

HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

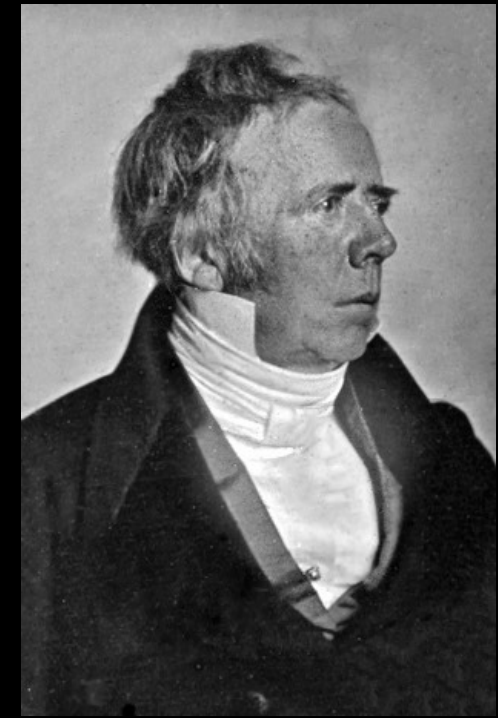
Additional Material

Philipp Windischhofer
October 28, 2023

Hans Christian Ørsted

Physicist, chemist

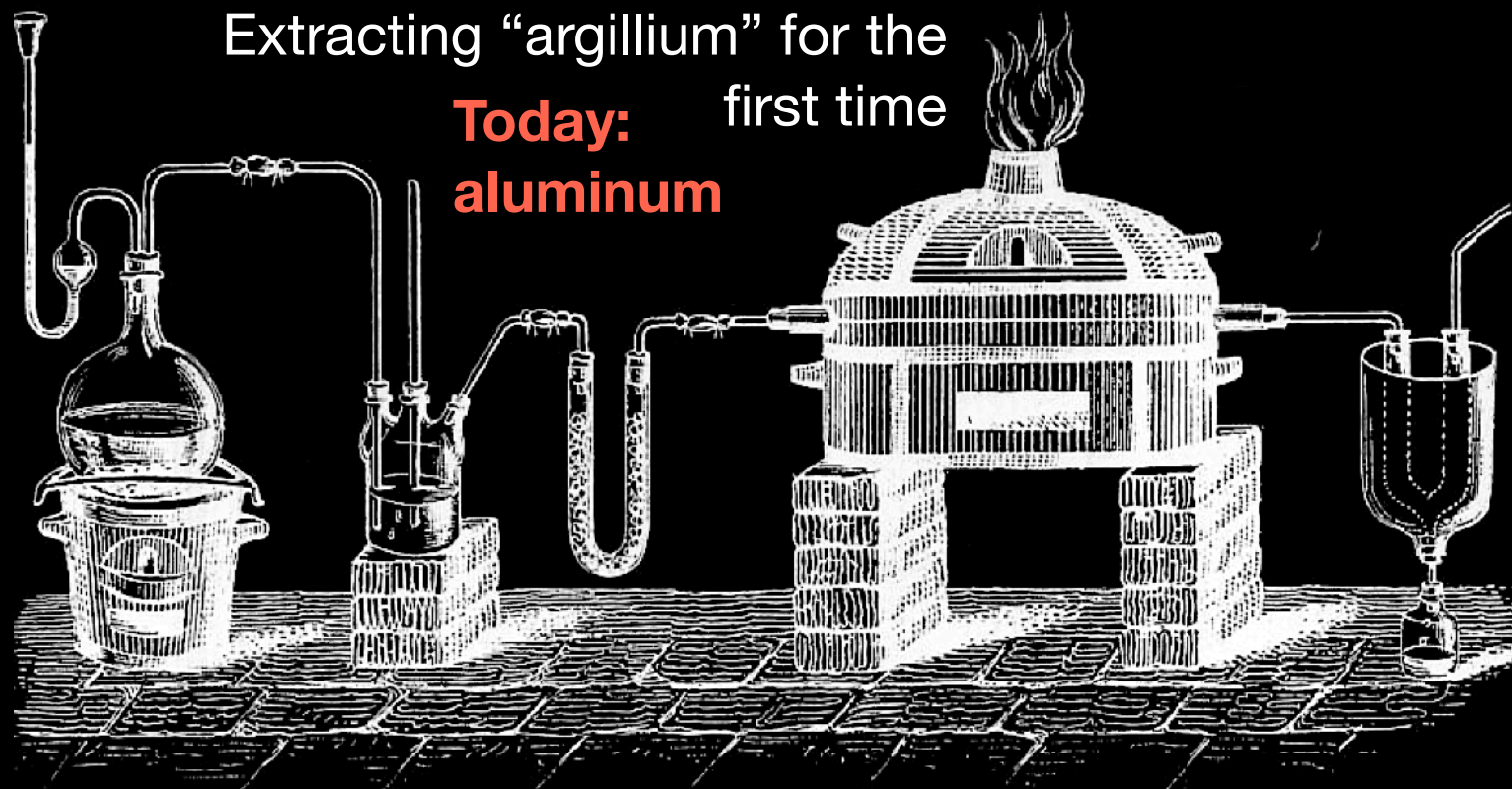
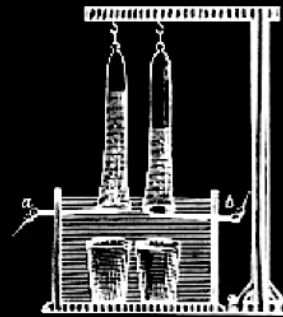
Thesis at Copenhagen: "The Architectonics of Natural Metaphysics"



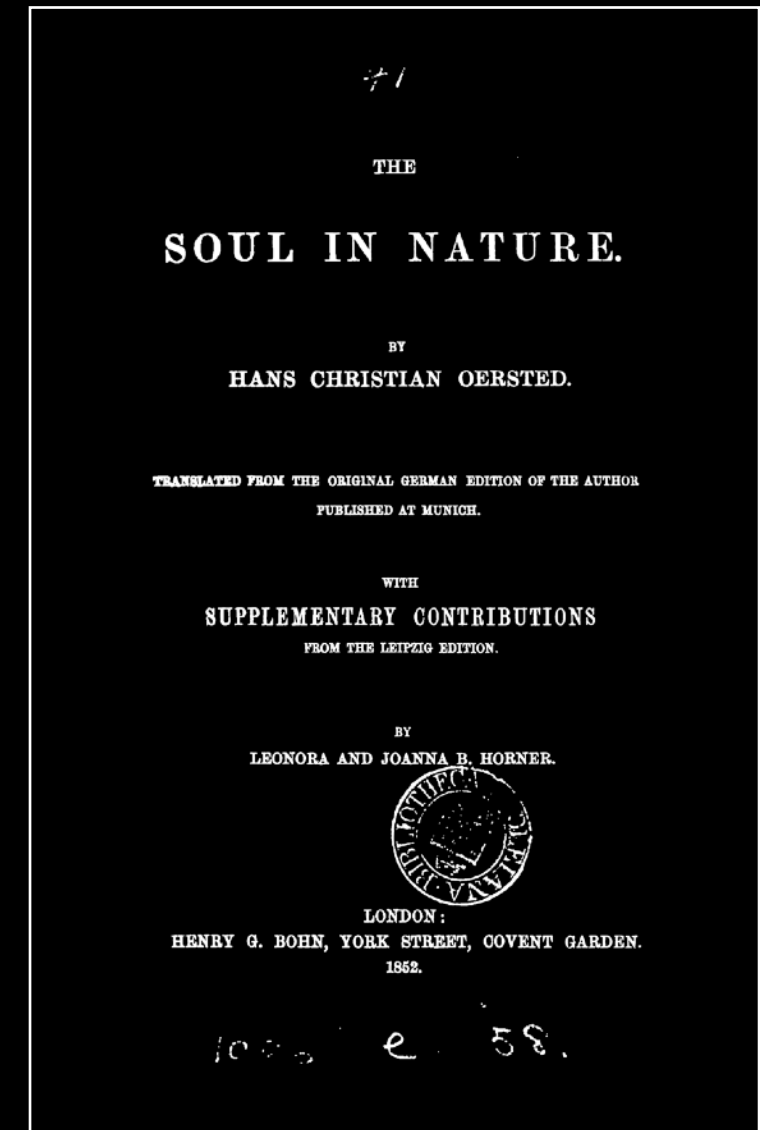
3-year travel scholarship:
Scientific tour around
Europe



J. Ritter



Extracting "argillium" for the
Today: first time
aluminum



THE
SOUL IN NATURE.

BY
HANS CHRISTIAN OERSTED.

TRANSLATED FROM THE ORIGINAL GERMAN EDITION OF THE AUTHOR
PUBLISHED AT MUNICH.

WITH
SUPPLEMENTARY CONTRIBUTIONS
FROM THE LEIPZIG EDITION.

BY
LEONORA AND JOANNA B. HORNER.



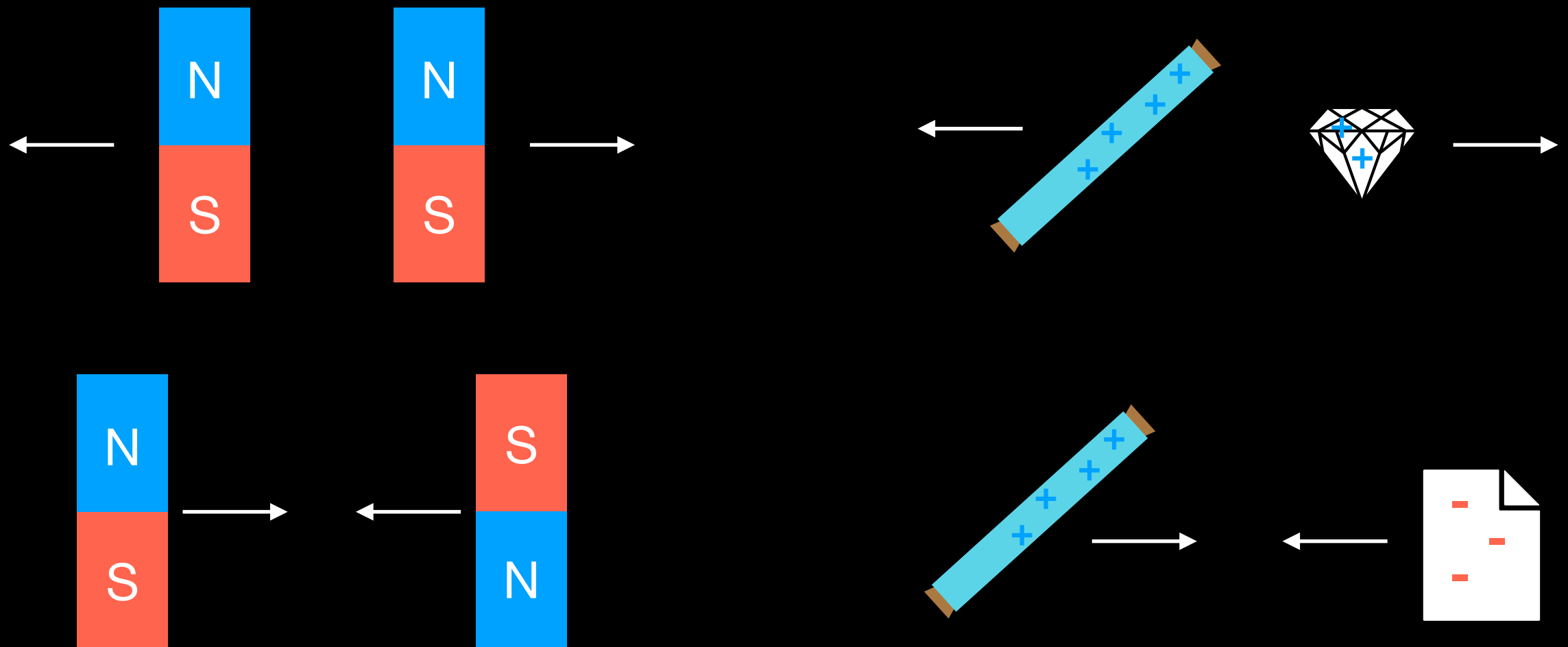
LONDON:
HENRY G. BOHN, YORK STREET, COVENT GARDEN.
1852.

1000 e 38.

Electricity and magnetism

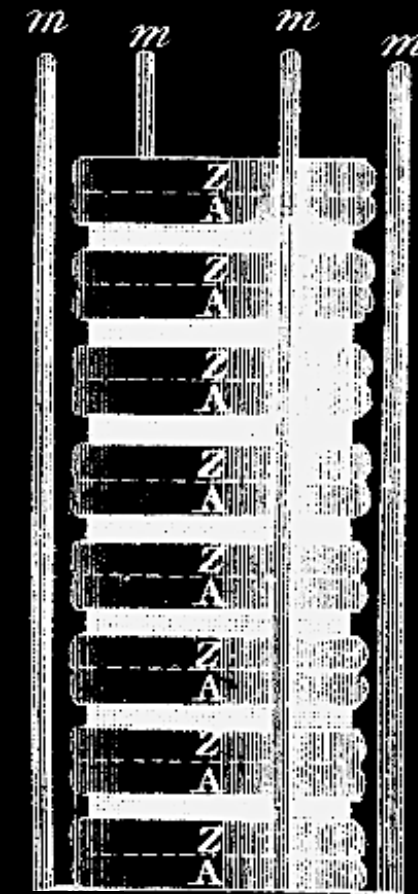
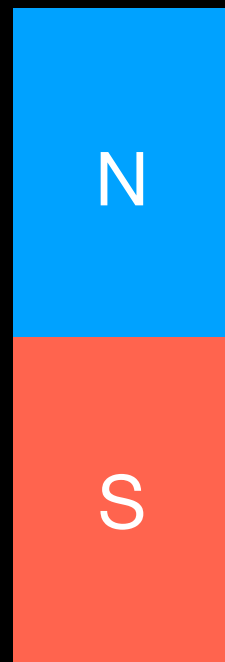
“The reasons for and against an essential resemblance between magnetism and electricity might seem to be nearly balanced.”

“Each of them consists of two powers, or directions of powers, of an opposite nature, submitted to the same laws of attraction and repulsion.”



Electricity and magnetism

“If we imagine a Voltaic pile, composed of minute and molecular elements, it would have the most perfect analogy with a magnet.”

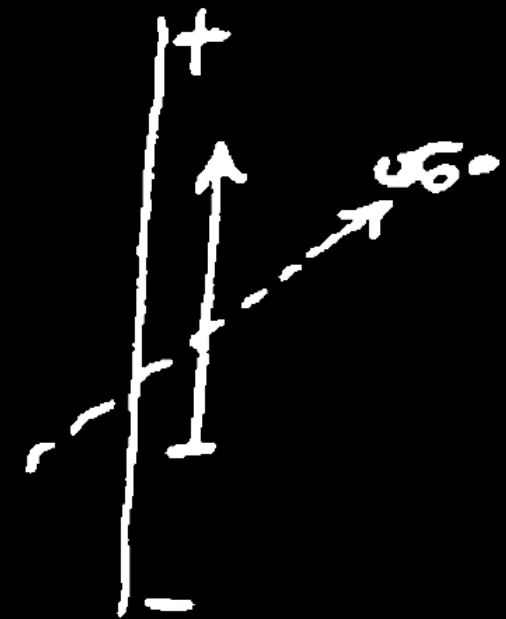
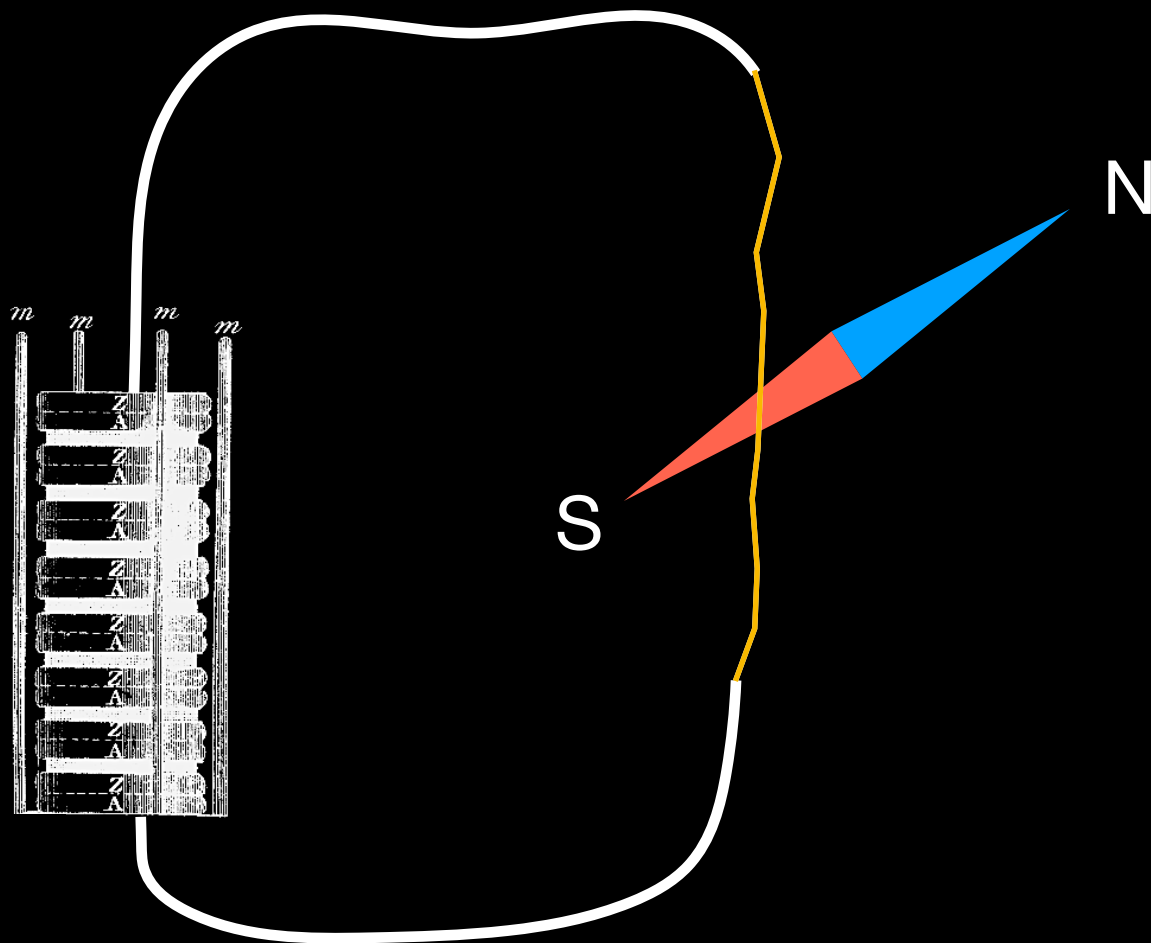


“It must be tested whether electricity in its most latent state has any action on the magnet as such.”

Electricity meets magnetism

“I called attention to the variations of the magnetic needle during a thunderstorm, and at the same time I set forth the conjecture that an electric discharge could act on the experiment.”

“Since I expected the greatest effect from a discharge associated with incandescence, I inserted in the circuit a very fine platinum wire above the place where the needle was located.”



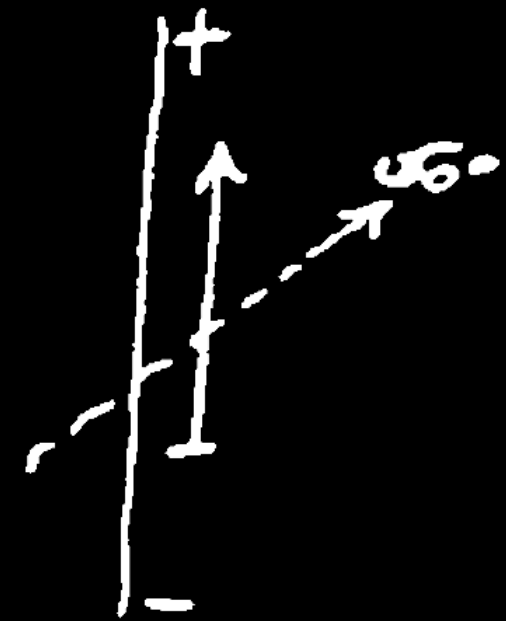
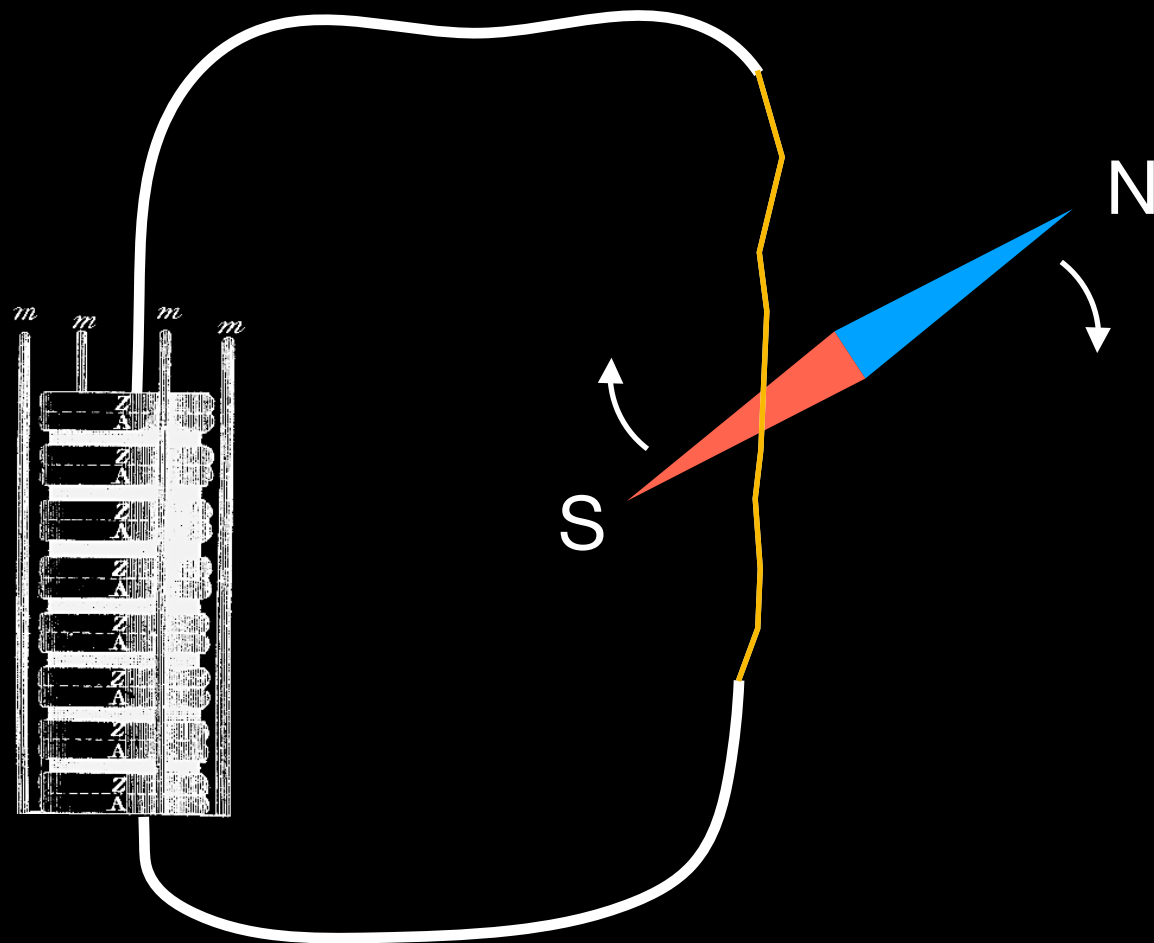
From Ørsted's notebook

Electricity meets magnetism

“The magnetic needle, though included in a box, was disturbed; but the effect was very feeble, and no particular law could immediately be observed from it.”

