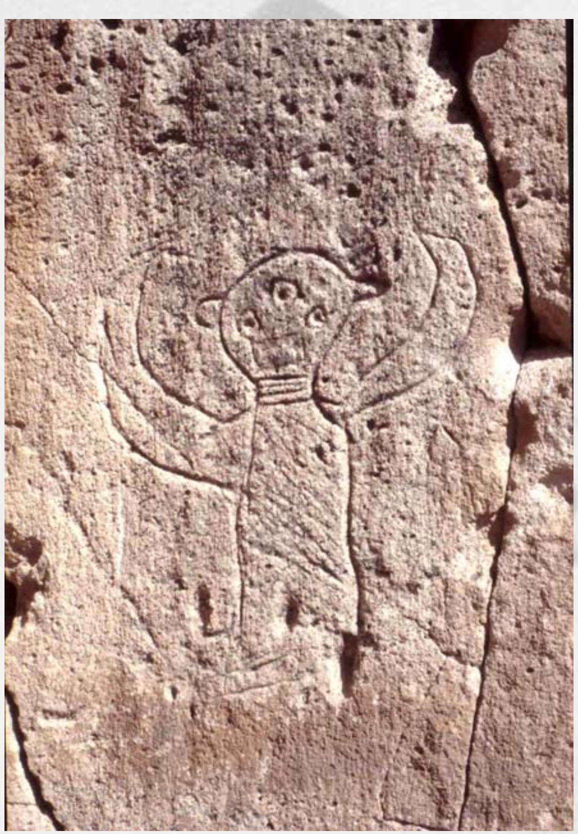
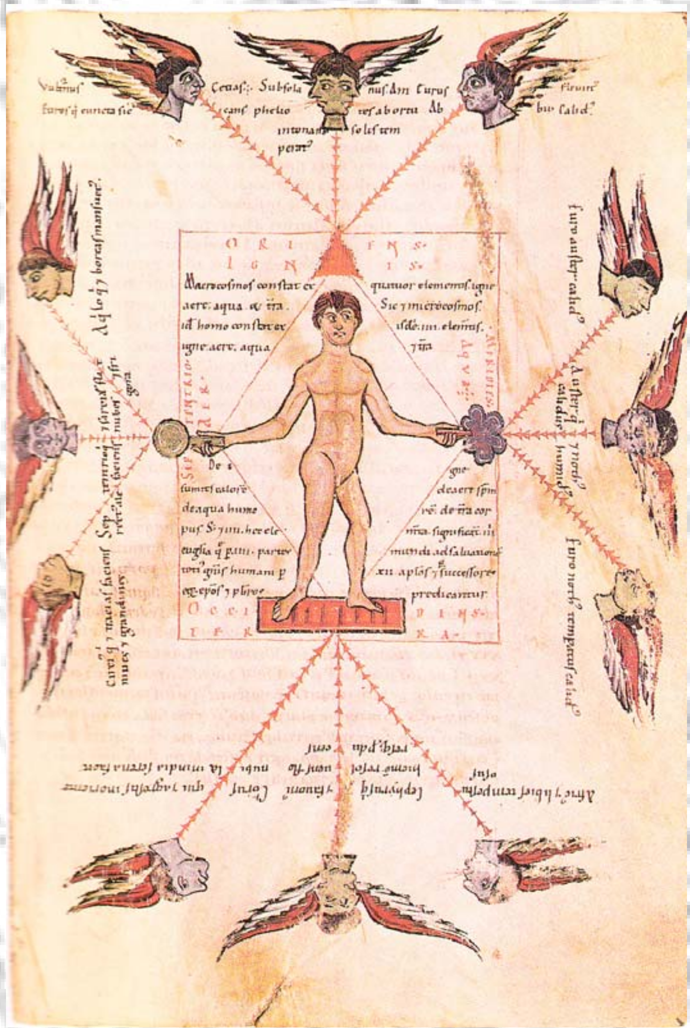
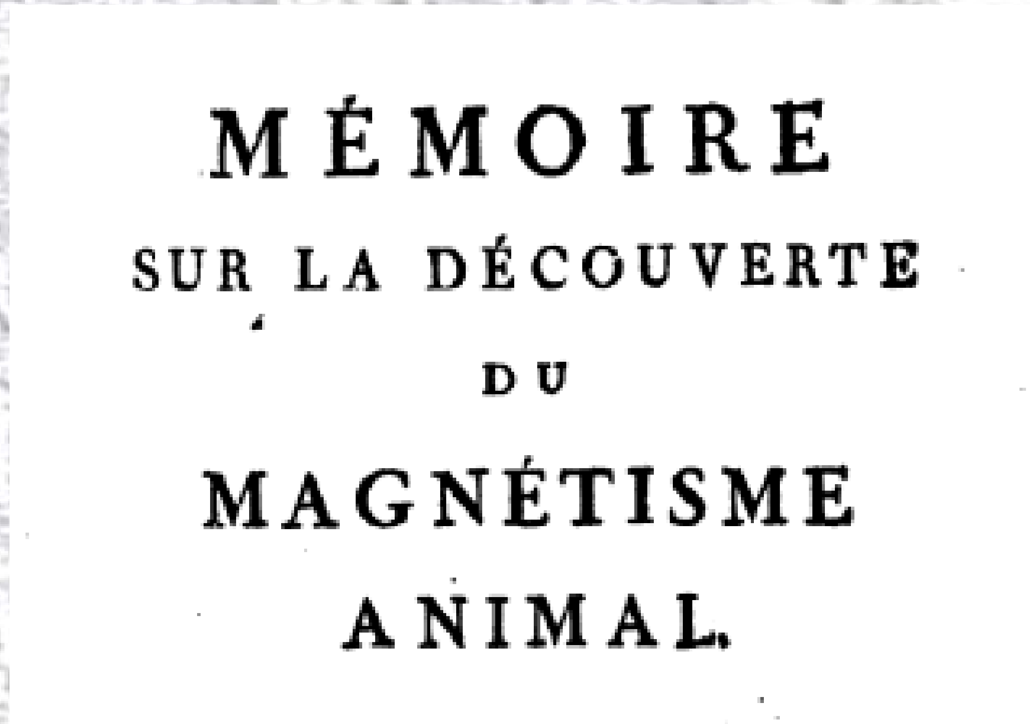
# Magnetism was never easy



# In the „beginning“, in the 18th century, „magnetism“ was still pure occultism




Franz Anton Mesmer
1734 - 1815


MÉMOIRE
SUR LA DÉCOUVERTE
DU
MAGNÉTISME
ANIMAL.