“The experiment made no strong impression on the audience.”

(He tried this during a lecture in winter 1819/20!)



From Ørsted's notebook

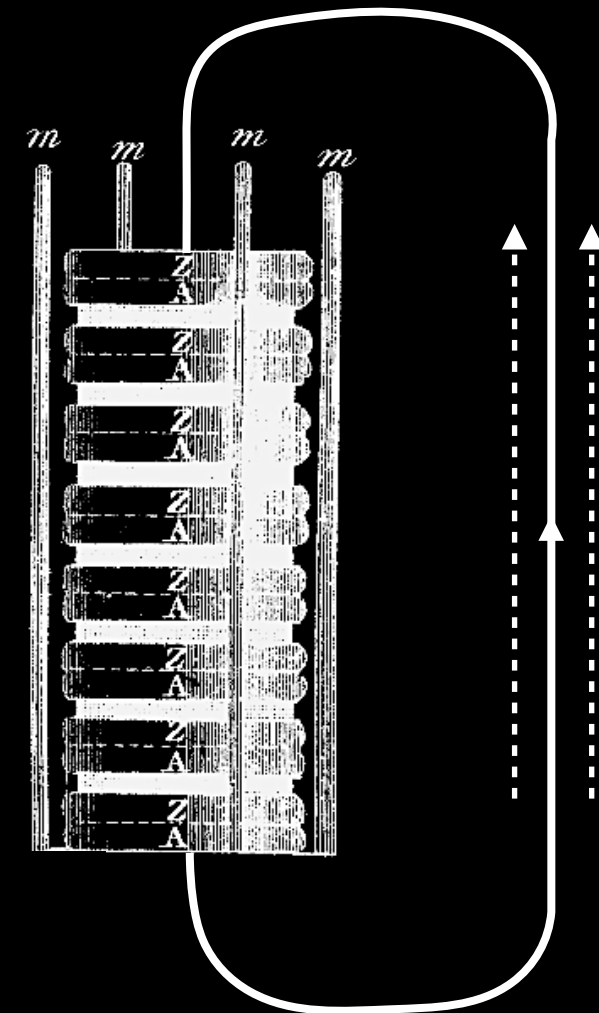
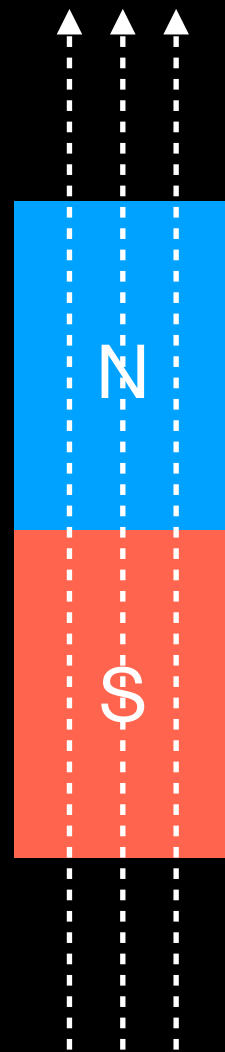
Finding the law

July 1820:

“Many days of experimenting were required before I could find the law governing the effect. As soon as I had discovered it, I rushed to publish the work.”

What is the magnetic effect of an electric current?

Along the direction of the current?



Finding the law

July 1820:

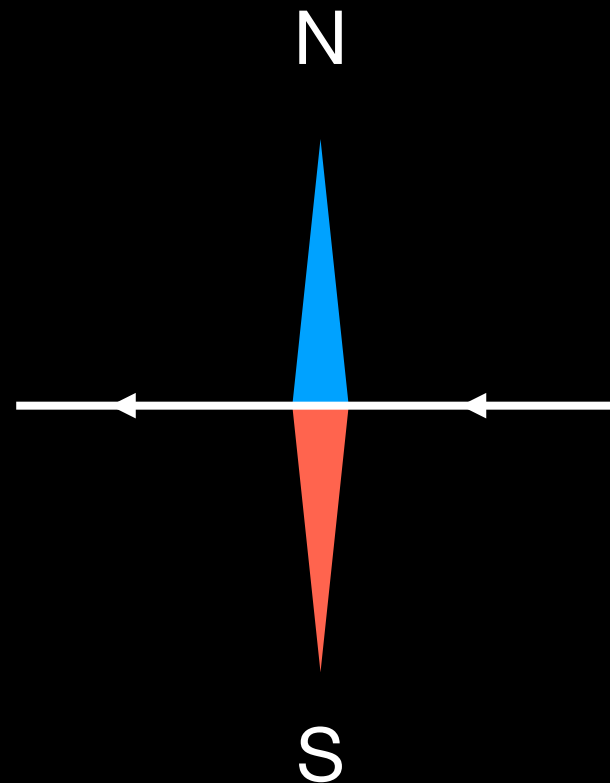
“Many days of experimenting were required before I could find the law governing the effect. As soon as I had discovered it, I rushed to publish the work.”

What is the magnetic effect of an electric current?

Along the direction of the current?

Wire in east-west
orientation:

Nothing!



“This had so often been tried in vain; it must be produced by a lateral action.”

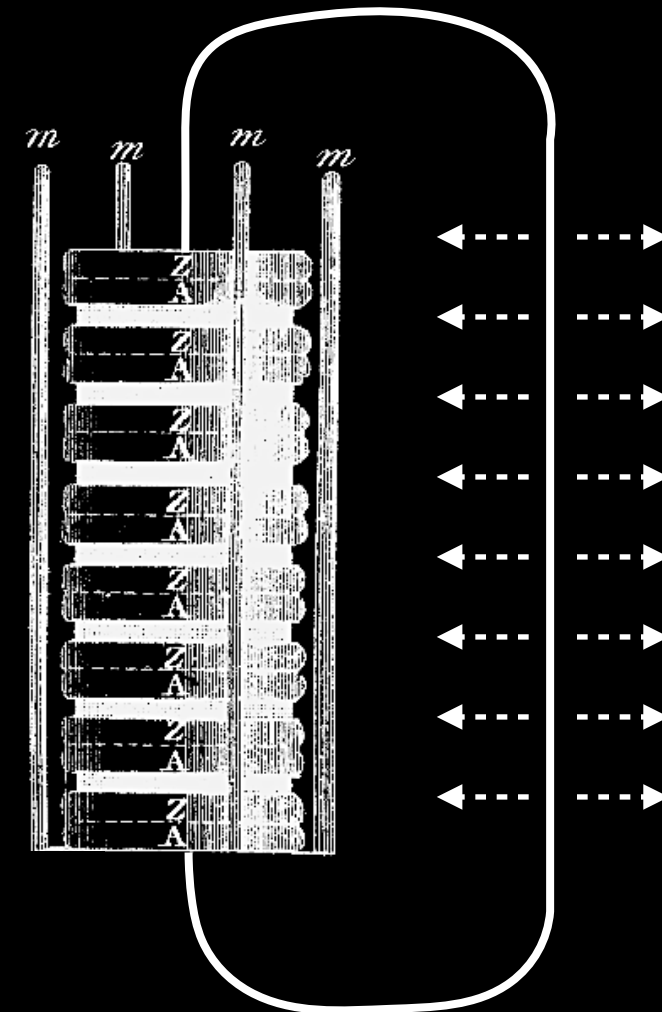
Finding the law

July 1820:

“Many days of experimenting were required before I could find the law governing the effect. As soon as I had discovered it, I rushed to publish the work.”

What is the magnetic effect of an electric current?

Outwards from the wire?



Finding the law

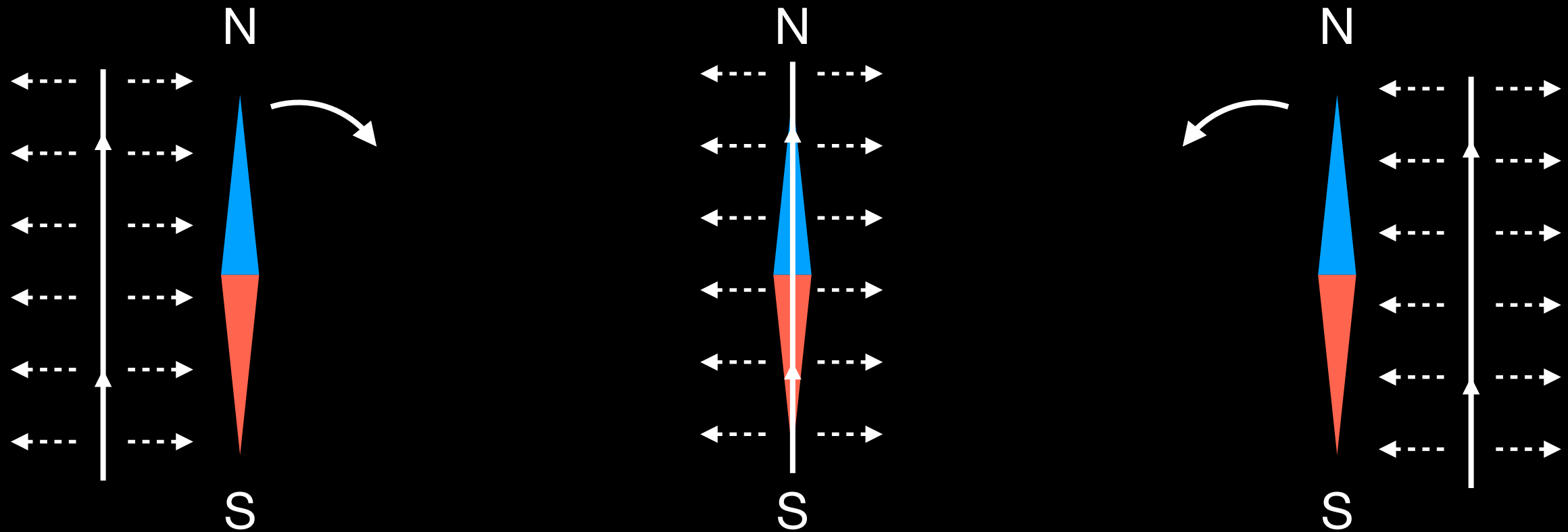
July 1820:

“Many days of experimenting were required before I could find the law governing the effect. As soon as I had discovered it, I rushed to publish the work.”

What is the magnetic effect of an electric current?

Outwards from the wire?

This is not what happened!



Finding the law

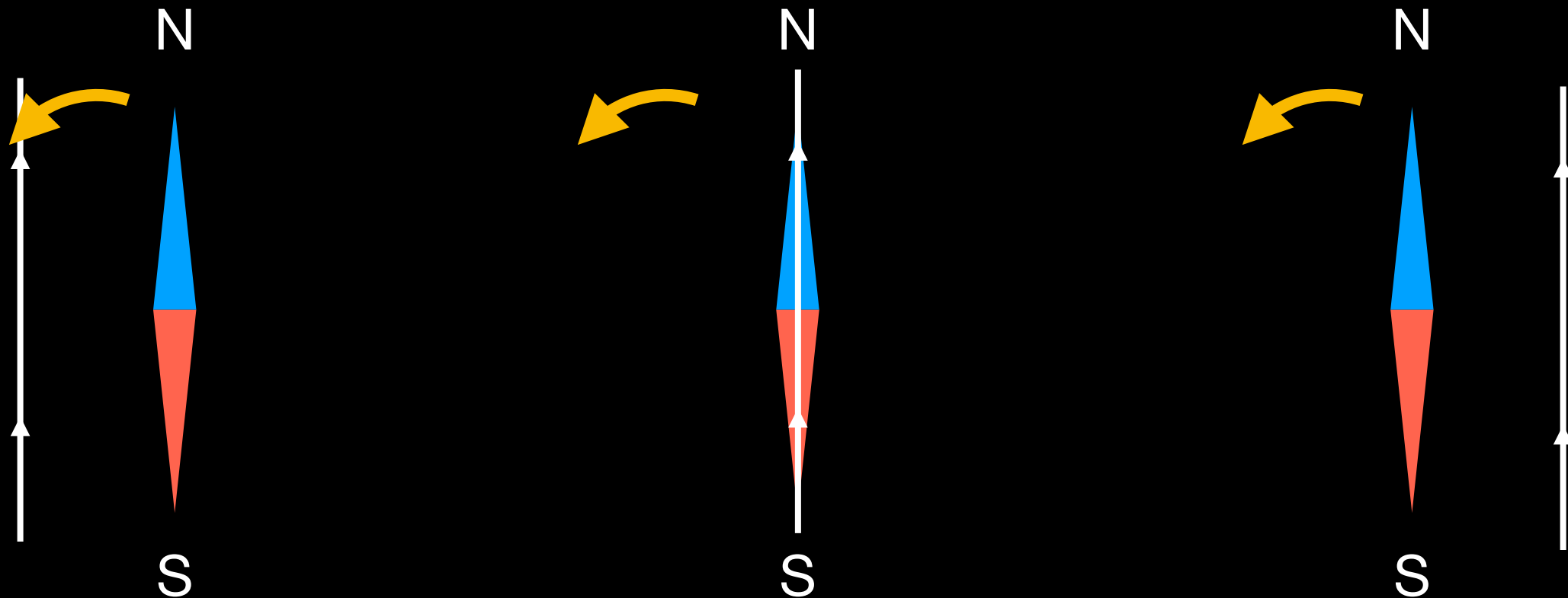
July 1820:

"Many days of experimenting were required before I could find the law governing the effect. As soon as I had discovered it, I rushed to publish the work."

What is the magnetic effect of an electric current?

Outwards from the wire?

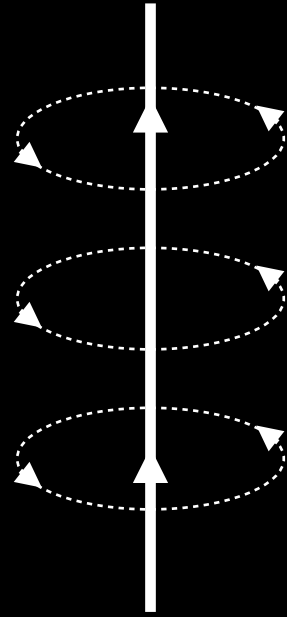
The needle always moved in the same direction!



Finding the law

What is the magnetic effect of an electric current?

A circular force around the wire!

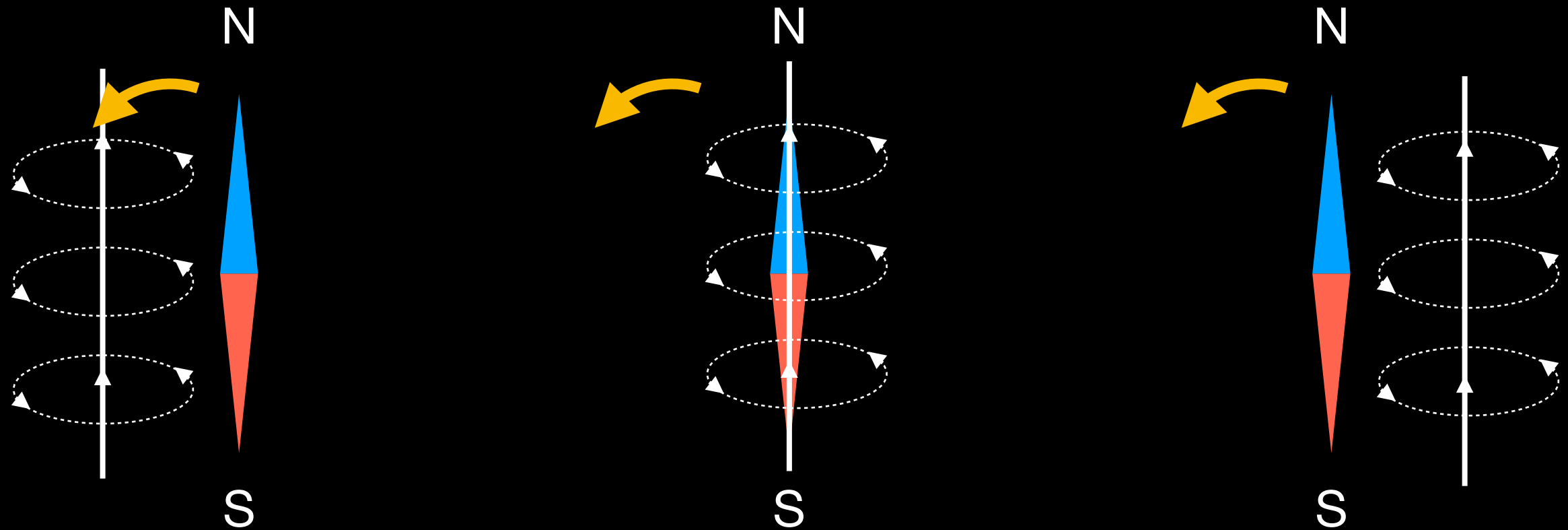


“A circular force was both unanticipated and inexplicable.”

Finding the law

What is the magnetic effect of an electric current?

A circular force around the wire!

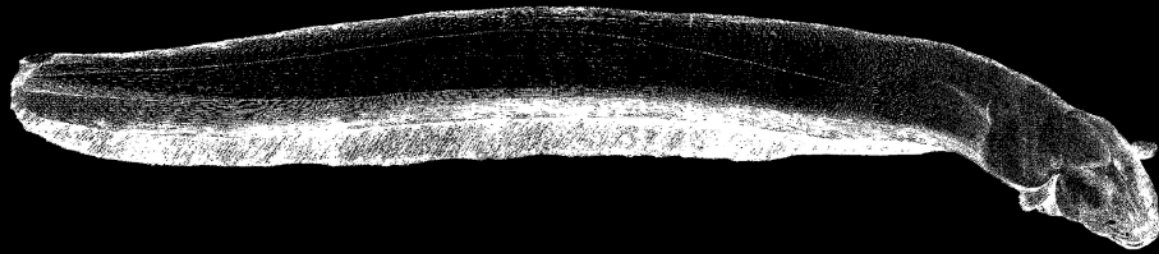


“A circular force was both unanticipated and inexplicable.”

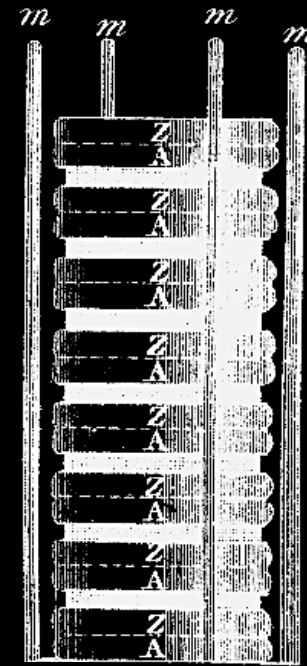
Electromagnetism in 1820

Utter confusion!

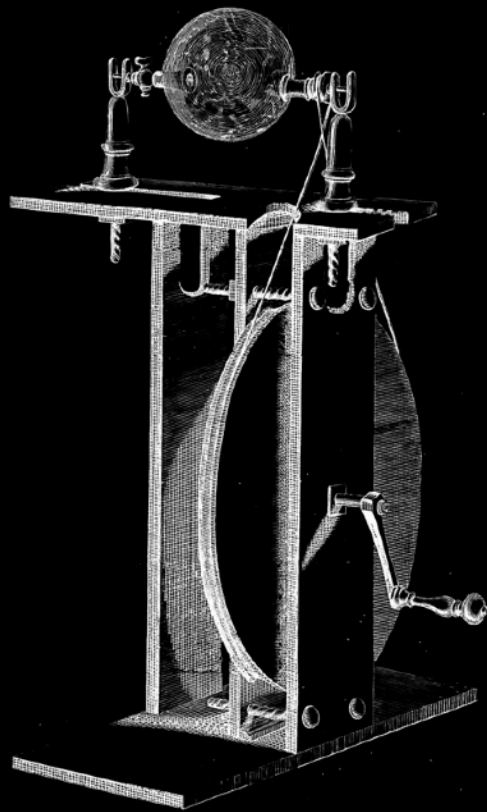
“Animal electricity”



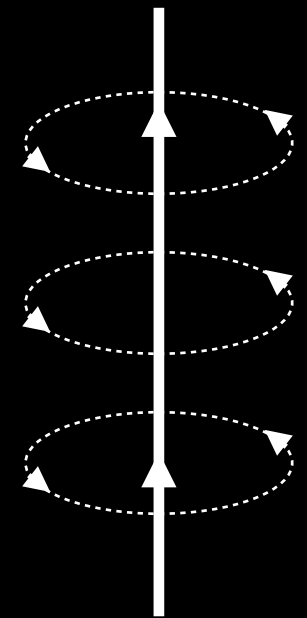
“Voltaic electricity”



“Ordinary electricity”



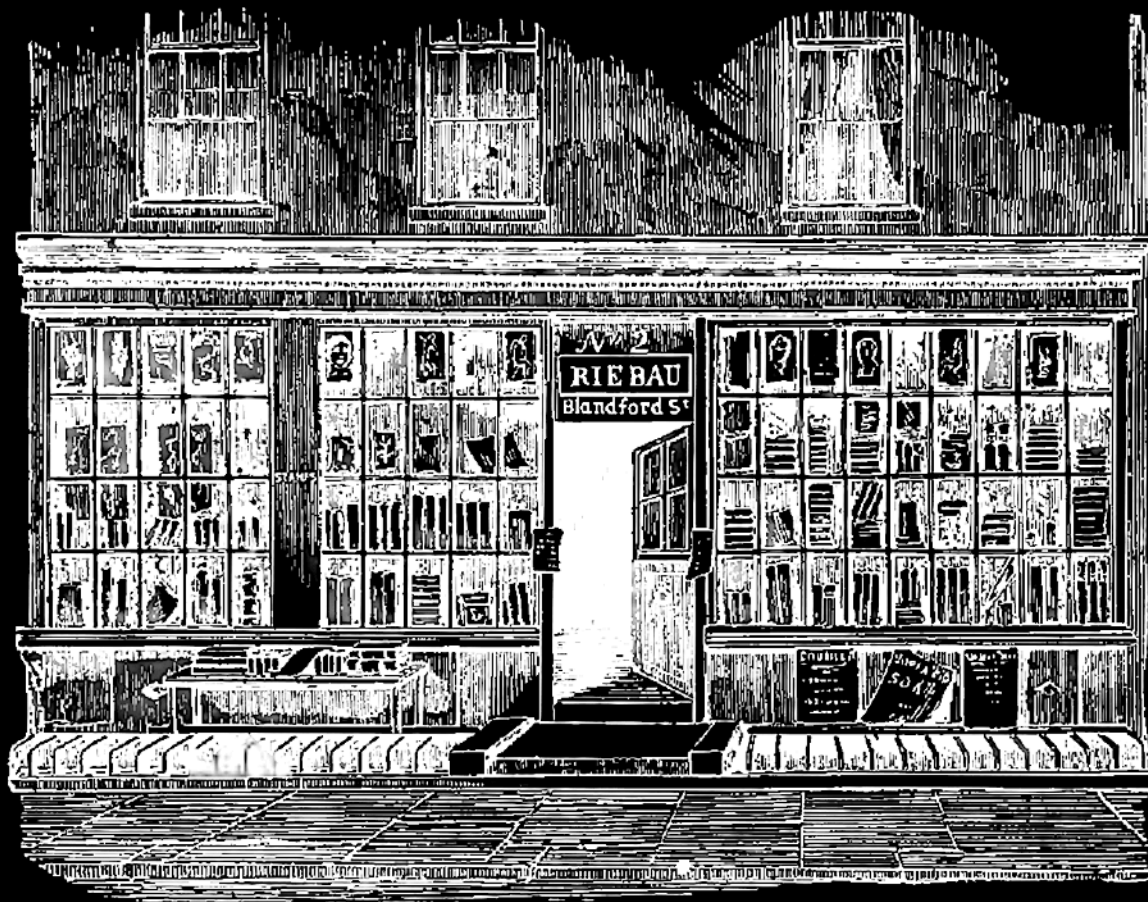
It will get worse before it gets better ...



“Electromagnetism”

Michael Faraday

Bookbinder, laboratory assistant, experimenter



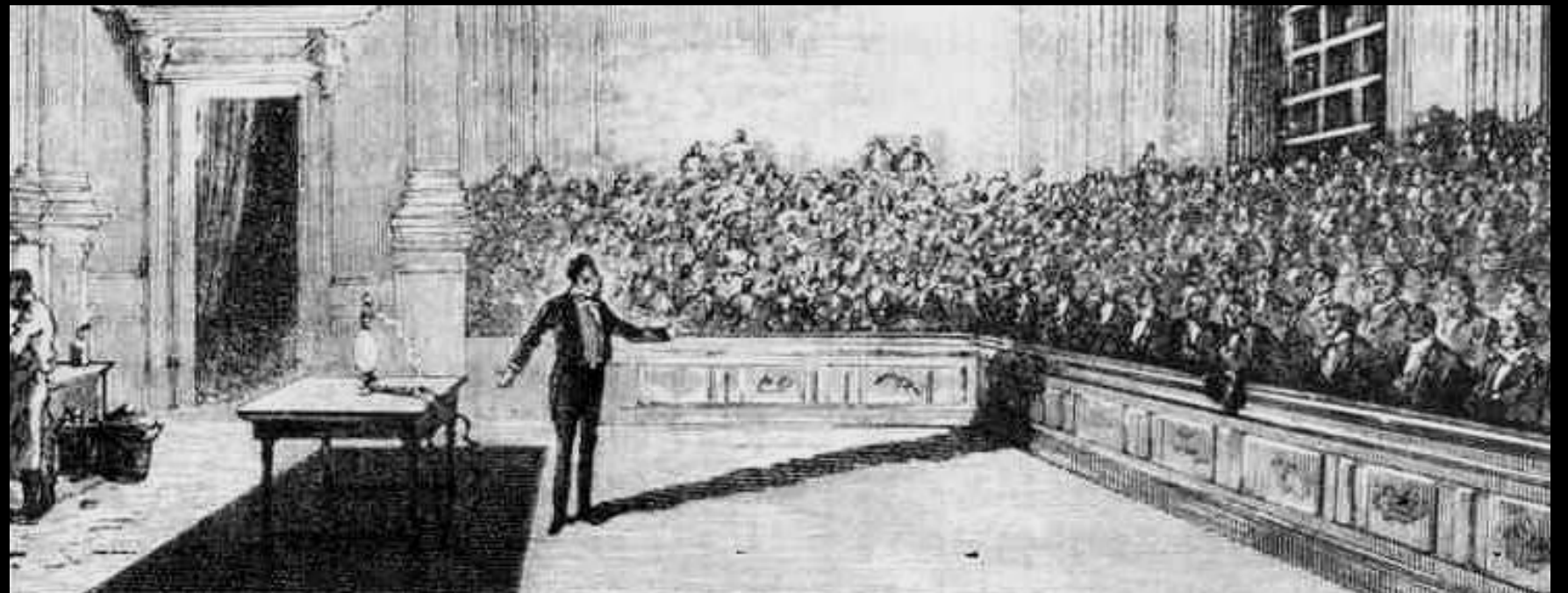
Bookbinder apprentice
at Riebau's

Dear Faraday,

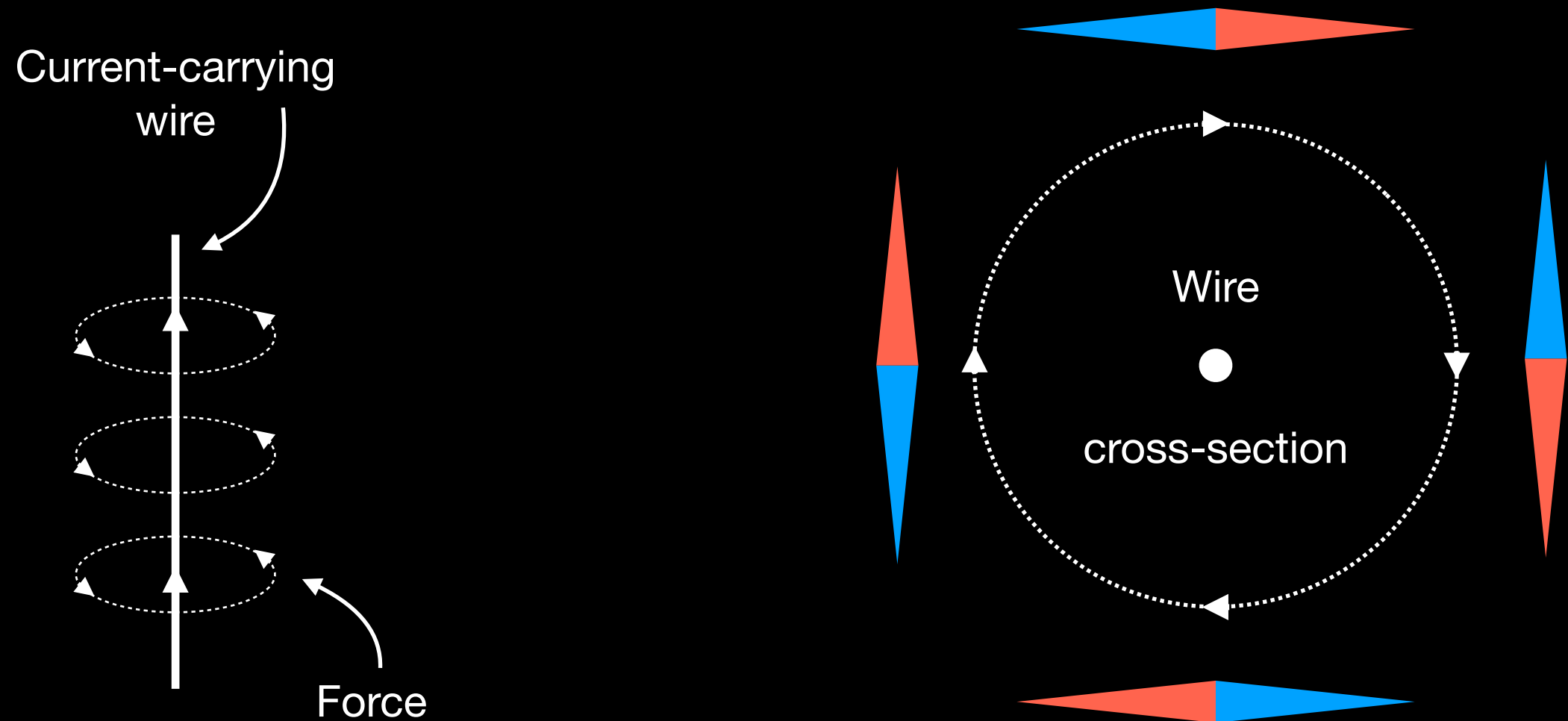
I write you this just to jog your memory that we expect from you this month and as early as suits you the remainder of the history of Electro-magnetism.

Yours very truly,
R. Phillips

Humphrey Davy's lectures
at the Royal Institution

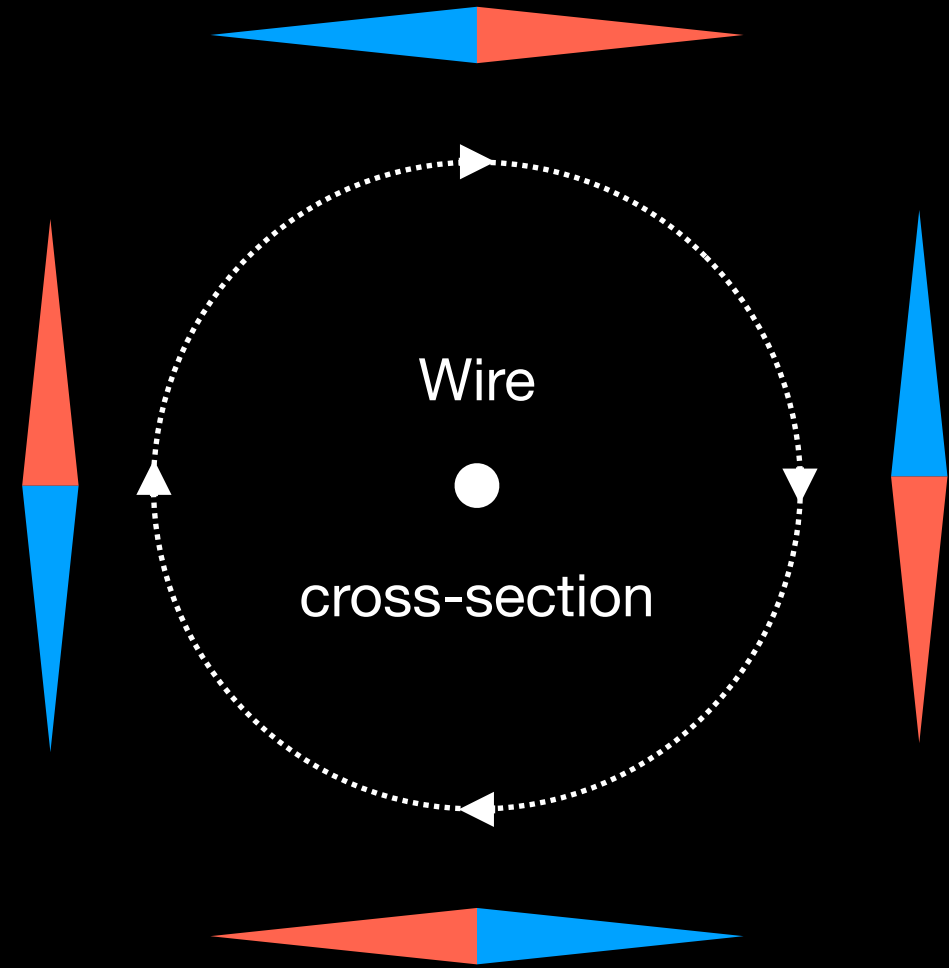
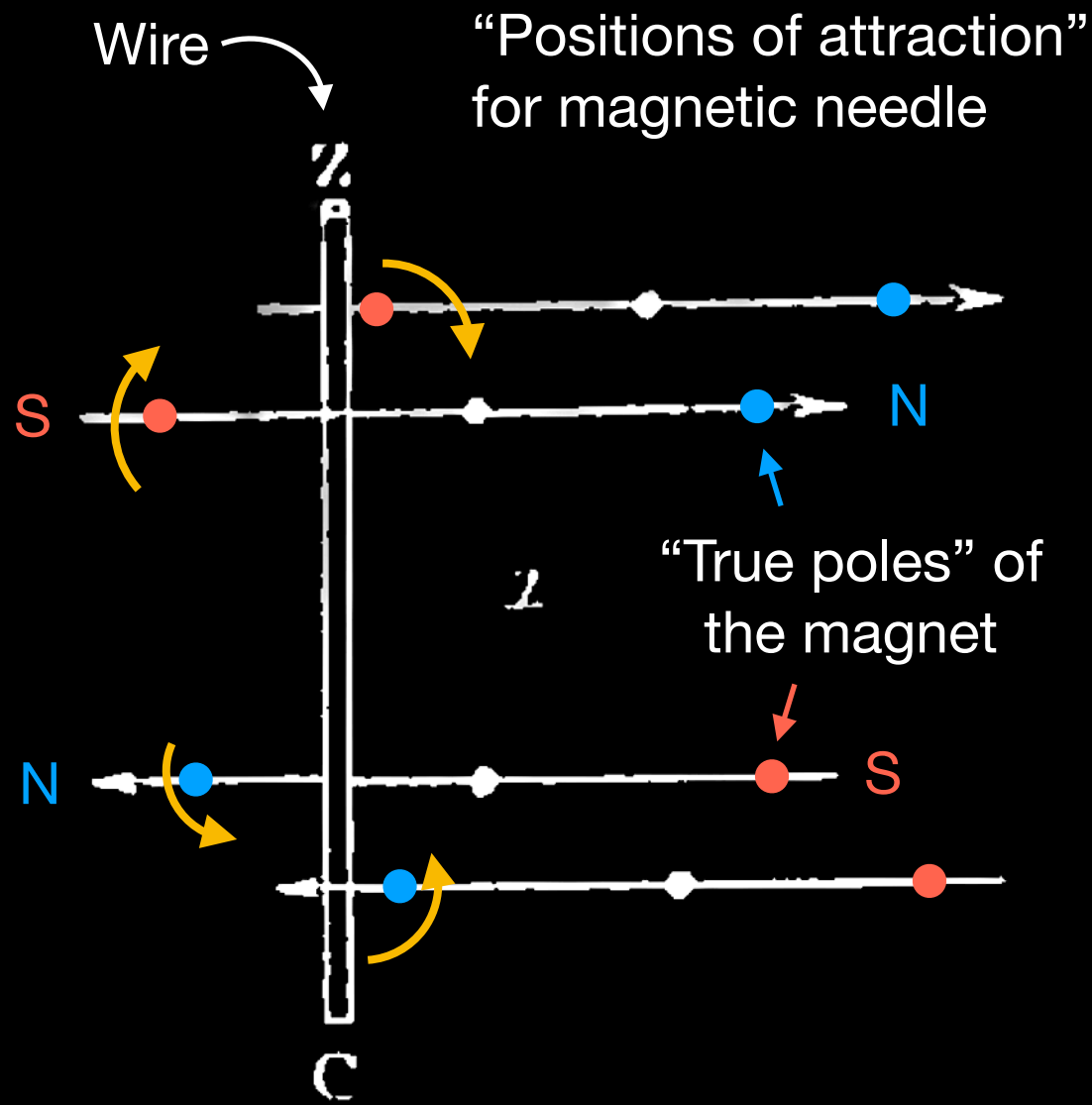


Reminder: Ørsted's discovery



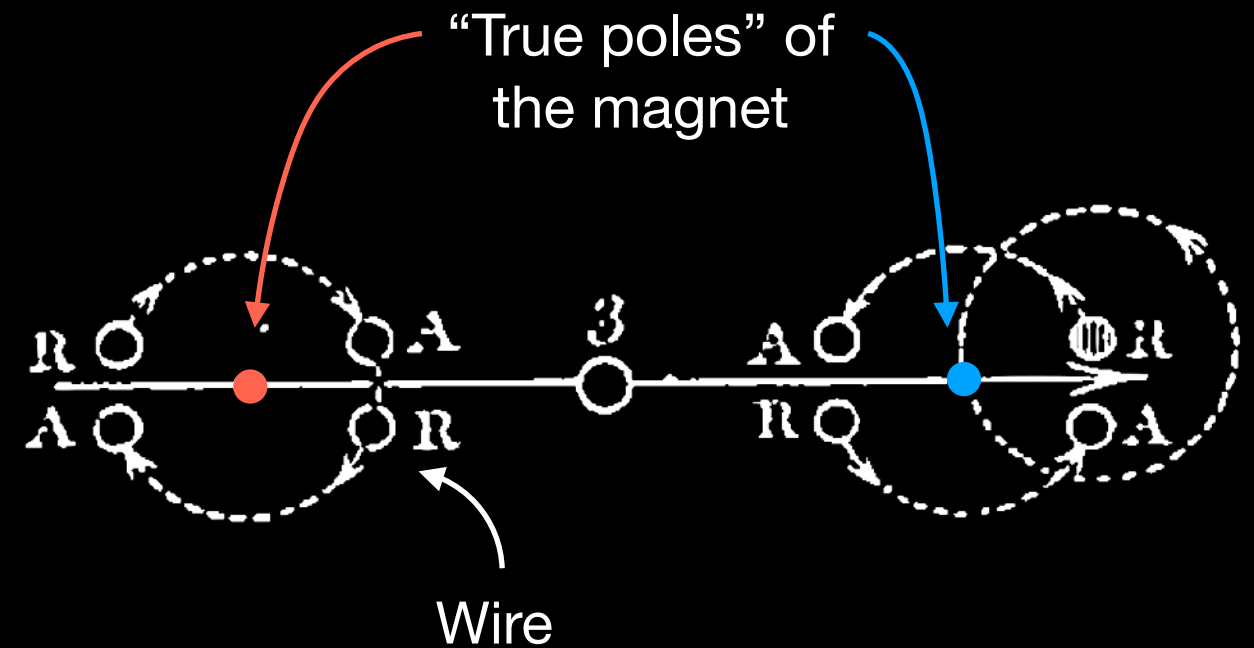
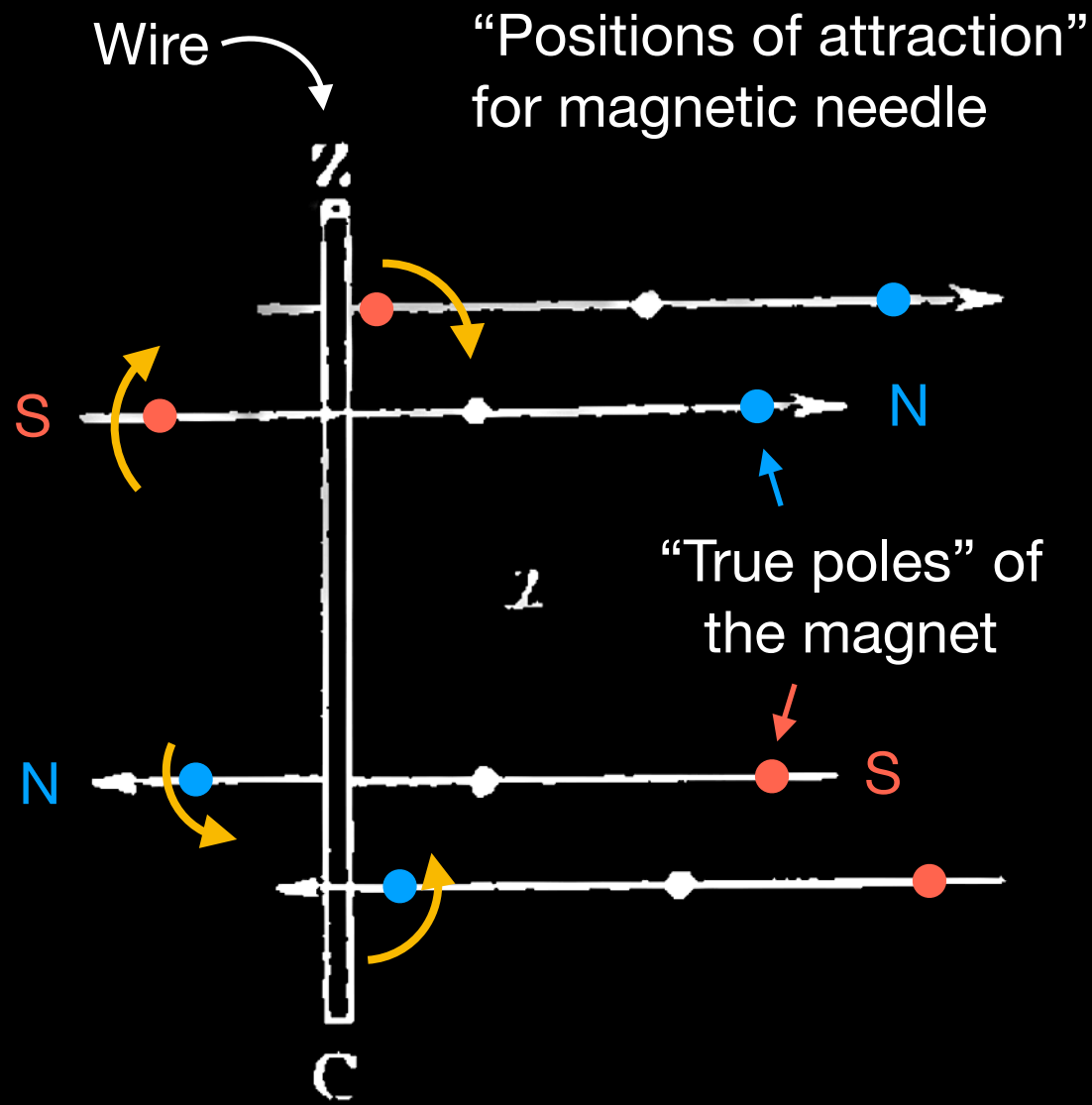
Ørsted: "A circular force was both unanticipated and inexplicable."