**1779**

*Antonii Mesmer, Dissertatio physico-medica de planetarum influxu*, Dissertation, Vienna 1766

**Only as an aftermath of the French encyclopedists and the French re-volution a new rationalism caused chemistry and physics to become „sciences".**

***July 14, 1789***

**The first scientific experiments in magnetism started around 1825, being part of what was then called *experimental philosophy*.**

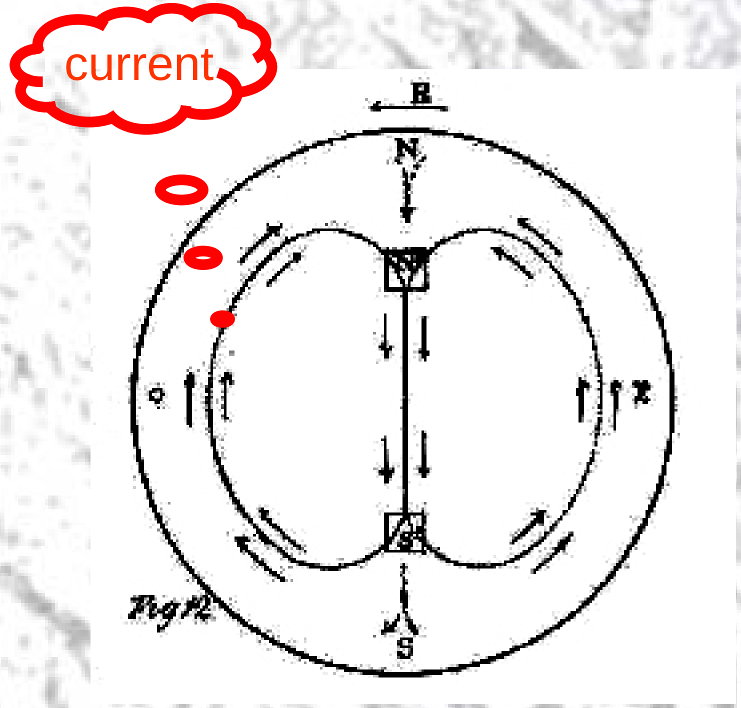
# High temperature studies

***"It was to me a point of great interest to ascertain whether, and at what temperature, cobalt would lose this power and become as the unmagnetic metals. To my surprise I found this to be very high, not merely much higher than with nickel, but far above that required for iron or steel, and nearly approaching the temperature of melted copper. That for iron is a moderate red heat, and that for nickel the temperature of boiling oil only. As the temperature rises, the magnetic force of the cobalt continues, apparently undiminished, to a certain degree of heat, and then suddenly ceases; and it comes on as suddenly in descending from still higher temperatures.***

***... it appears that only iron, nickel and cobalt are magnetic, or can be made  magnetic amongst metals ... and that it is only a difference of temperature which distinguishes these three from the rest, just as it also in a similar respect distinguishes them from each other".***

***Michael Faraday, 1845***

# Electro-magnetic induction

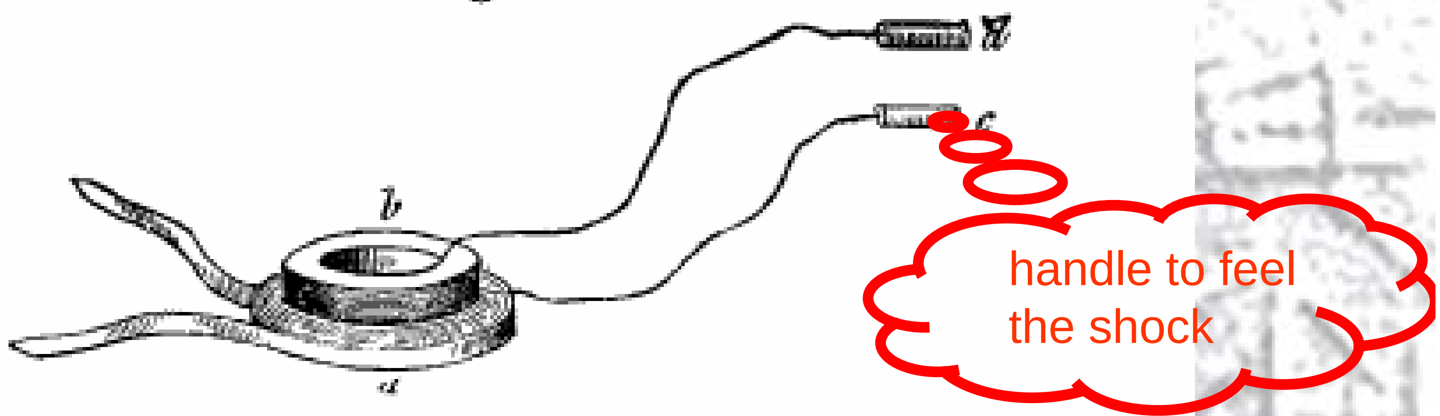



Rotating metal disk

*"If figure 12 be examined, it will be instantly seen that it results in the most simple manner from the action of the two poles. Thus, as far as the upper or north pole only is concerned, the currents are as in figure 6. But as with the north pole, the current de-termined by it moves from the circum-ference towards the centre, so with the south pole, in the same or cor-responding position, the currents move from the centre to the circumference; and consequently in fig. 12 they are continued along the diameter N, S, through the centre of the plate, to return in the direction of the arrows upon the sides E, O".*

*Michael Faraday, 1840*

Fig. 3.




*a* represents coil No. 1, *b* helix No. 1, and *c*, *d*, handles for receiving the shock.

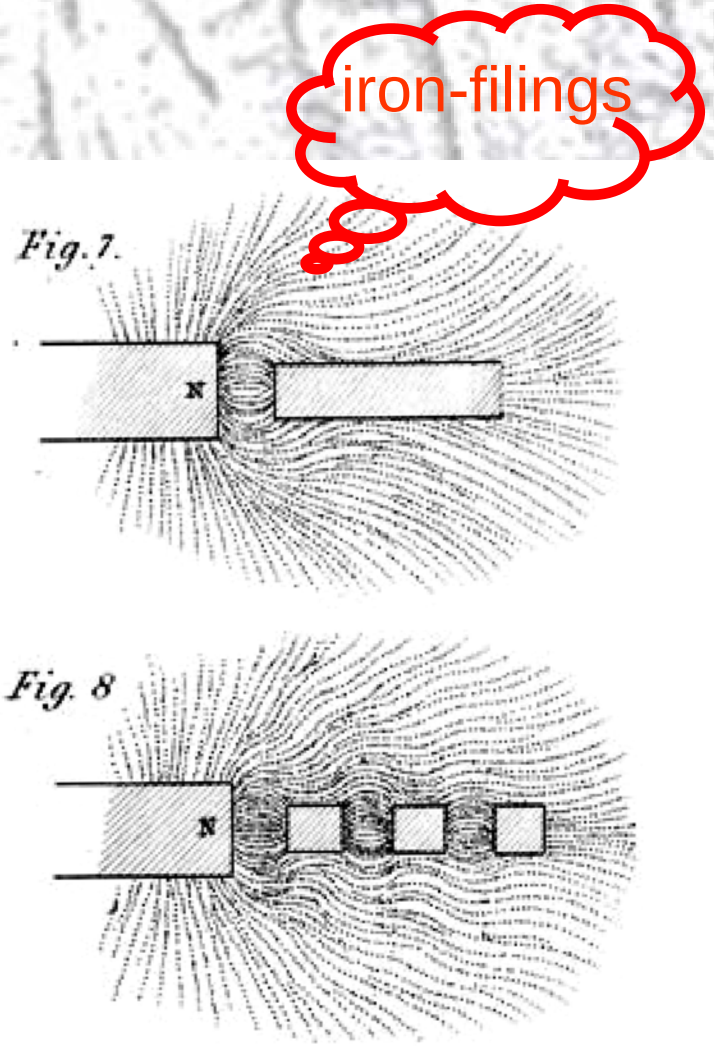
This arrangement being made, currents of increasing intensity were passed through the coil by constantly retaining one of its ends in the cup of mercury forming one extremity of the battery, and successively plunging the other end into the cups which served to form the connexions of the several elements of the battery. With the current from one element, the shock at breaking the circuit was quite severe; but at making the same it was very feeble, and could be perceived in the fingers only or through the tongue.

***Joseph Henry, 1841***

Michael Faraday
1791 - 1867

Joseph Henry
1797 - 1878

# Lines of magnetic force




***"If we take a large bar-magnet, and place a piece of soft iron, about half the width of the magnet, and three or four times as long as it is wide, end on to, and about its own width from one pole, and covering that with paper, then observe the forms of the lines of force by iron-filings; it will be seen how beautifully those issuing from the magnet converge, by fine inflections, on to the iron, entering by a comparatively small surface, and how they pass out in far more diffuse streams by a much larger surface at the further part of the bar, fig. 7. If we take several pieces of iron, cubes for instance, then the lines of force, which are altogether outside of them, may be seen undergoing successive undulations in contrary directions, fig. 8".***

***Michael Faraday, 1855***

# James Clerk Maxwell
# 1831 - 1879

XLIV. *On Physical Lines of Force.* *By* J. C. Maxwell, *Professor of Natural Philosophy in King's College, London*†.

[With a Plate.]

Part II.—*The Theory of Molecular Vortices applied to Electric Currents.*

**Philosophical Magazine Series 4 21, 161 (1861)**

The Maxwell-Faraday equation (Faraday's law of induction) is of the form

$$\nabla \times E = -\frac{\partial B}{\partial t} ,$$

where $E$ is the electric field, $B$ the magnetic field, and $t$ the time.

By the end of the 19th century physics was considered to be „complete“. Nothing „new“ was expected, since

- mechanics & the concept of motions (Newton)
- astronomy (*Mechanique Celeste*, Laplace)
- electro-magnetism (Faraday, Henry, Maxwell)
- thermodynamics („the concept of heat“; Joule, Clausius, Helmholtz, Gibbs, Maxwell, Boltzmann)
- hydrodynamics (Poisson, Challis, Stokes, Navier)

had been solved satisfactorily mostly in the spirit of 19th century French mathematics (Lagrange, Laplace, Legendre, Poisson, etc.), namely in terms of differential equations and distribution functions.

# The „missing link“:

**In terms of macroscopic magnetism only one connection was missing, namely that to thermodynamics, i.e., the Landau-Lifshitz-(Gilbert) equation, 1935, was a kind of late-comer:**

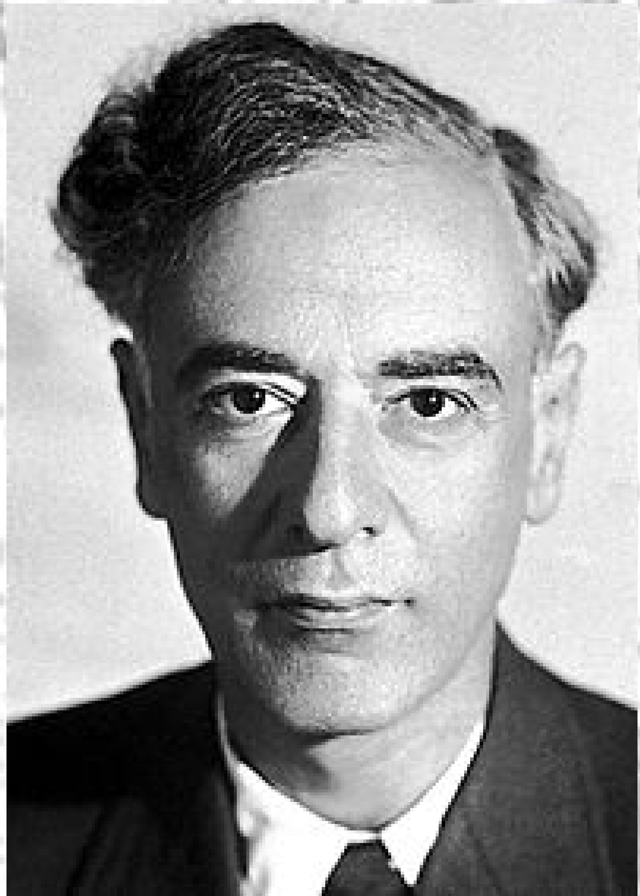
$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}^{\mathrm{eff}} + \alpha \frac{\vec{M}}{M_0} \times \left( \vec{M} \times \vec{H}^{\mathrm{eff}} \right) ,$$