Faraday takes over



“It was evident, also, that the pole [of the magnet] had a tendency to revolve round the wire, and necessarily, therefore, the wire round the pole.”

Faraday takes over

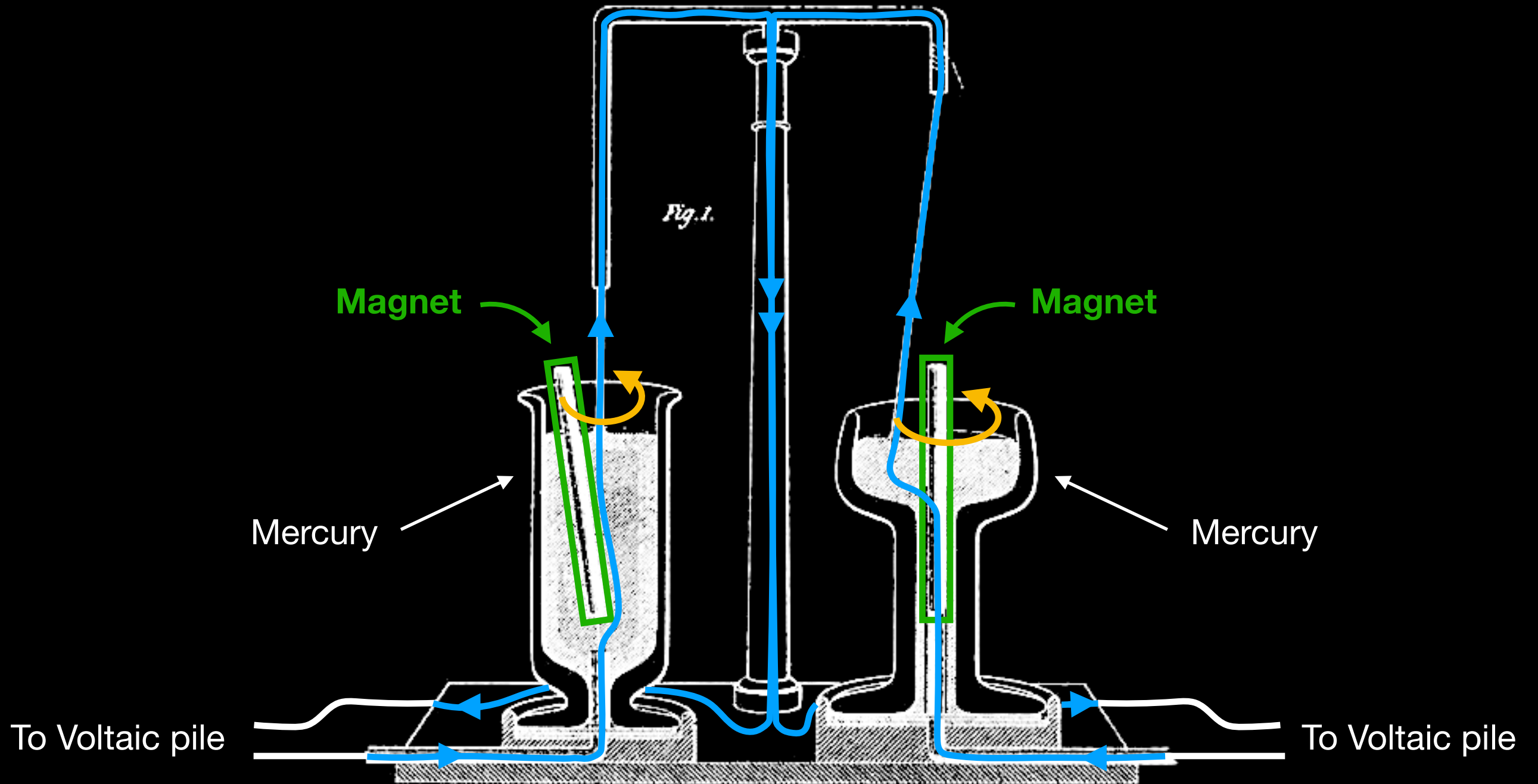


“It was evident, also, that the pole [of the magnet] had a tendency to revolve round the wire, and necessarily, therefore, the wire round the pole.”

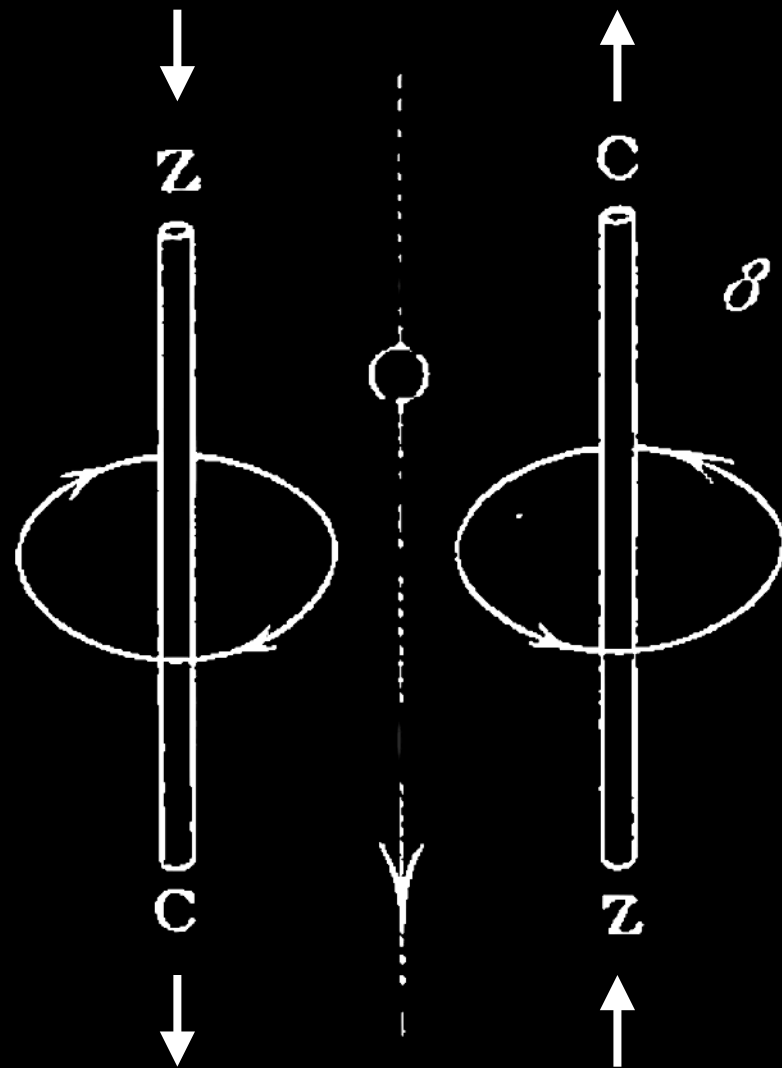
The first electric “motor” (1821)

“Rotation of a pole
around a wire”

“Rotation of a wire
around a pole”



Other wire arrangements



“If two wires in opposite states be arranged parallel to each other, and the pole be brought near them, it will circulate round either of them.”

“But as the wires have opposite currents, it moves in opposite directions round the two.”

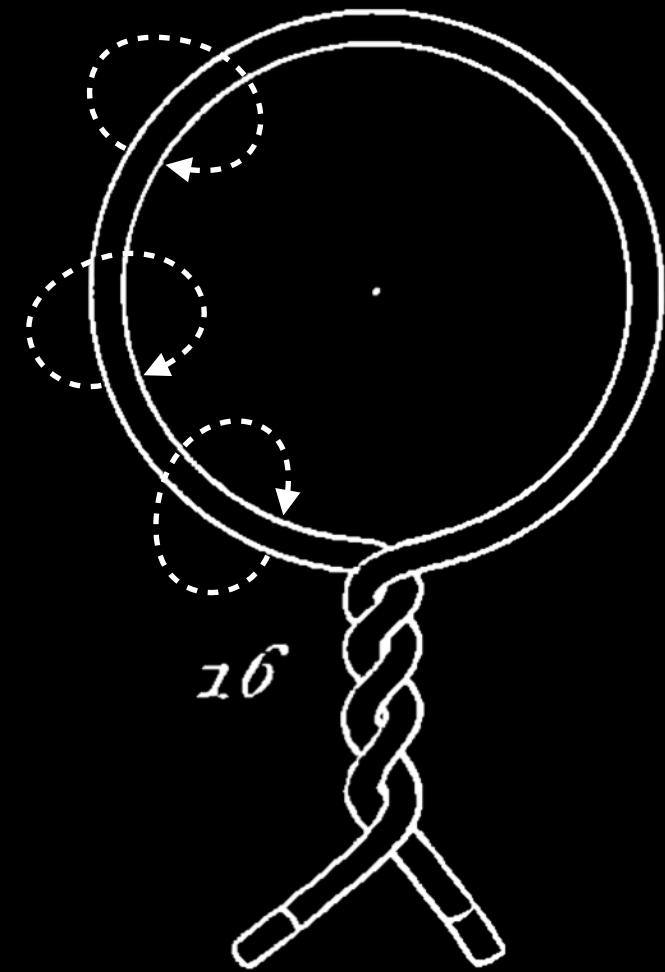
“When equidistant from them, the pole is propelled in a right line perpendicular to the wires, either receding or approaching.”

“It exhibits the curious appearance of first being attracted by the two wires, and afterwards repelled.”

Magnetic effects from multiple wires *superimpose*

Other wire arrangements

[source]



“With iron filings, the appearance was extremely beautiful and instructive; they arranged themselves in lines, passing through the ring parallel to its axis, and then folding up on either side as radii round to the edge; so that they represented, exactly, the lines which a pole would have described [...]”

William Sturgeon

Shoemaker, gunner, instrument maker, lecturer



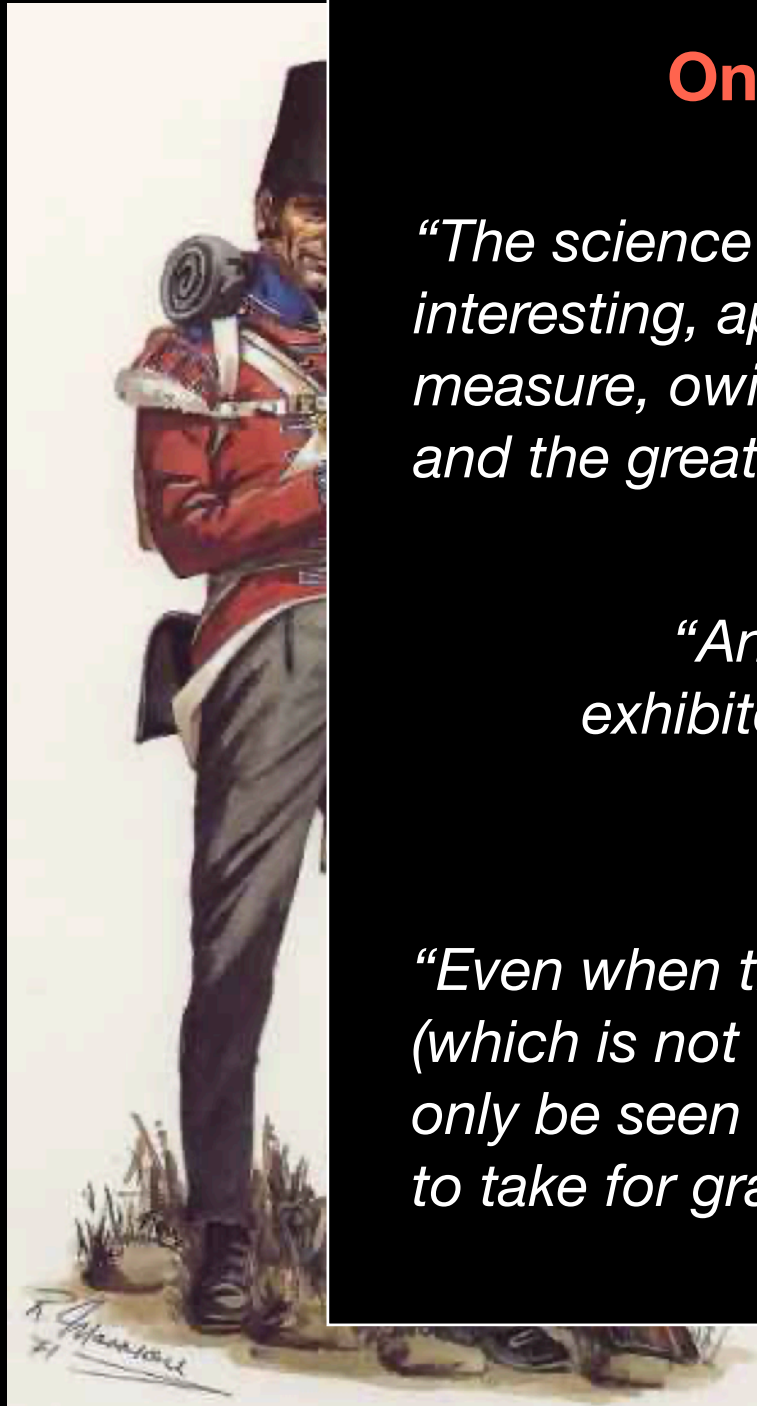
at Woolwich

On the science of electromagnetism:

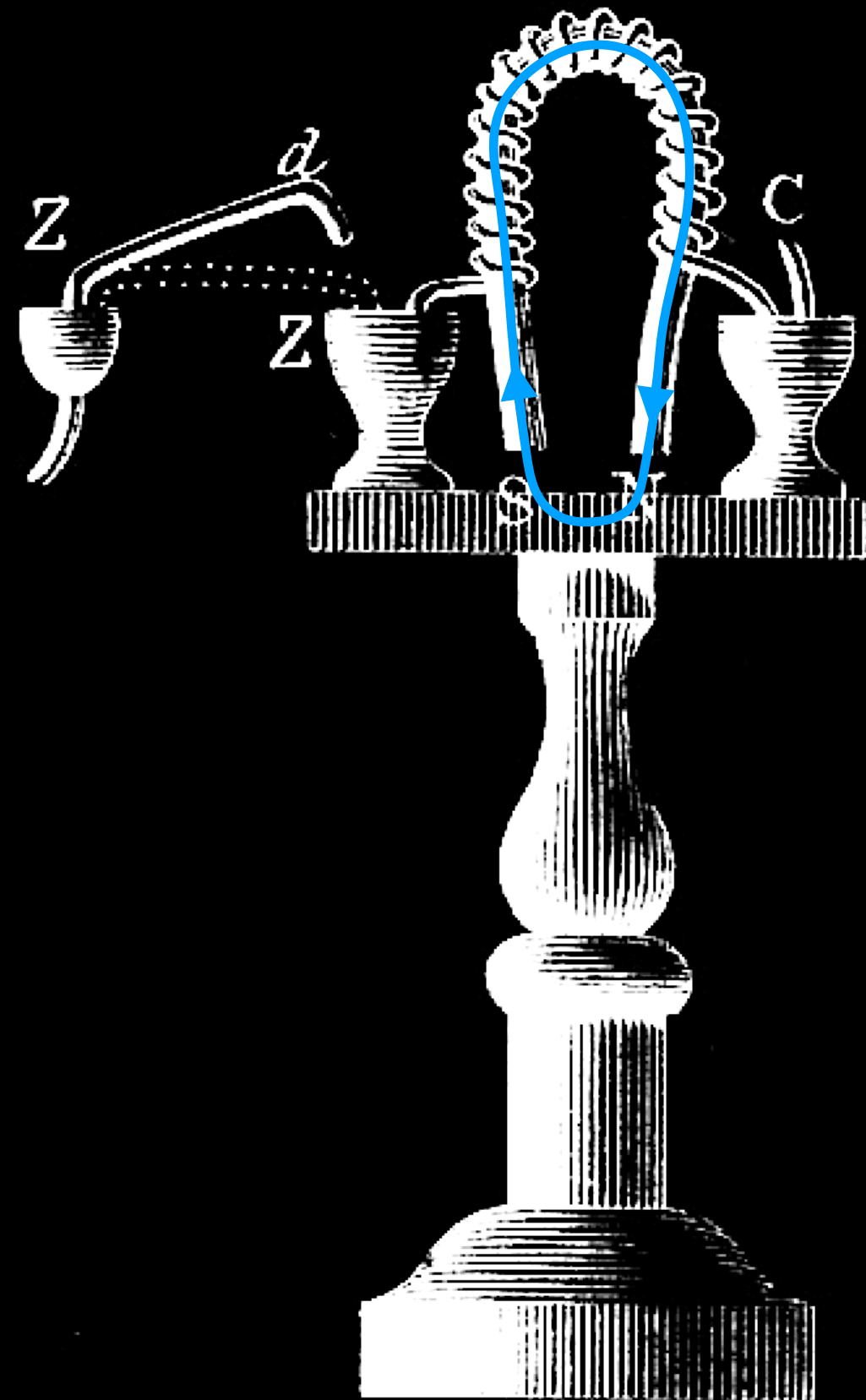
“The science of electro-magnetism, although so generally interesting, appears to be very little understood, in a great measure, owing to the difficulty of making the experiments, and the great expense attending the process.”

“Another obstacle is that the experiments being hitherto exhibited on so small a scale are by no means calculated to illustrate the subject in public lectures.”

“Even when the experimenter succeeds to his wishes (which is not frequently the case), the experiment can only be seen by a very near observer, others are obliged to take for granted what they hear reported [...]”