$$\vec{M} = \frac{1}{N} \sum_{i=1}^{N} \vec{M}_i ,$$

$$\vec{H}^{\mathrm{eff}} = -\frac{\partial \mathcal{F}}{\partial \vec{M}} = -\nabla_{\vec{M}} \mathcal{F} ,$$

*F* is the **Helmhotz internal (free) energy**

**The LLG definitely is nowadays the hobby-horse of micro-magnetics and of a variety of „macro-spin“ models.**

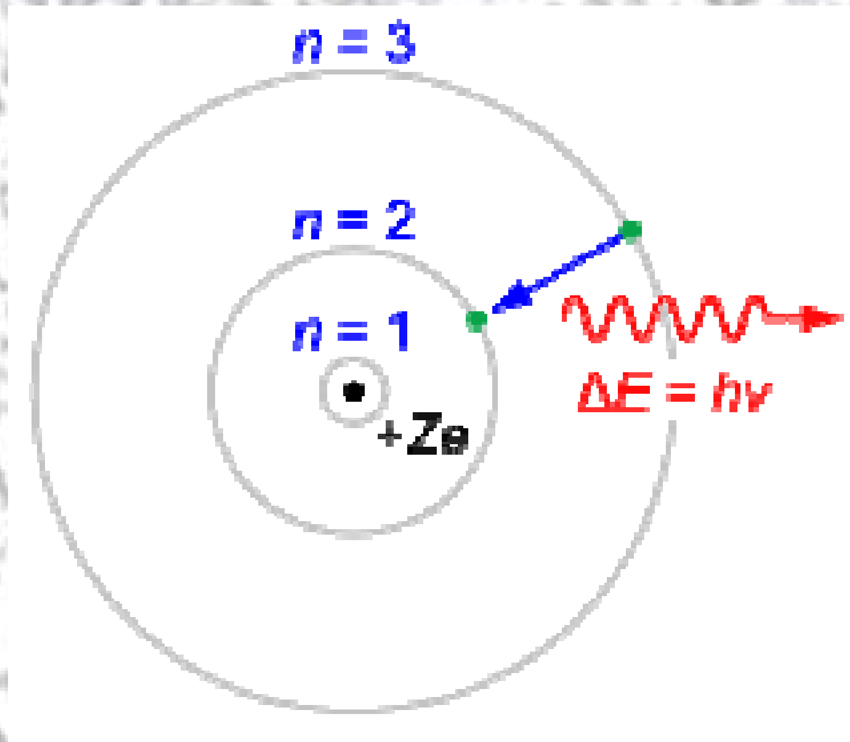


**Lev Davidovich Landau**
**1908 - 1968**

**Evgeny Mikhailovich Lifshitz**
**1915 - 1985**

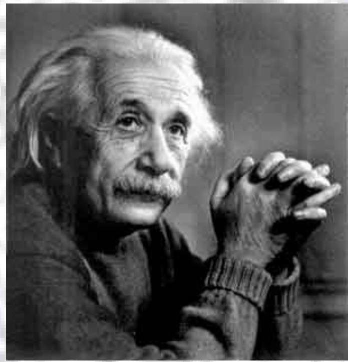
**As is sufficiently well-known, new conceptual difficulties arose at the turn of the 19th to the 20th century: the misery of not being able to interprete line spectra satisfactorily.**

**Niels Bohr**
**1885 - 1962**




**Bohr‘s atomic model, 1913**

# a few years earlier



**Although Maxwell had already connected „light“ with electric fields, it was the speed of light that suddenly seemed to bridge the gap between „light“ and the concept of mass:**

**In 1905 Albert Einstein published a mass-light relation,**

$$E = mc^2$$

**(„theory of special relativity“), which quickly seemed to put physics in a completely new context. And puzzled many.**

# The birth of Quantum Mechanics
# 1922 - 1926

XXXV. *A Tentative Theory of Light Quanta.*
*By* LOUIS DE BROGLIE *.

I. *The Light Quantum.*

THE experimental evidence accumulated in recent years seems to be quite conclusive in favour of the actual reality of light quanta. The photoelectric effect, which is the chief mechanism of energy exchange between radiation and matter, seems with increasing probability to be always governed by Einstein's photoelectric law. Experiments on the photographic actions, the recent results of A. H. Compton on the change in wave-length of scattered X-rays, would be very difficult to explain without using the notion of the light quantum.

**Phil. Mag. <u>47</u>, 446 (1924)**

**Louis de Broglie**
**1892 - 1987**

Erwin Schrödinger
1887 - 1981

Immerhin seien zu der Schwingungsvorstellung hier noch einige Bemerkungen erlaubt. Vor allem möchte ich nicht unerwähnt lassen, daß ich die Anregung zu diesen Überlegungen in erster Linie den geistvollen Thèses des Hrn. Louis de Broglie[1]) verdanke und dem Nachdenken über die räumliche Verteilung jener „Phasenwellen", von denen er gezeigt hat, daß ihrer stets eine *ganze Zahl*, entlang der Bahn gemessen, auf jede Periode oder Quasiperiode des Elektrons entfallen.