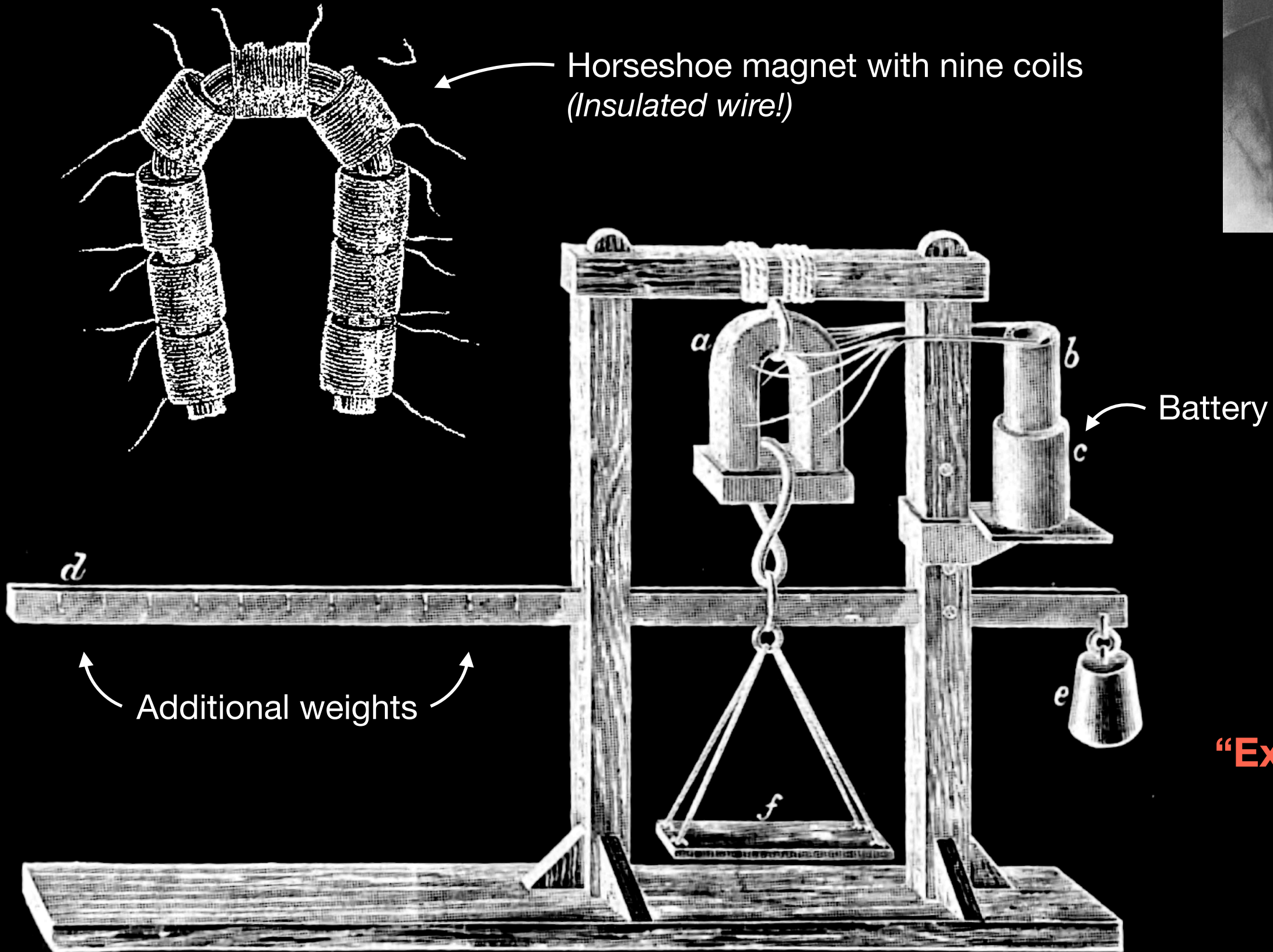
The first electromagnet (1826)



“On making the galvanic connexion through the copper wire, the iron wire becomes a strong horse-shoe magnet, and will support a heavy bar of iron; but on lifting the connecting wire, the weight immediately drops.”



Larger magnets: Joseph Henry



**“Experiment 13.
All nine coils:
lifted 650 lbs”**

Back to Faraday: electrical induction

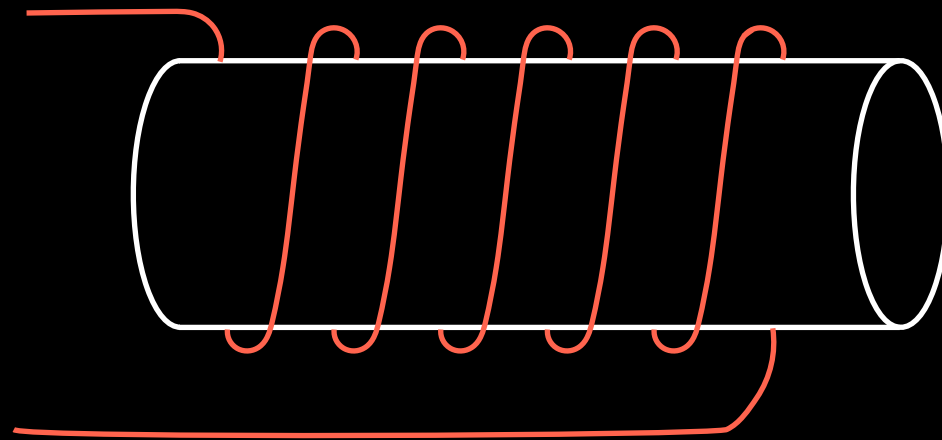
“The hope of obtaining electricity from ordinary magnetism [has] stimulated me at various times to investigate experimentally the inductive effect of electric currents.”

“I lately arrived at positive results.”

*V. Experimental Researches in Electricity. By MICHAEL FARADAY, F.R.S.,
M.R.I., Corr. Mem. Royal Acad. of Sciences of Paris, Petersburg, &c. &c.*

Read November 24, 1831.

The first experiment



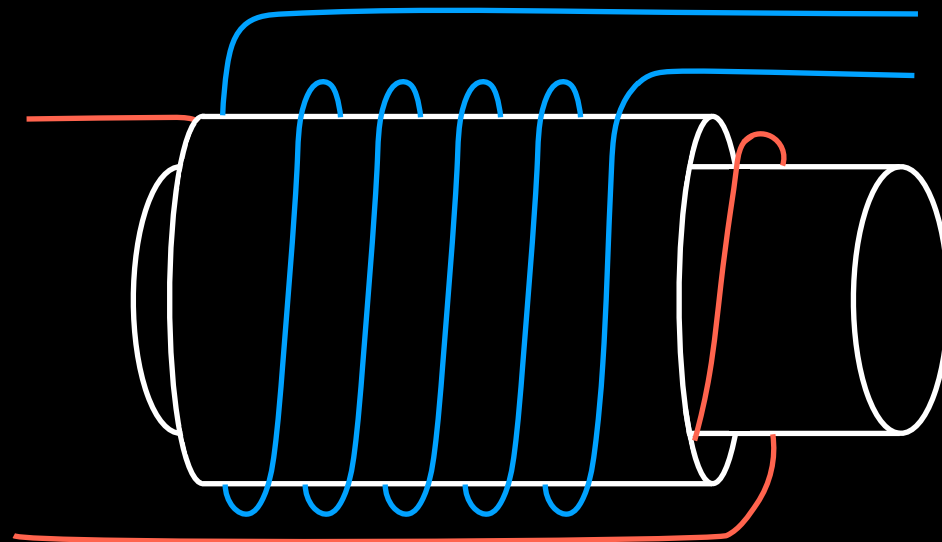
“About twenty-six feet of copper wire were wound round a cylinder of wood as a helix.”

The first experiment



“This helix was covered with [cotton cloth] ...”

The first experiment

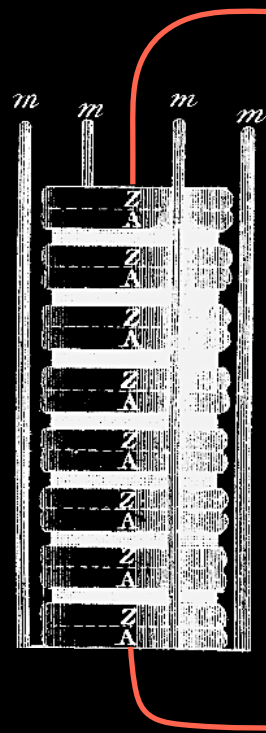


“... and then a second wire applied in the same manner.”

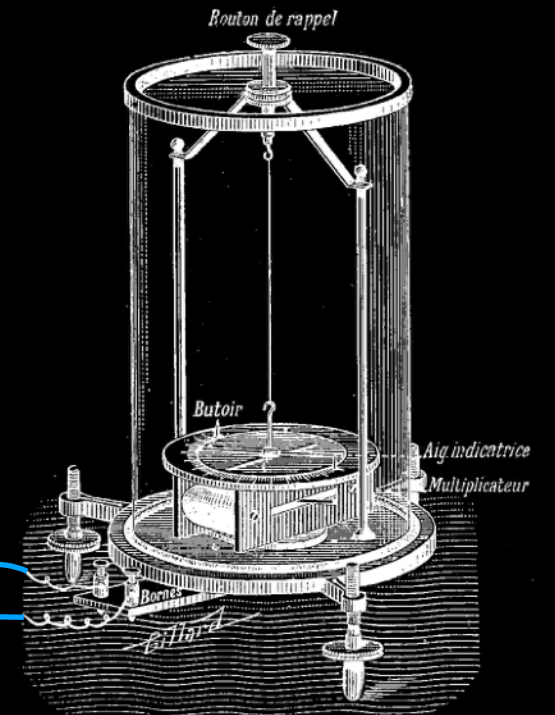
“This produced two principal helices, closely interposed, having the same direction, and not touching anywhere.”

The first experiment

Voltaic pile

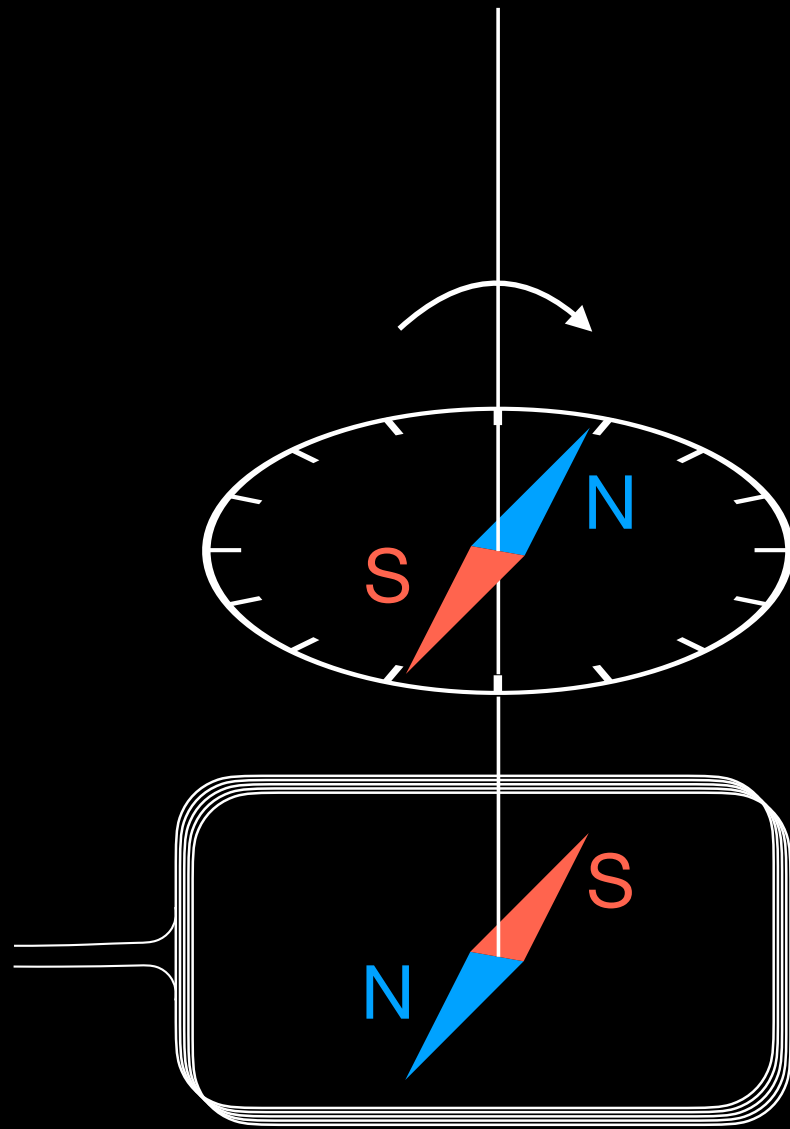


Galvanometer



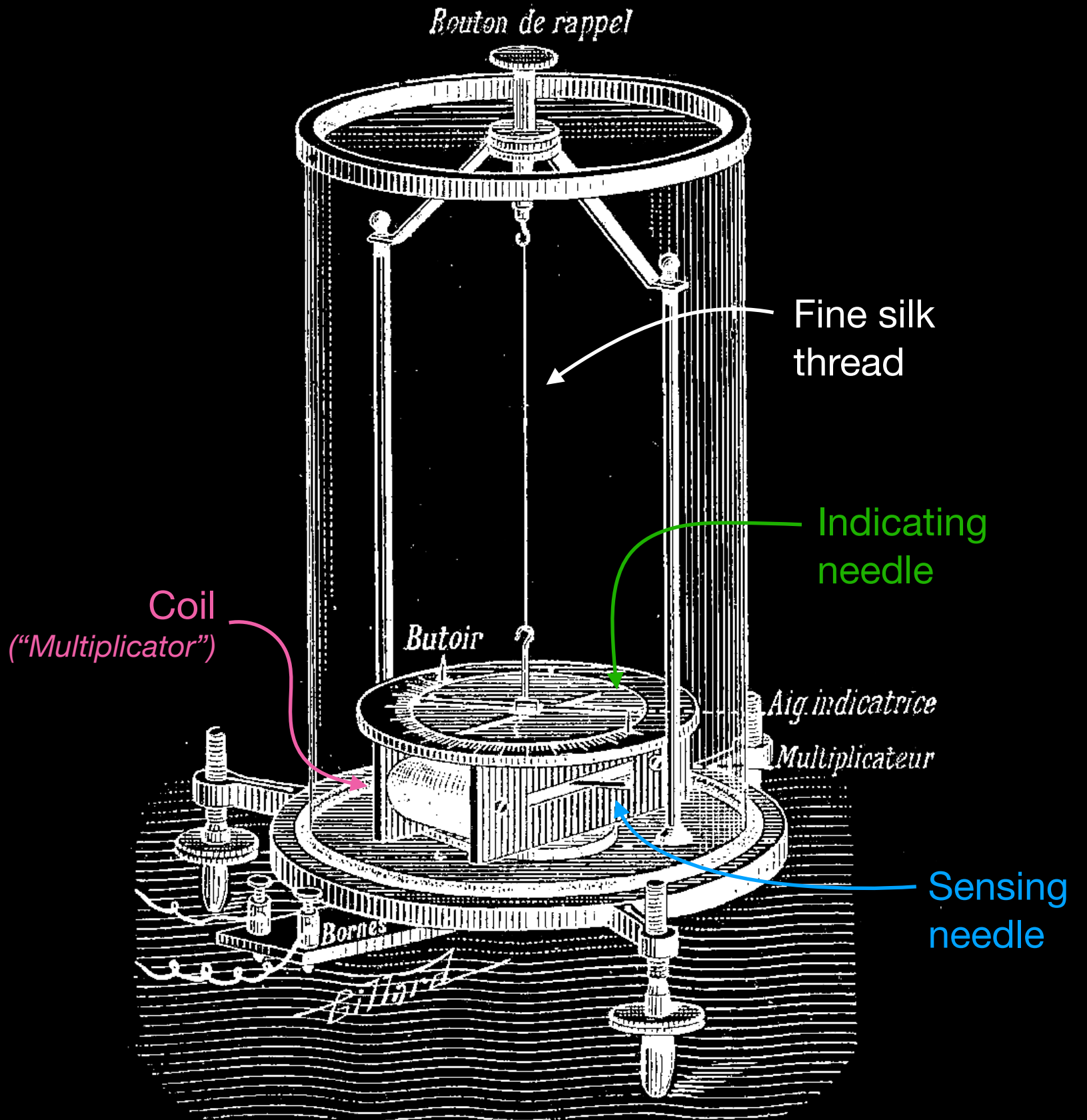
“One of these helices was connected with a galvanometer, the other with a voltaic battery.”

Faraday's Galvanometer



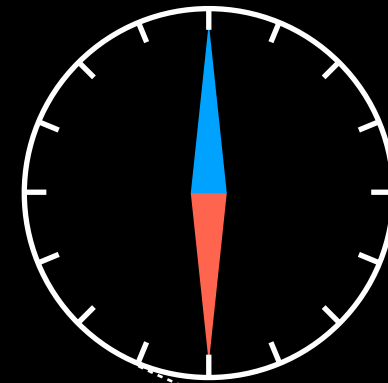
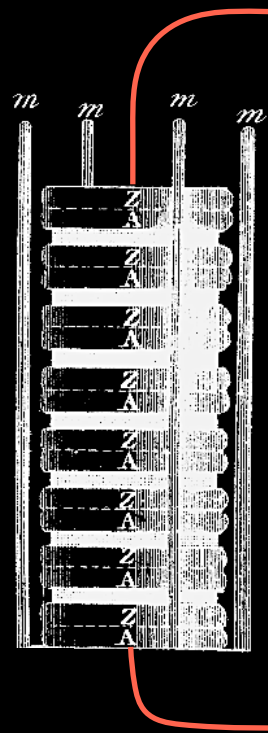
Two magnetic needles in opposite orientation:

Compensation of Earth's magnetic field

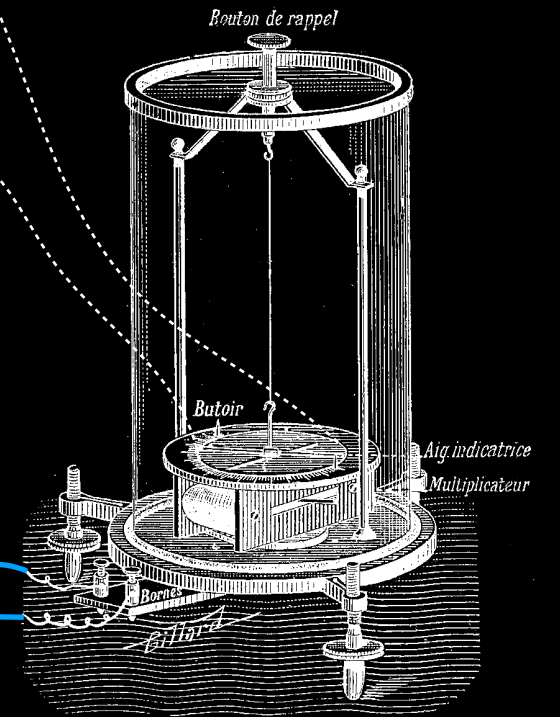


The first experiment

Voltaic pile

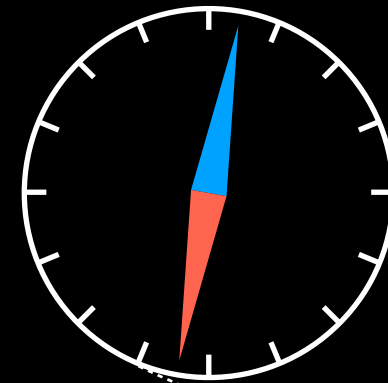
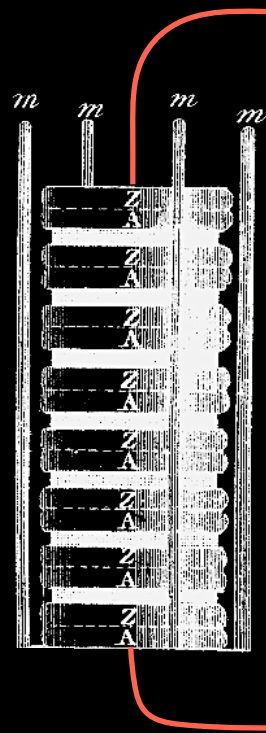


Galvanometer

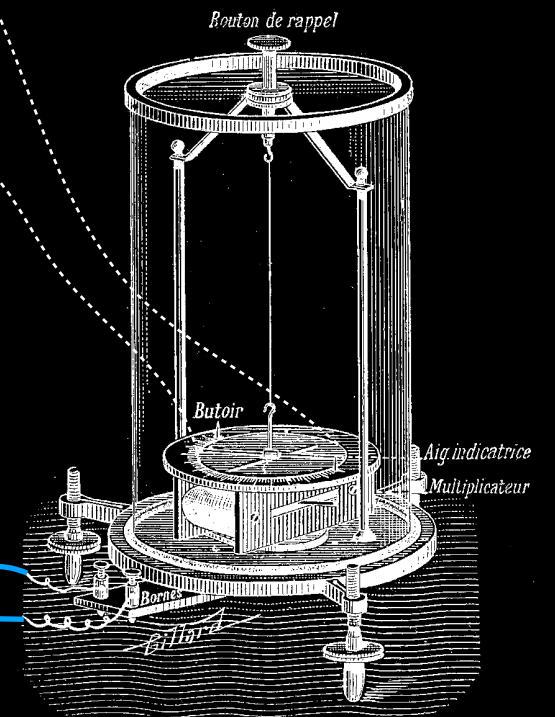


The first experiment

Voltaic pile



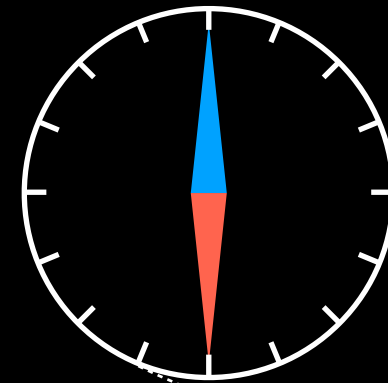
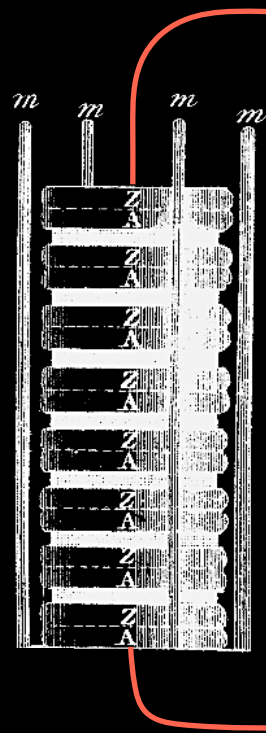
Galvanometer



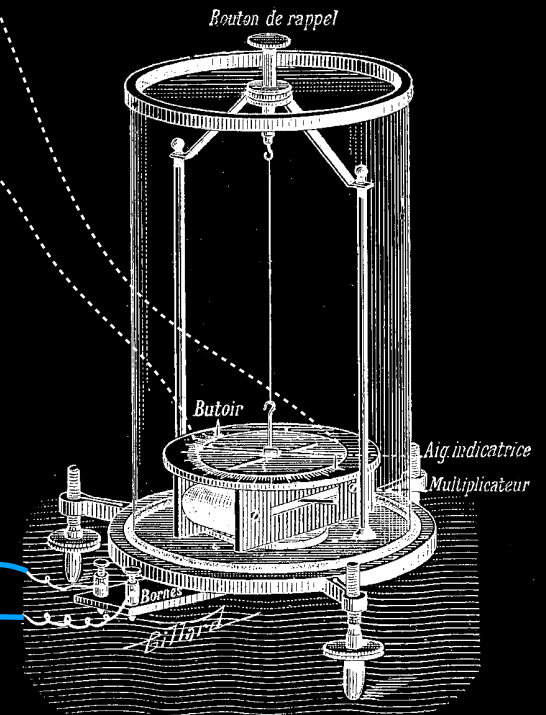
“When the contact was made, there was a sudden and very slight effect at the galvanometer.”