Es mag Bedenken erregen, daß diese Schlüsse sich auf die Beziehung (22) in ihrer *näherungsweisen* Gestalt (nach Entwicklung der Quadratwurzel) gründen, wodurch die Bohrsche Frequenzbedingung selbst scheinbar den Charakter einer Näherungsformel erhält. Das ist aber nur scheinbar und wird völlig vermieden, wenn man die *relativistische* Theorie entwickelt, durch welche überhaupt erst ein tieferes Verständnis vermittelt wird. Die große additive Konstante $C$ hängt natürlich aufs innigste zusammen mit der Ruhenergie $mc^2$ des Elektrons.

From Schrödinger's first paper, Ann, Phys. **79**, 361 (1926)

**At the same time another experiment added to the confusion*) and made magnetism even less easy to under-stand.**

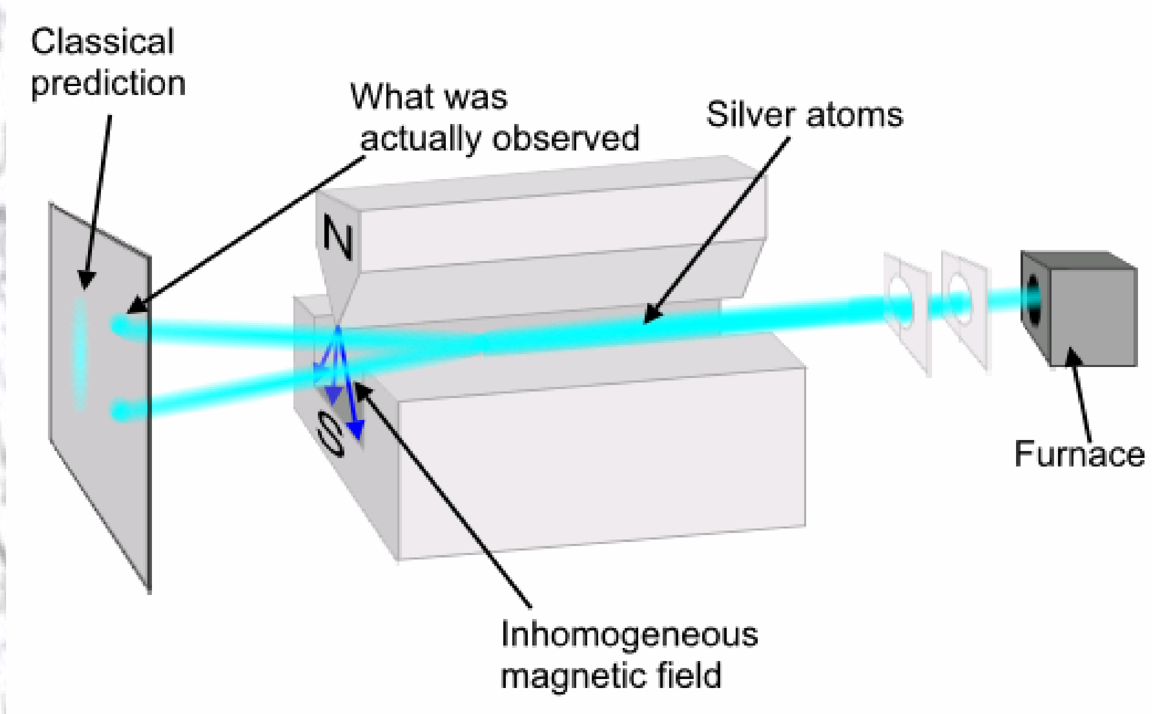
***„… although he was a theoretician, he constantly hung around with the experimentalists“***

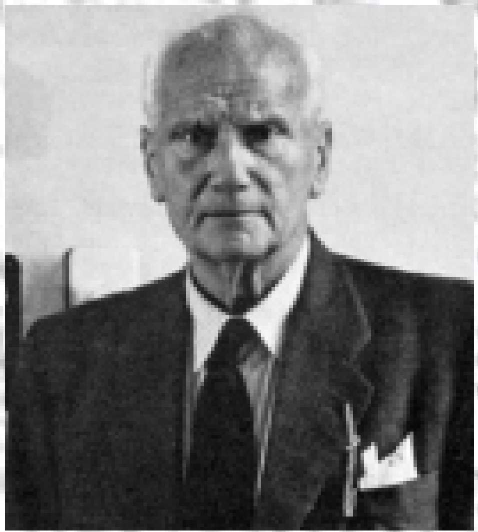
Max Born in a letter to Albert Einstein

***) and still does!**

Otto Stern
1888 - 1969

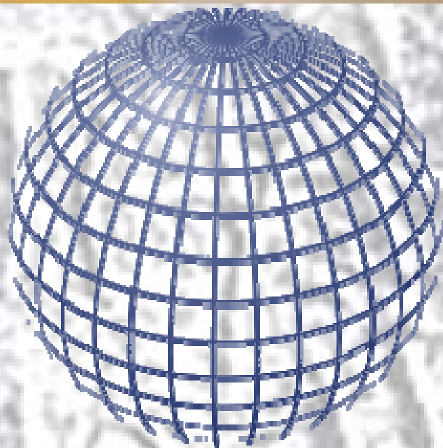
# The spin 1922



Walter Gerlach
1889 – 1979
(by the way, an intern of Farm Hill after 1945)

Wolfgang Pauli
1900 - 1958



Paul Dirac
1902 - 1984

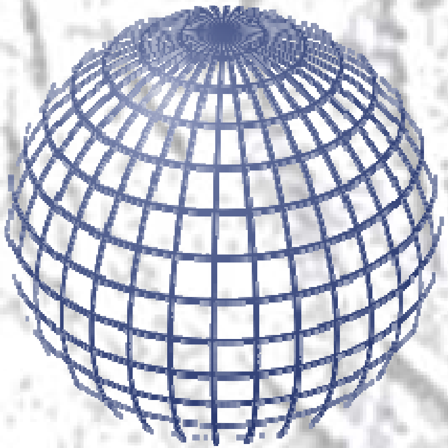
**W. Pauli,**
**Z. f. Physik <u>43</u>, 1 (1927)**

*The Quantum Theory of the Electron.*

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

**Proc. Roy. Soc. <u>A117</u>, 610 (1928)**



The „world“ of Schrödinger: functions belonging topo-logically to a two-sided surface ($2\pi$ world)

The „world“ of Pauli & Dirac: functions belonging topo-logically to a one-sided surface ($4\pi$ world)

**This - perhaps - is the conceptual level on which presently (time-independent) magnetism ought to be discussed microscopically.**

**What is still missing, however, is the concept of time (in order to describe magnetism on a ns-, fs- and perhaps as-level !!!)**

**Using a time-dependent Dirac equation in the presence of an external electro-magnetic field???**

$$\boxed{\frac{\partial\psi}{\partial t} = \frac{1}{i\hbar}\mathcal{H}_{\mathrm{D}}\psi}$$

$$\boxed{\mathcal{H}_{\mathrm{D}}(\vec{r},t) = c\vec{\alpha}\cdot\vec{\Pi} + \beta m_{\mathrm{e}}c^2 + eV\boldsymbol{I}_4}$$

$$\boxed{\vec{\Pi} = (\vec{p} - e\vec{A})\boldsymbol{I}_4}$$

(present day *terra incognita*!!!)

**… at least two long-known (time-independent?) effects could finally be explained microscopically.**

**Guess the name of the following famous effect!**

3. Between the paraboloidal poles of an electromagnet, the middle part of the flame from a Bunsen burner was placed. A piece of asbestos impregnated with common salt was put in the flame in such a manner that the two D-lines were seen as narrow and sharply defined lines on the dark ground. The distance between the poles was about 7 mm. If the current was put on, the two D-lines were distinctly widened. If the current was cut off they returned to their original position. The appearing and disappearing of the widening was simultaneous with the putting on and off of the current. The experiment could be repeated an indefinite number of times.

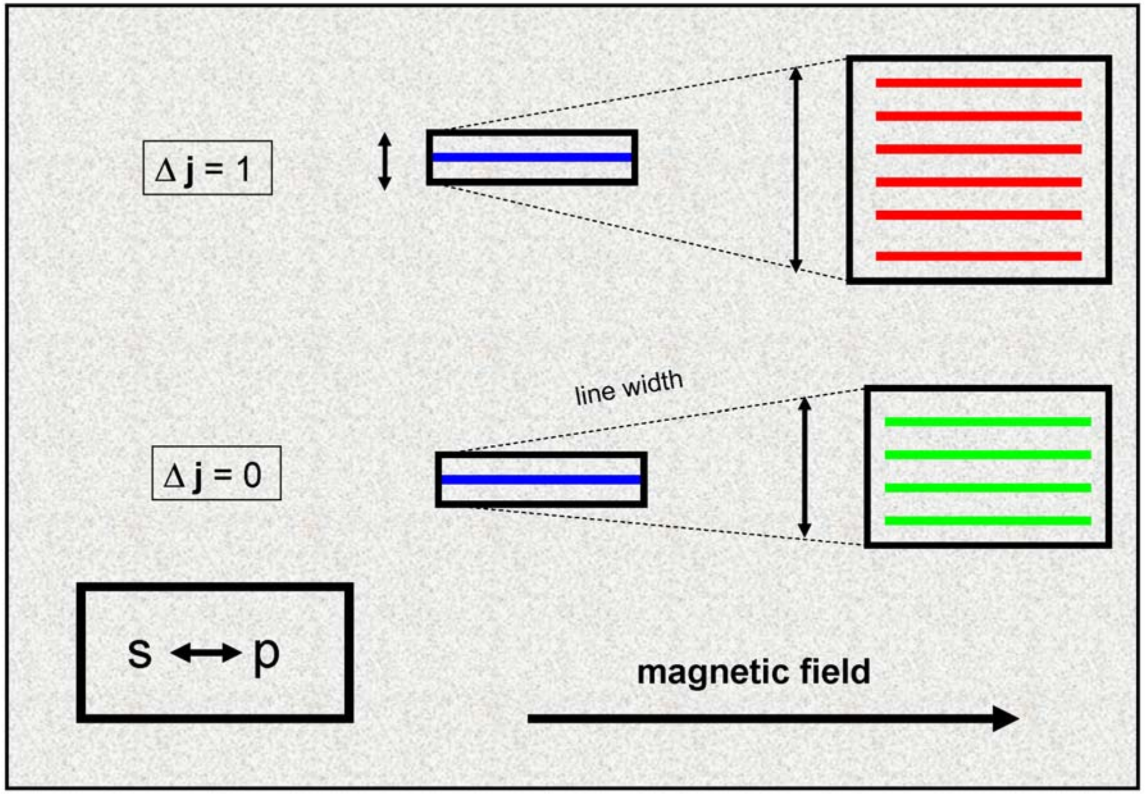
4. The flame of the Bunsen was next interchanged with a flame of coal-gas fed with oxygen. In the same manner as in § 3, asbestos soaked with common salt was introduced into the flame. It ascended vertically between the poles. If the current was put on again the D-lines were widened, becoming perhaps three or four times their former width.