The first experiment

Voltaic pile



Galvanometer

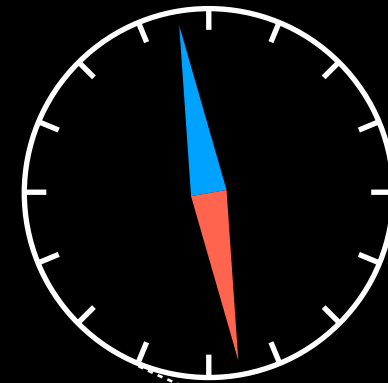
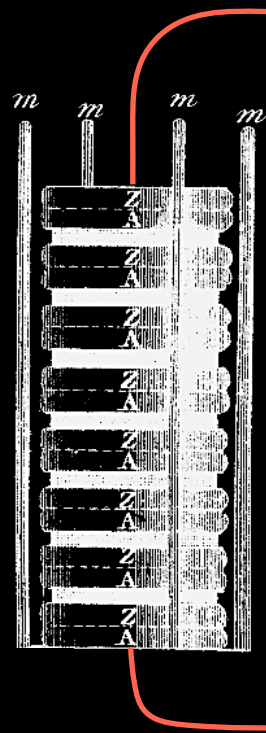


“When the contact was made, there was a sudden and very slight effect at the galvanometer.”

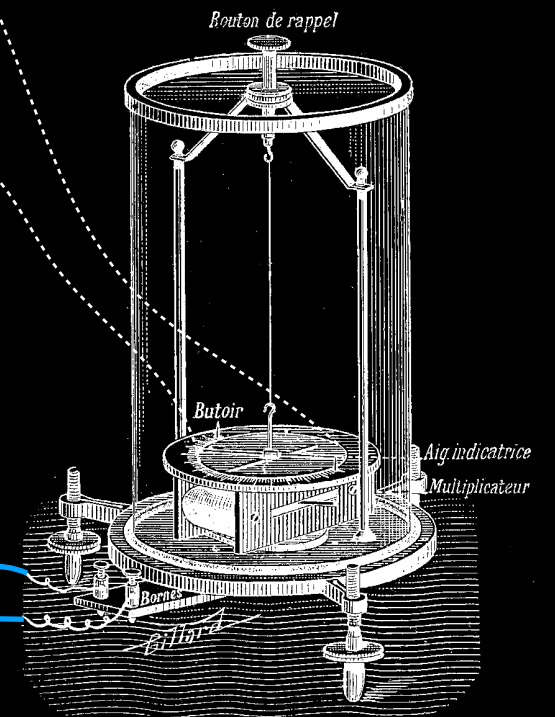
“But whilst the voltaic current was continuing to pass through the one helix, no galvanometrical appearances of any effect could be perceived, although the active power of the battery was proved to be great.”

The first experiment

Voltaic pile



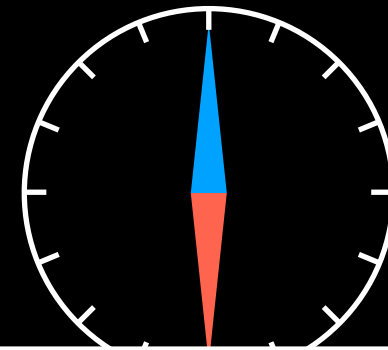
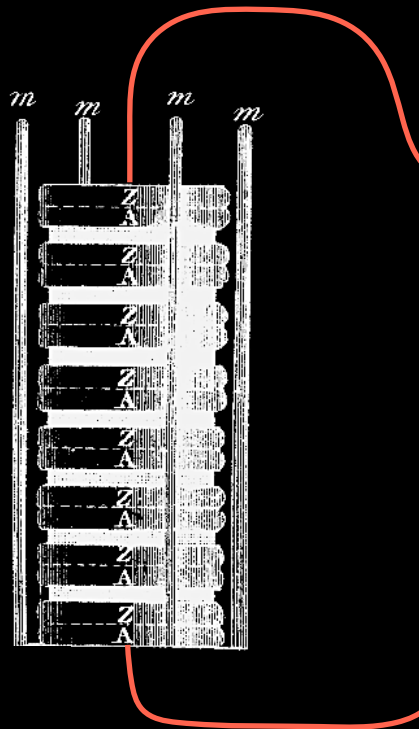
Galvanometer



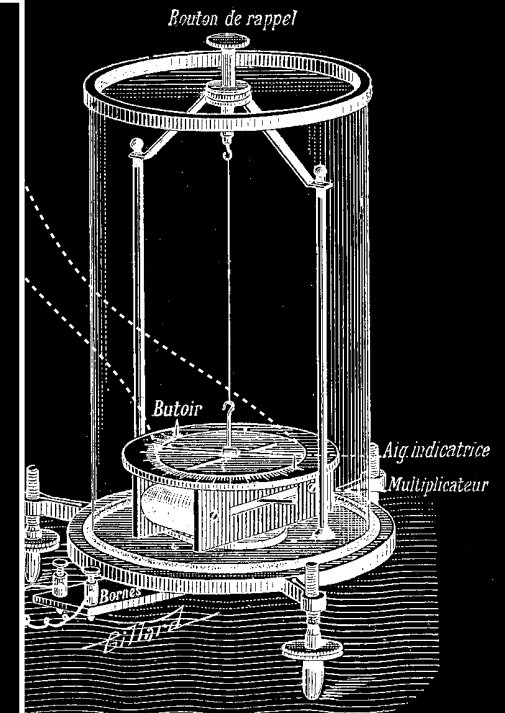
“There was also a similar slight effect, but in the opposite direction, when the contact with the battery was broken.”

The first experiment

Voltaic pile



Galvanometer



"[...] it continued for an instant only, and partook more of the nature of the shock of a common Leyden jar than of that from a voltaic battery."

"I could obtain no evidence by the tongue, by spark, or by heating fine wire, of the electricity passing through the wire under induction."

"There was also a similar slight effect, but in the opposite direction, when the contact with the battery was broken."

Increasing the strength

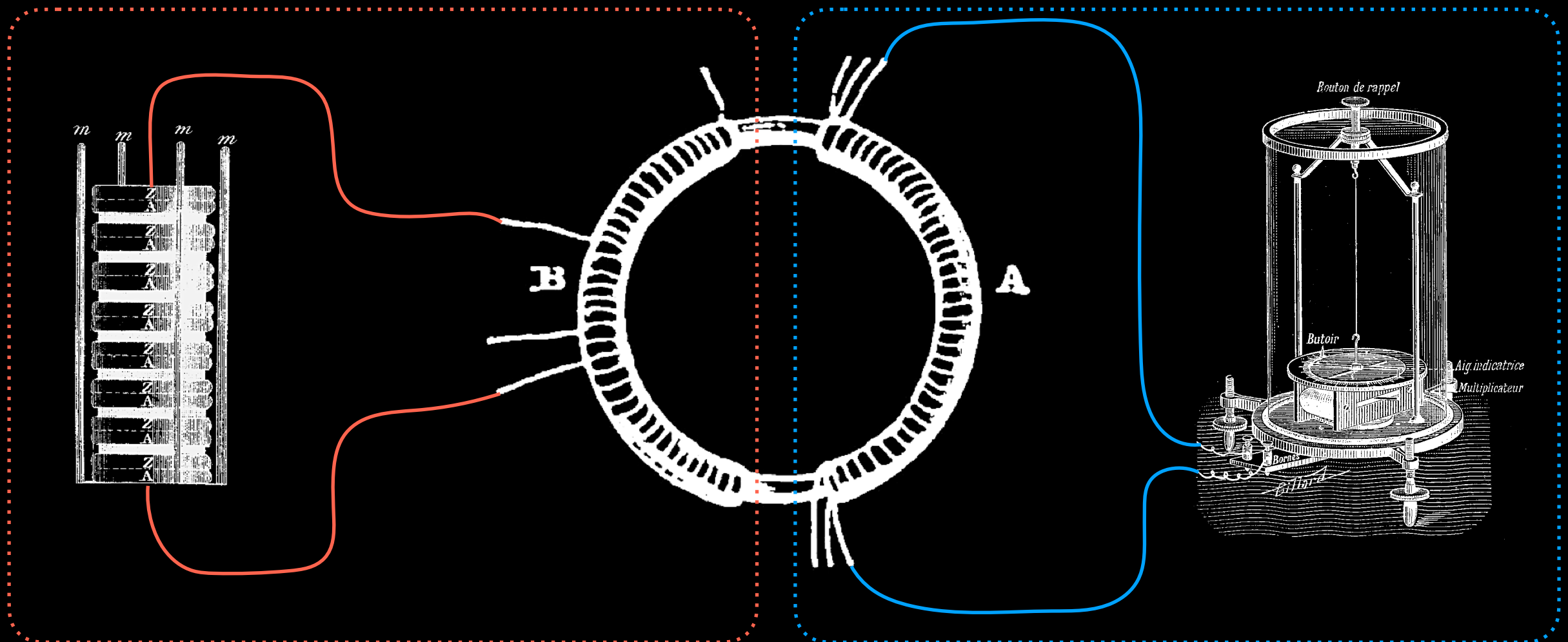
“A welded ring was made of soft round bar-iron, [several] helices were put round the ring.”

“The helix B was connected by copper wires with a galvanometer; the wires of A were connected with a battery of ten pairs of plates.”

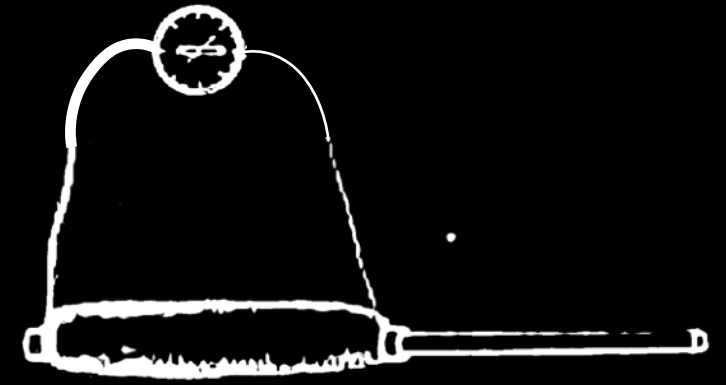
“The galvanometer was immediately affected, and to a degree far beyond what has been described.”

Electromagnet: “transmitter”

Coil: “receiver”

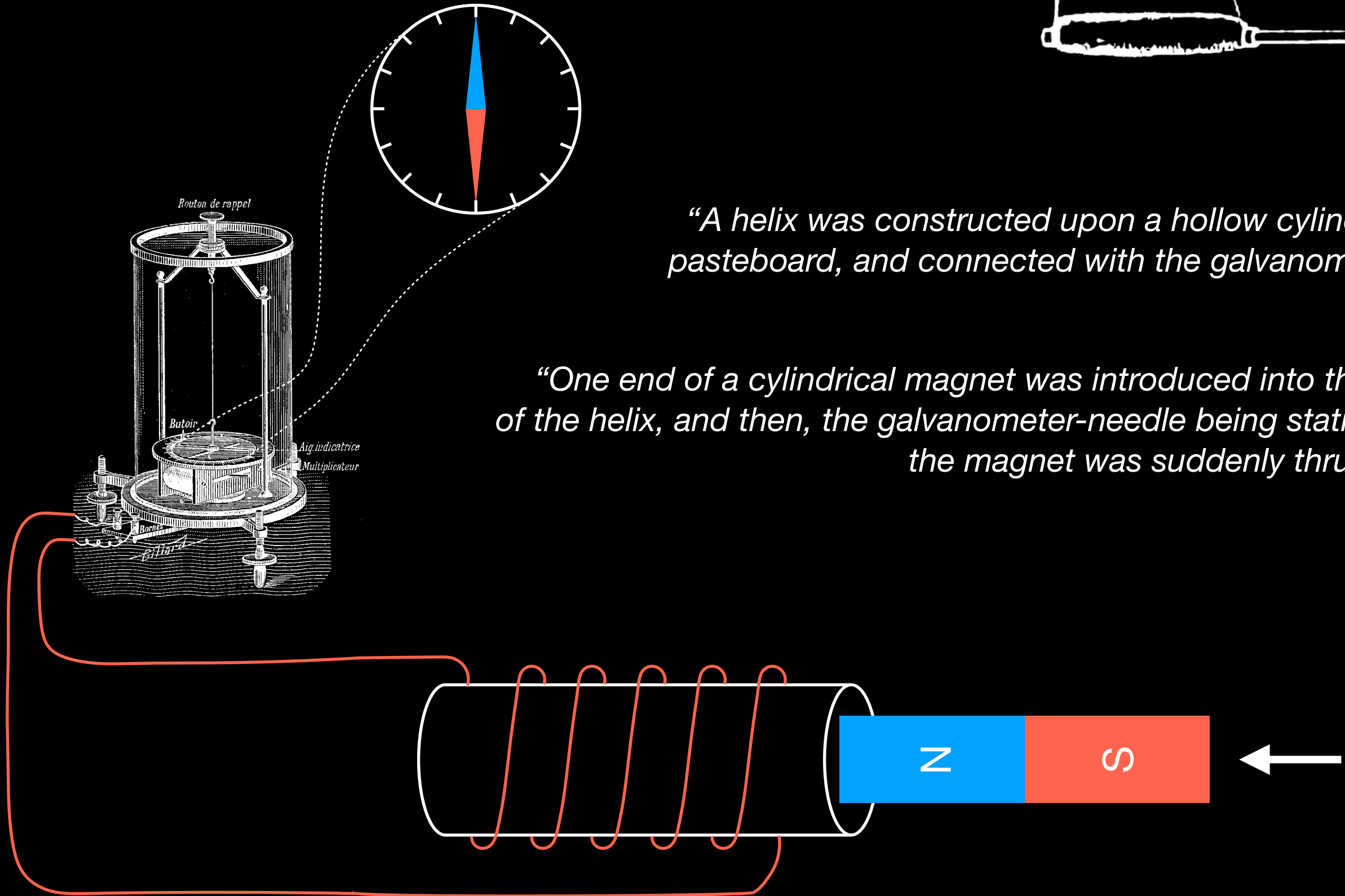


Electricity from motion

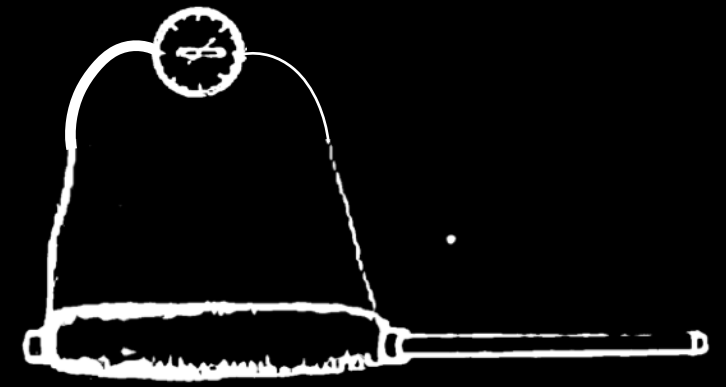


“A helix was constructed upon a hollow cylinder of pasteboard, and connected with the galvanometer.”

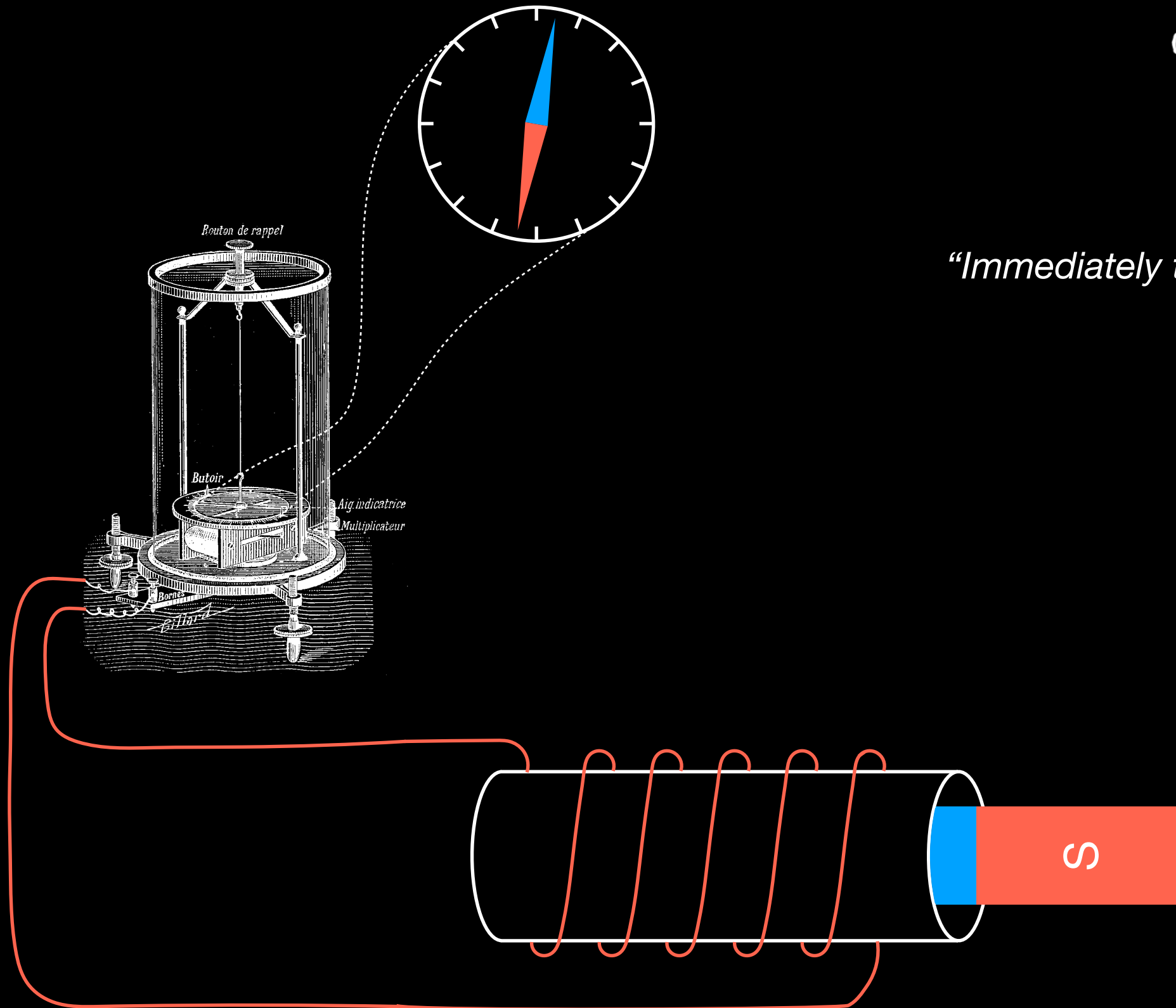
“One end of a cylindrical magnet was introduced into the axis of the helix, and then, the galvanometer-needle being stationary, the magnet was suddenly thrust in.”



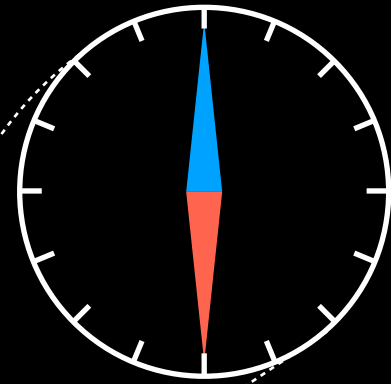
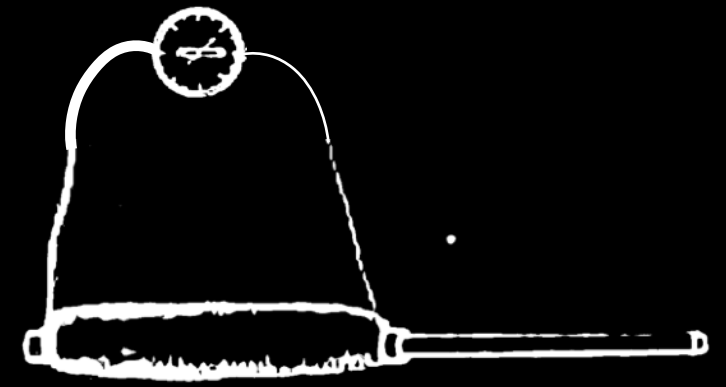
Electricity from motion



“Immediately the needle was deflected.”