5. With the red lines of lithium, used as carbonate, wholly analogous phenomena were observed.

6. Possibly the observed phenomenon (§§ 3, 4, 5) will be regarded as nothing of any consequence.

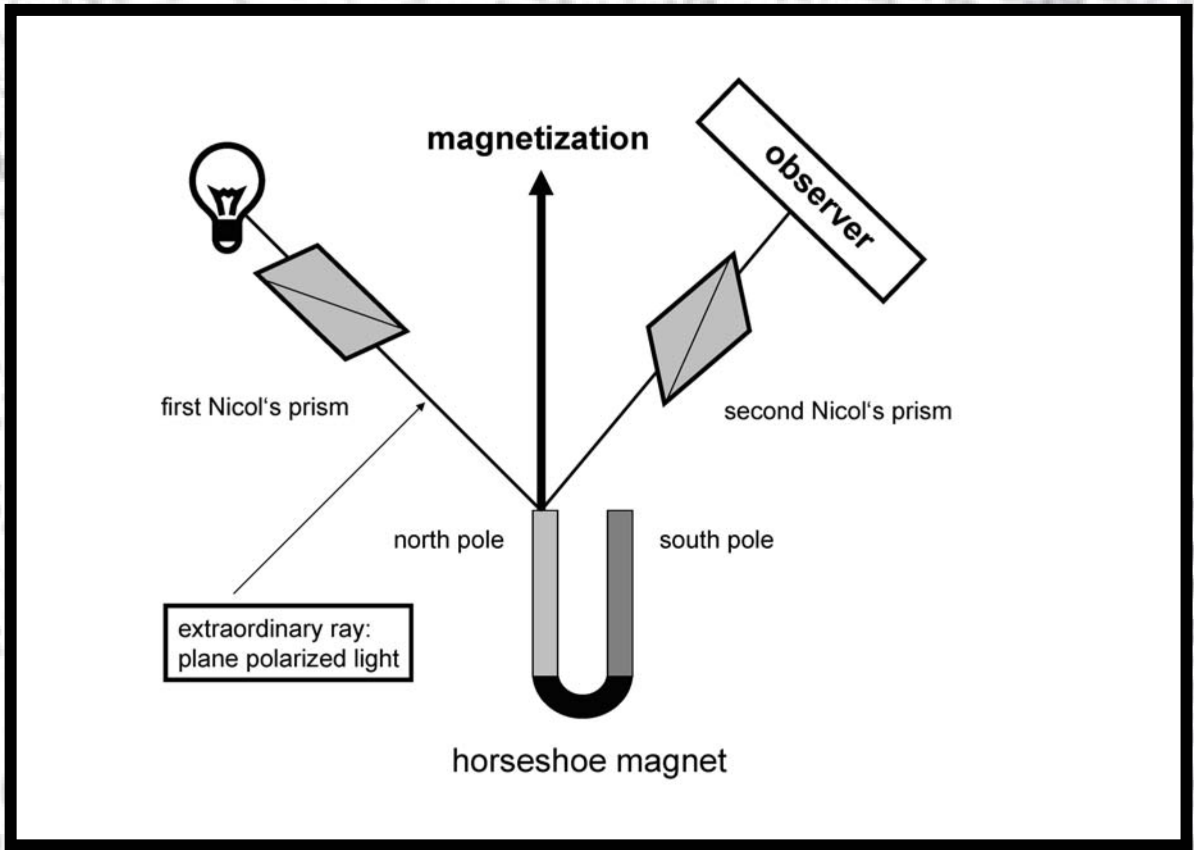
XXXII. *On the Influence of Magnetism on the Nature of the Light emitted by a Substance.* *By* Dr. P. Zeeman*.

## 1897



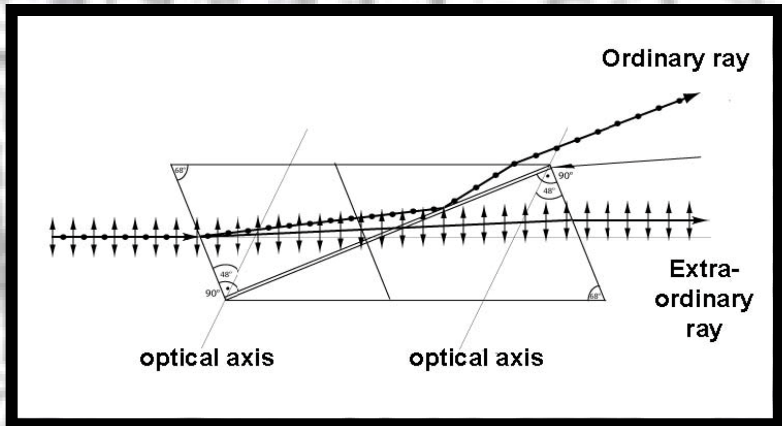

Pieter Zeeman
1865 - 1943

# Zeeman effect

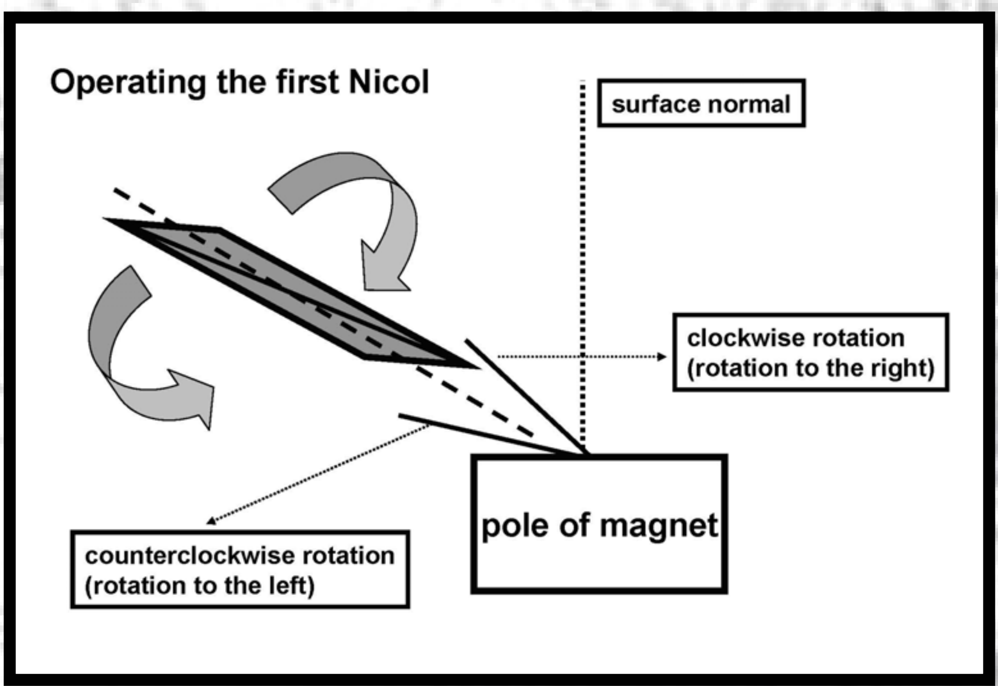


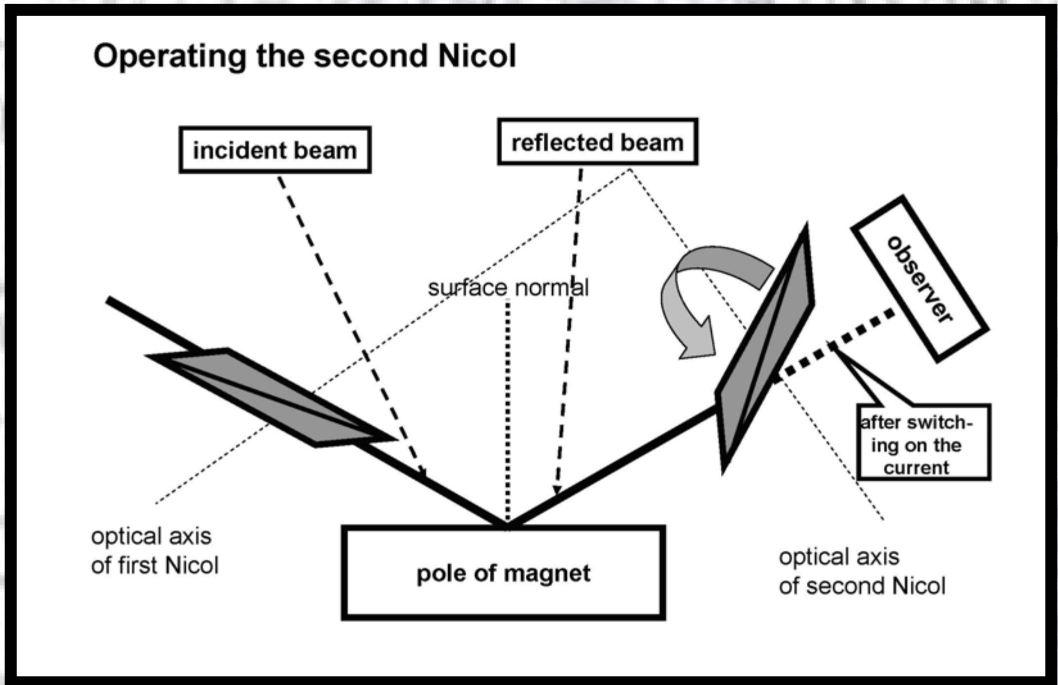

**your equipment:**
**1 light source**
**2 Nicols**
**1 horseshoe magnet**

**… and what is this effect?**




Nicol's prisma



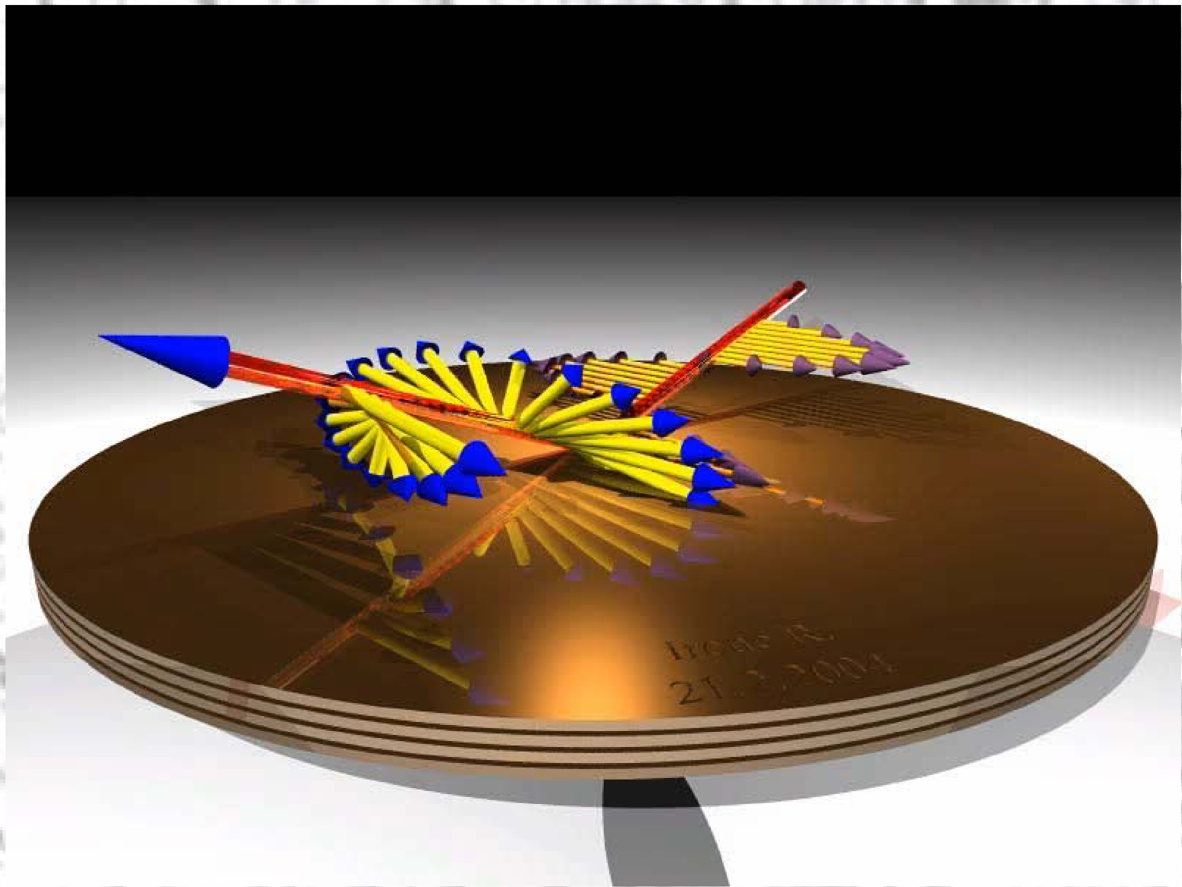

## Let's do the experiment together:

1. turn the left Nicol: bad luck - with or without magnetic field - nothing happens!
2. go back, switch on the current (magnetic field) turn the right Nicol

BINGO!!

# Kerr effect

**1877**




John Kerr
1824 - 1907

(pump-probe: fs-magnetism!!!)

**Well, Borje, I wish you all the best for your birthday, or, as we say: up to 120!**

By the way, we met the first time in Los Alamos around 1985 – therefore as a reminder a

Kokopeli