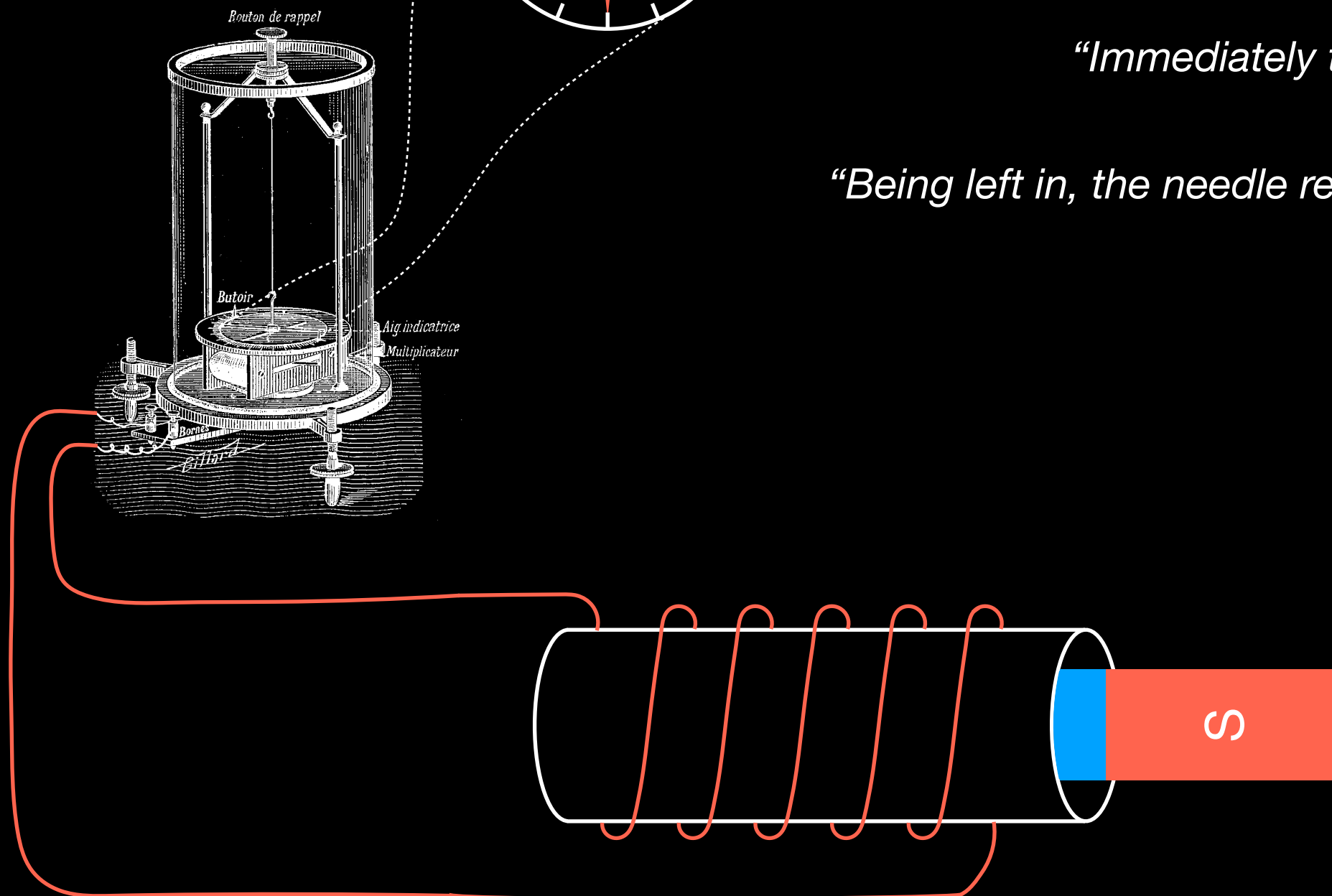


Electricity from motion

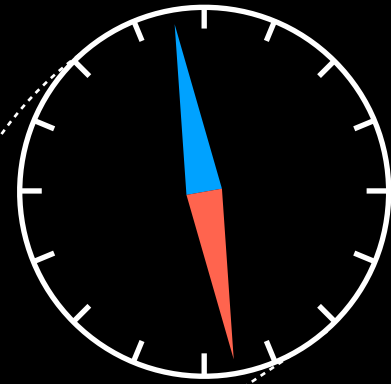
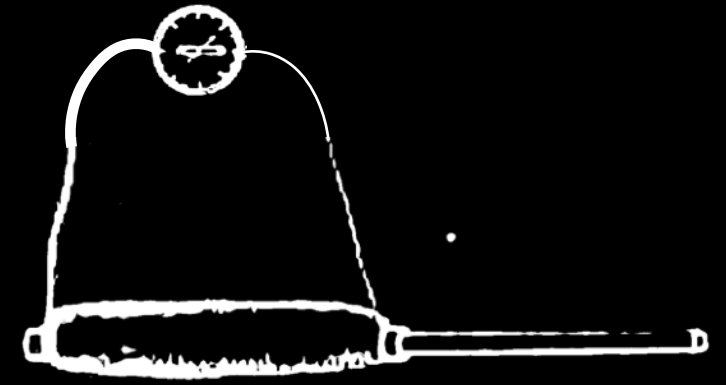


“Immediately the needle was deflected.”

“Being left in, the needle resumed its first position ...”



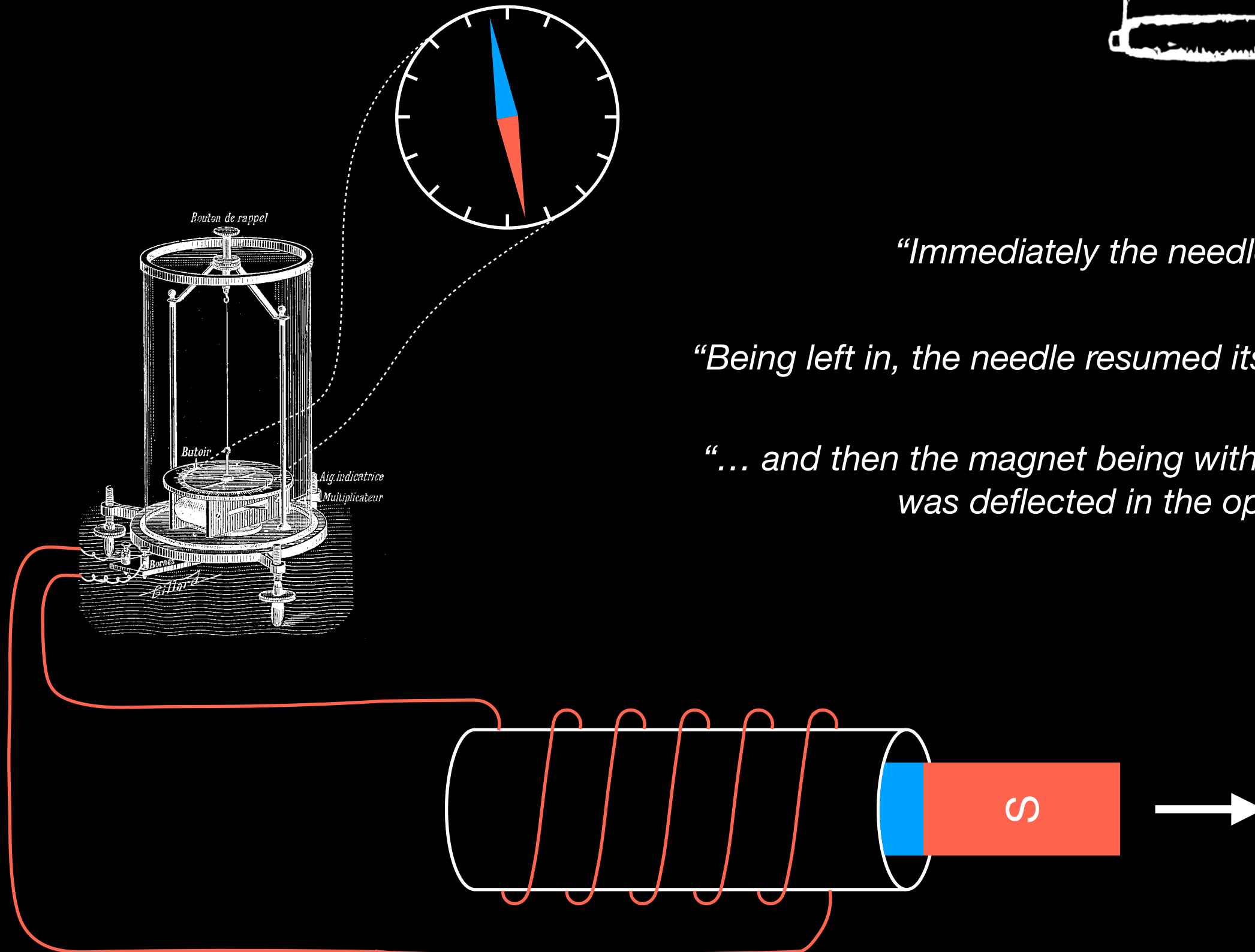
Electricity from motion



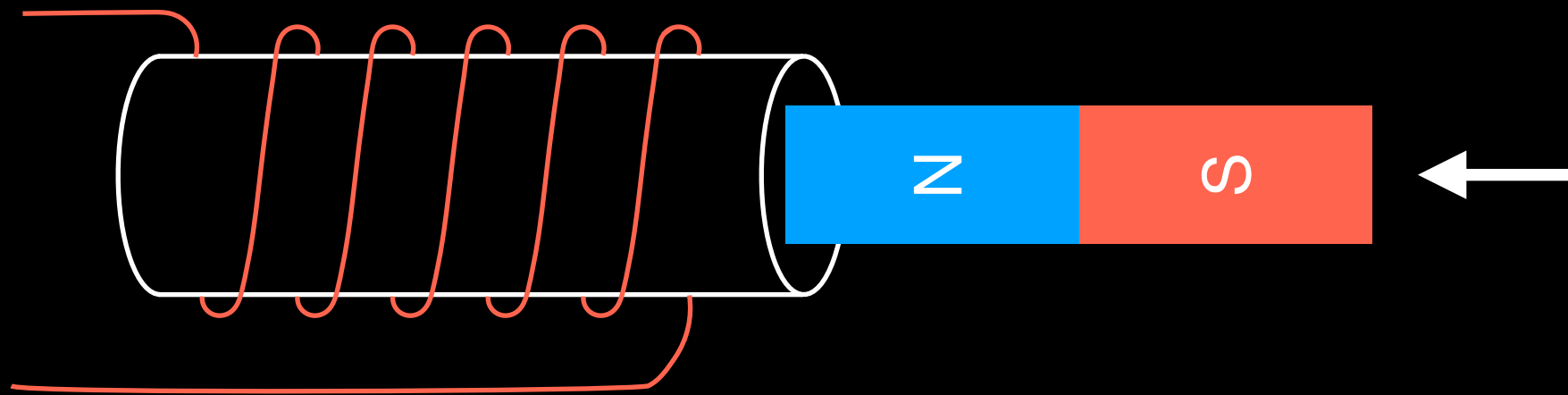
“Immediately the needle was deflected.”

“Being left in, the needle resumed its first position ...”

“... and then the magnet being withdrawn the needle was deflected in the opposite direction.”



The law of induction



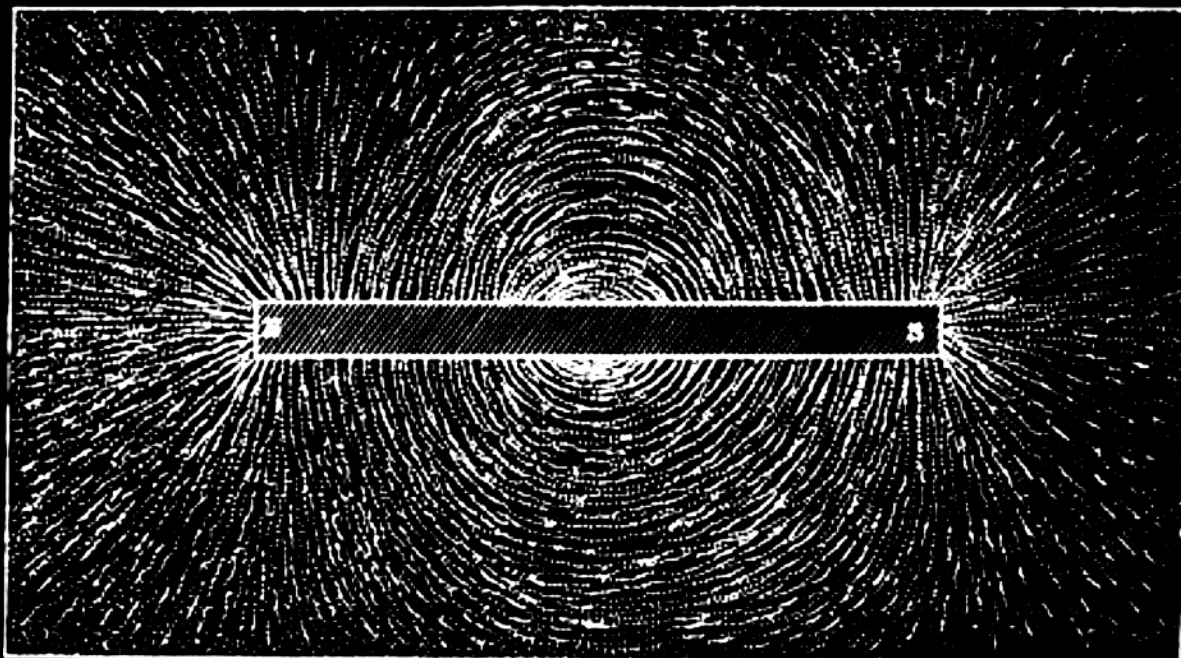
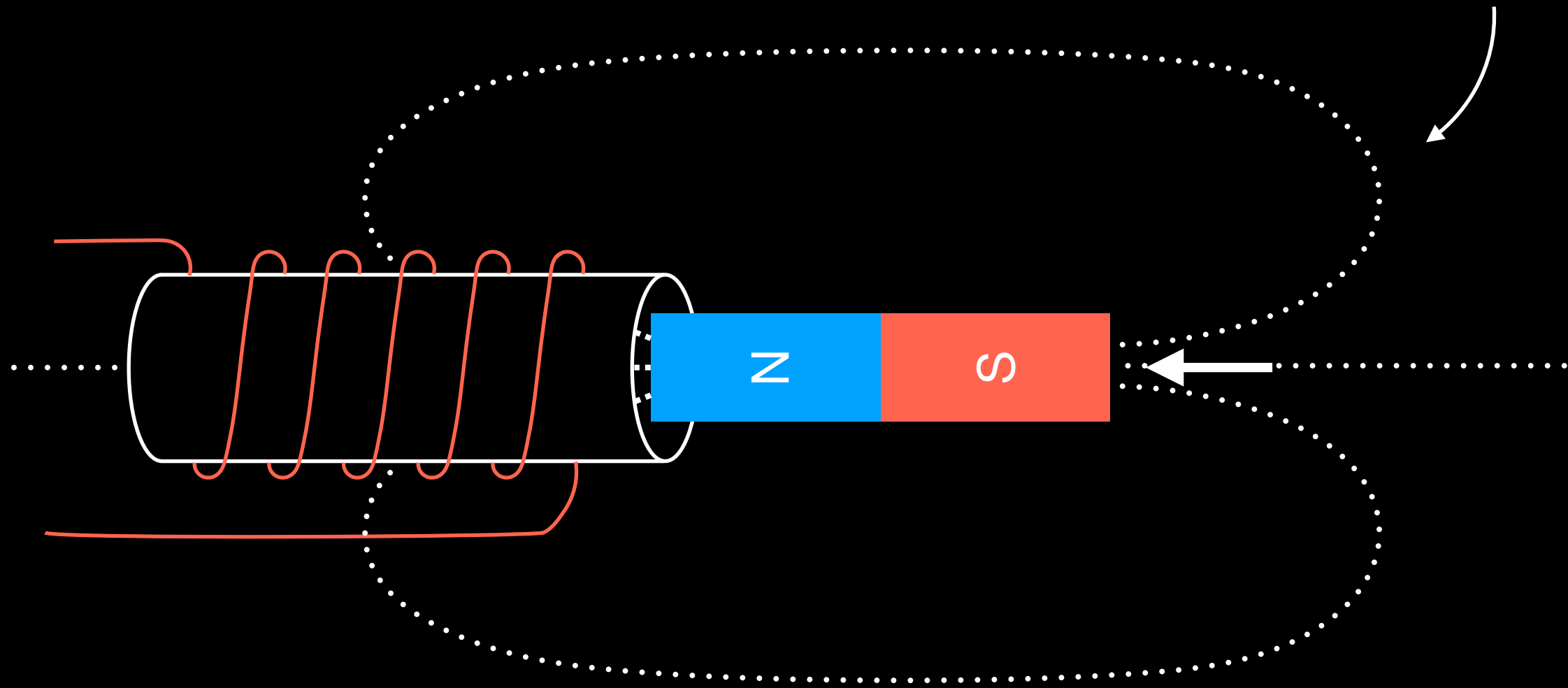
“The law which governs the evolution of electricity by magneto-electric induction is very simple, although rather difficult to express.”

“If the wire moves so as to cut the magnetic curves [...], then a current of electricity is evolved in the wire.”

(Abridged version)

The law of induction

“By magnetic curves, I mean the lines of magnetic forces, which would be depicted by iron filings.”



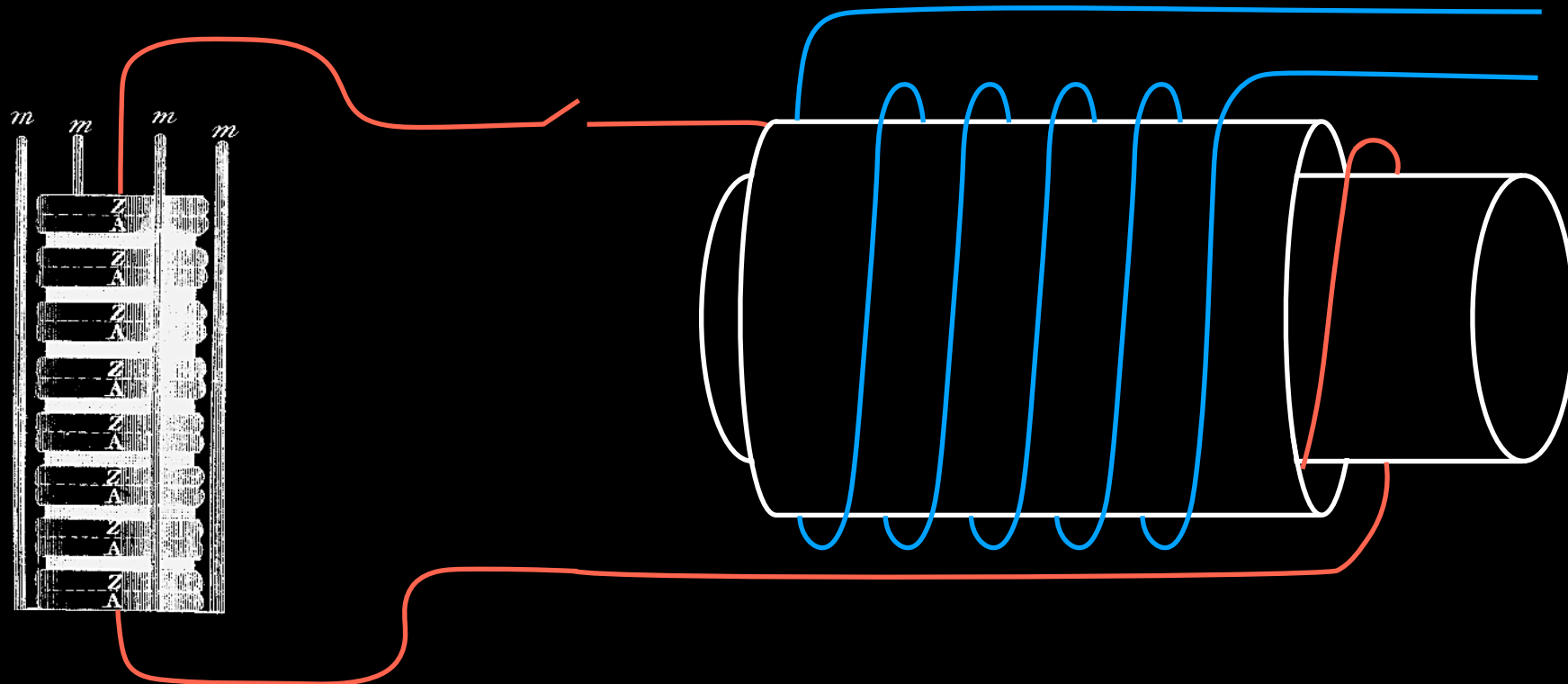
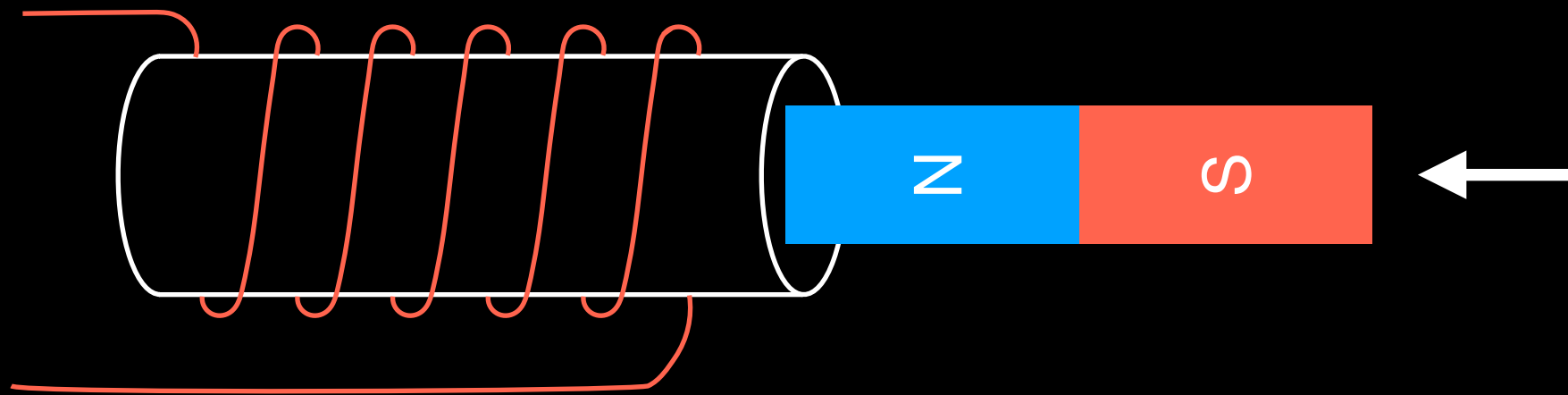
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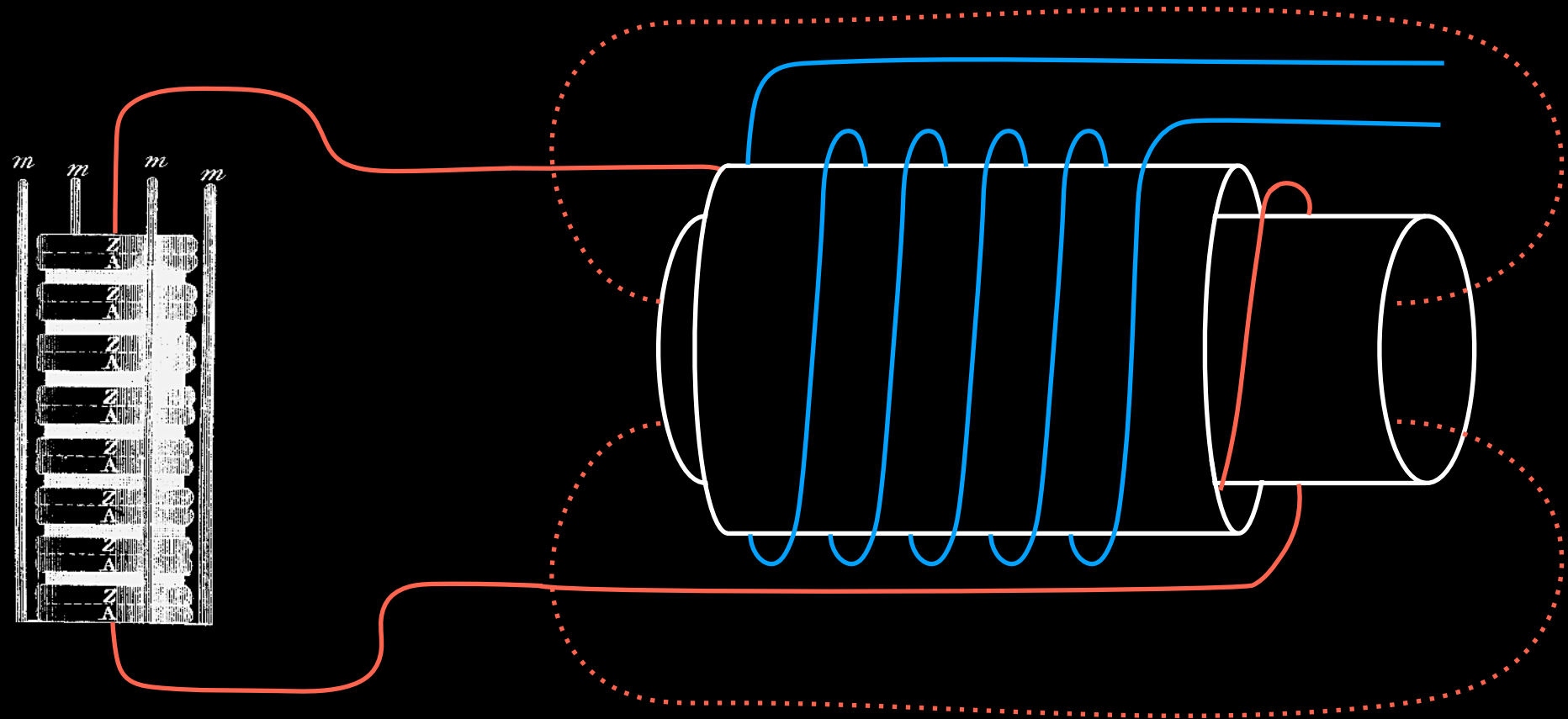
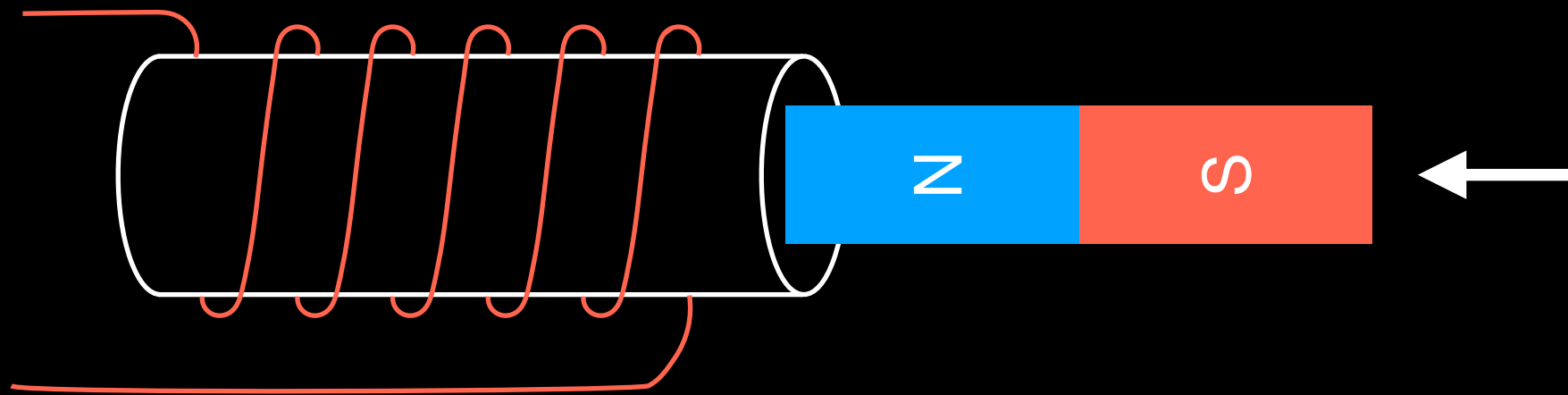
The law of induction

Turning on an electromagnet produces (almost identical) “lines of magnetic forces” that cut the wires



The law of induction

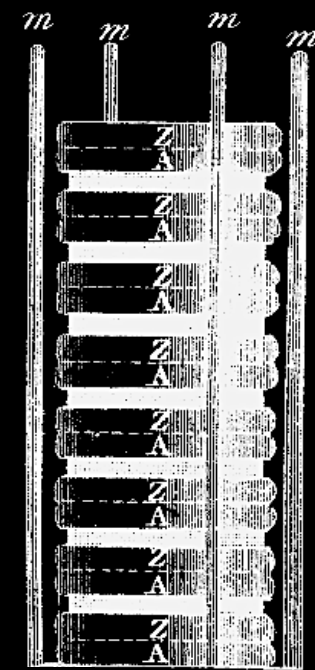
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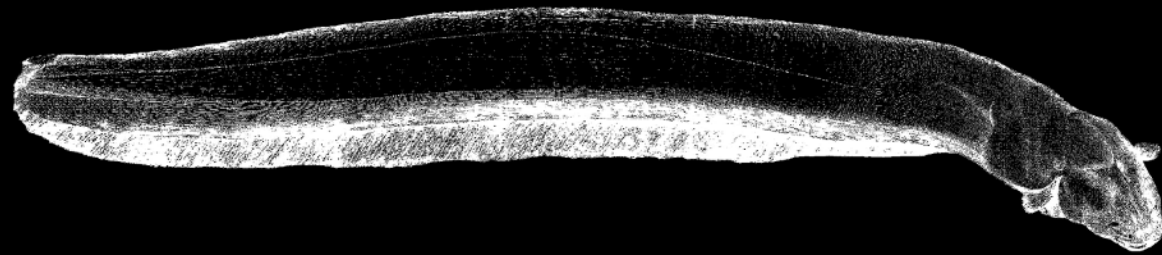
Different kinds of electricity?

“The progress of the electrical researches brought me to a point at which it was essential that no doubt should remain of the identity or distinction of electricities excited by different means.”

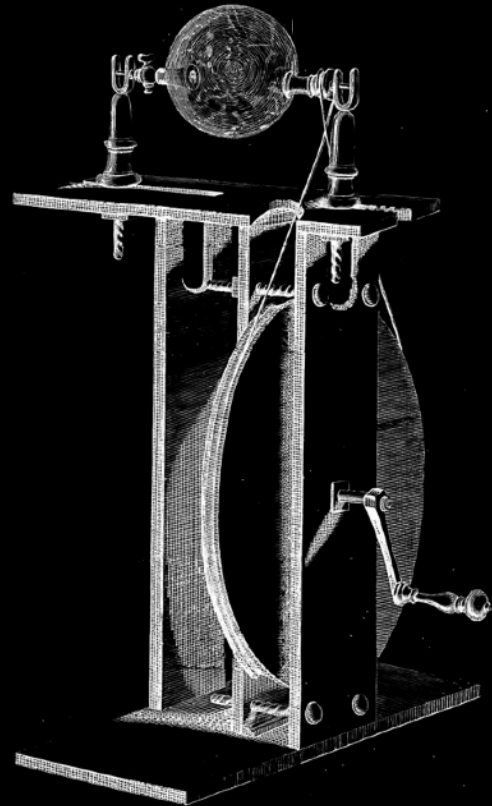
“Voltaic electricity”



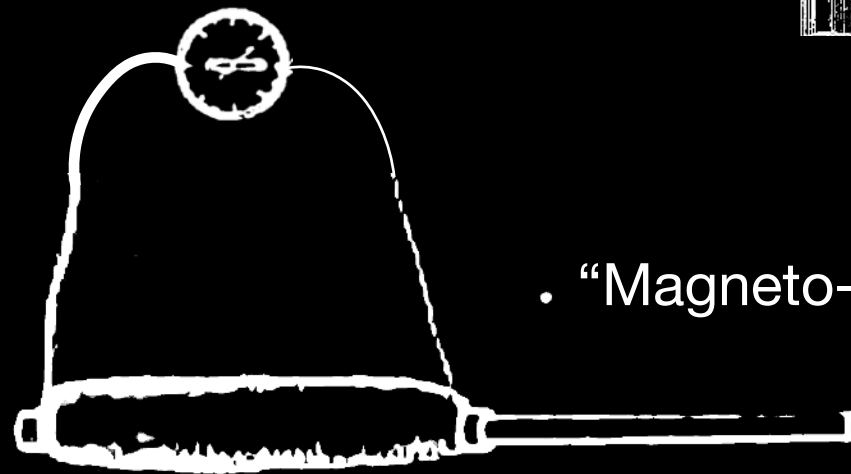
“Animal electricity”



“Common electricity”

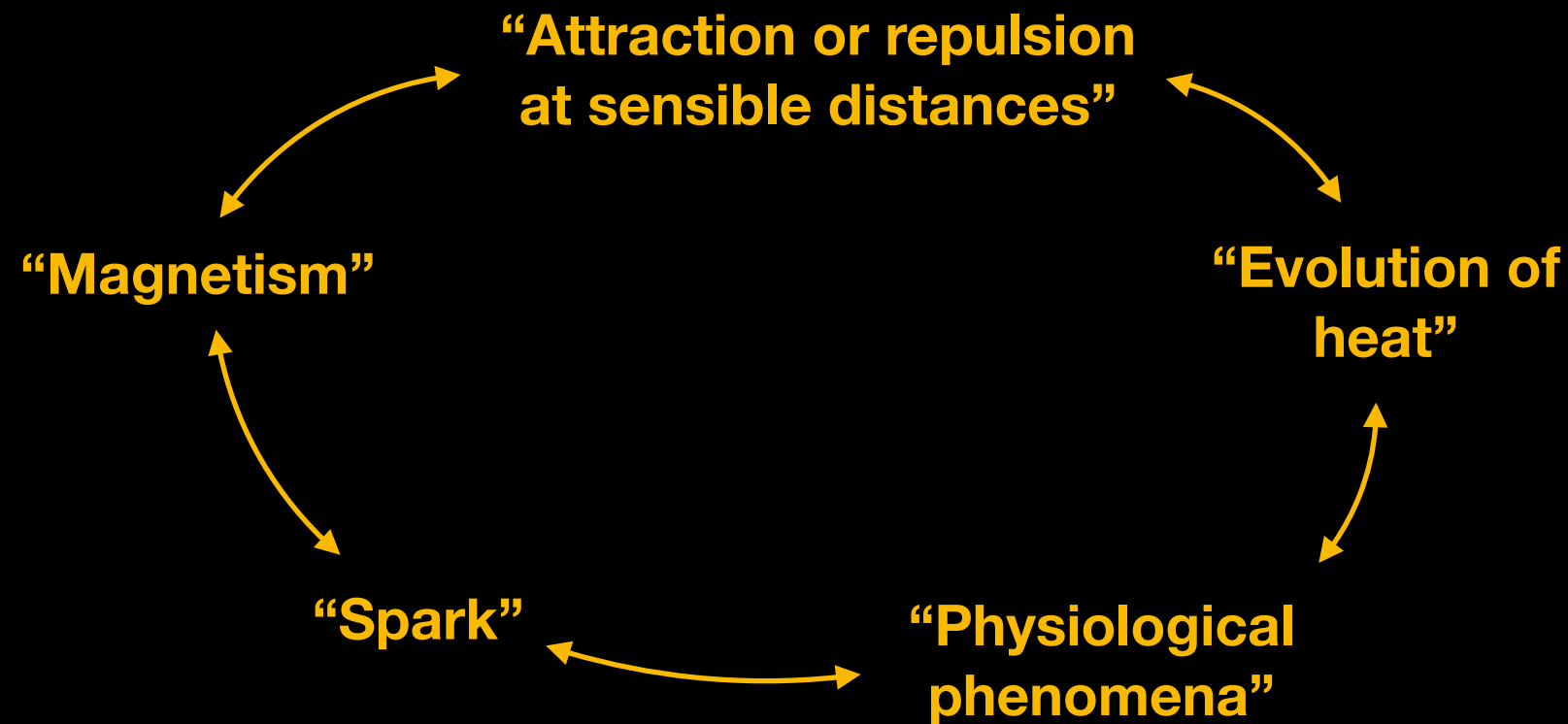


“Magneto-electricity”



Effects of electricity

“The various phenomena exhibited by electricity may, for the purpose of comparison, be [summarized]:”



“It will be my object to compare electricities from different sources, and especially common and voltaic electricities, by their power of producing these effects.”

If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck!

Assembling the facts

“The deflections were in the same direction as if a voltaic current had been passed through the galvanometer; the positively charged surface of the Leyden jar coincided with the positive end of the voltaic apparatus [...]”

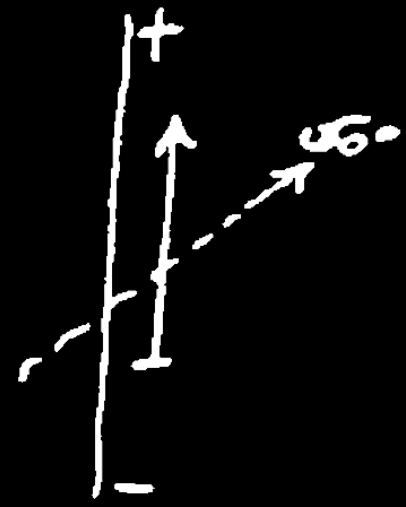
“The brilliant star of light produced by the discharge of a voltaic battery is known to all as the most beautiful light that man can produce by art.”

	Physiological Effects.	Magnetic Deflection.	Magnets made.	Spark.	Heating Power.	Attraction and Repulsion.	Discharge by Hot Air.
Voltaic electricity	X	X	X	X	X	X	X
Common electricity...	X	X	X	X	X	X	X
Magneto-Electricity..	X	X	X	X	X	X	
Animal Electricity...	X	X	X	+	+		

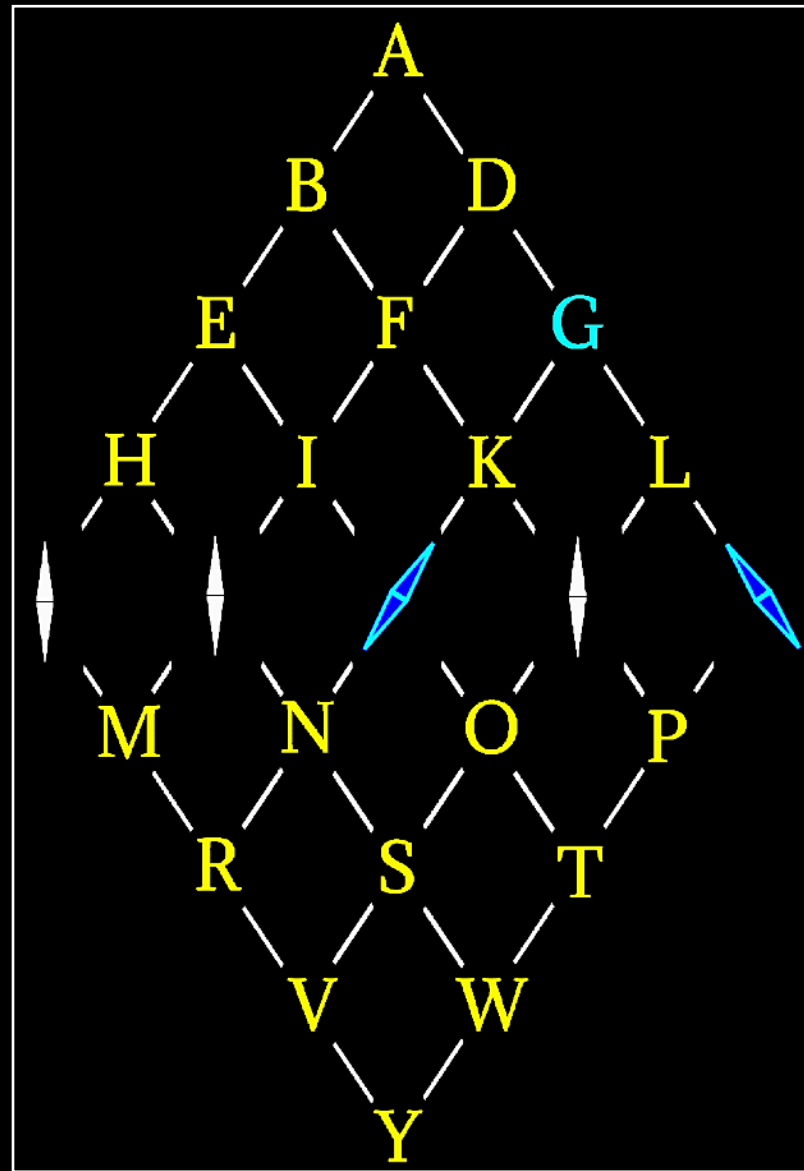
“The general conclusion which must be drawn from this collection of facts is, that electricity, whatever may be its source, is identical in its nature.”

Electricity connects the world

Electromagnets + wires = needle telegraph



From Ørsted's notebook

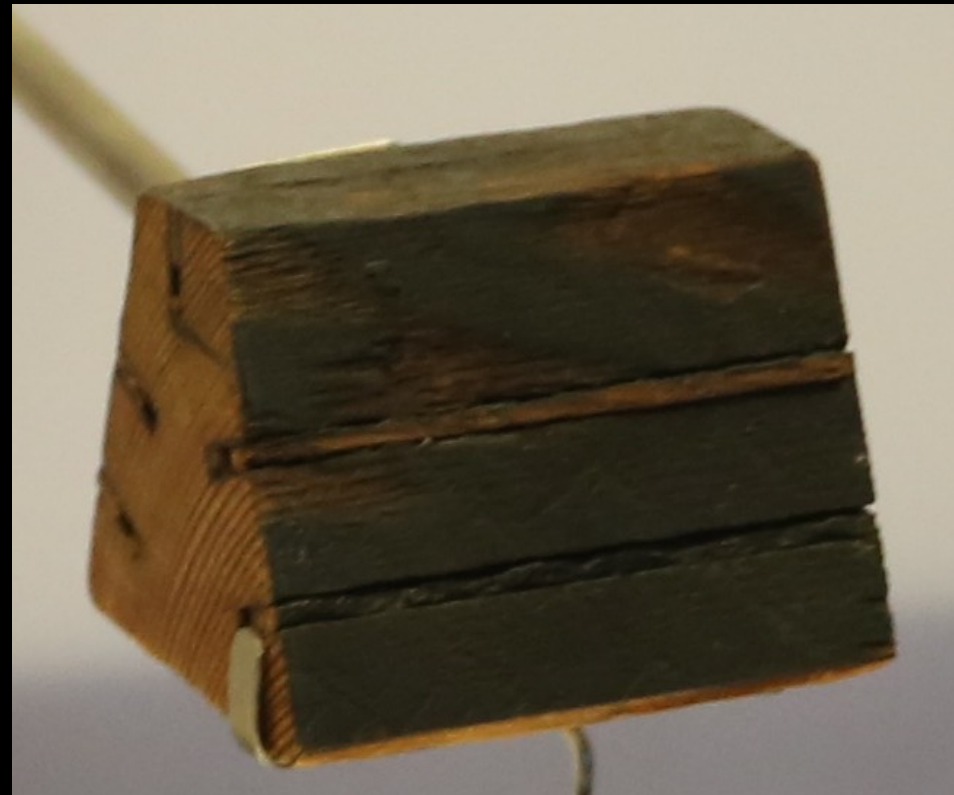


Cooke-Wheatstone telegraph (1837):

Five-needle telegraph

Used commercially along 13 miles of Great Western Railway (UK)

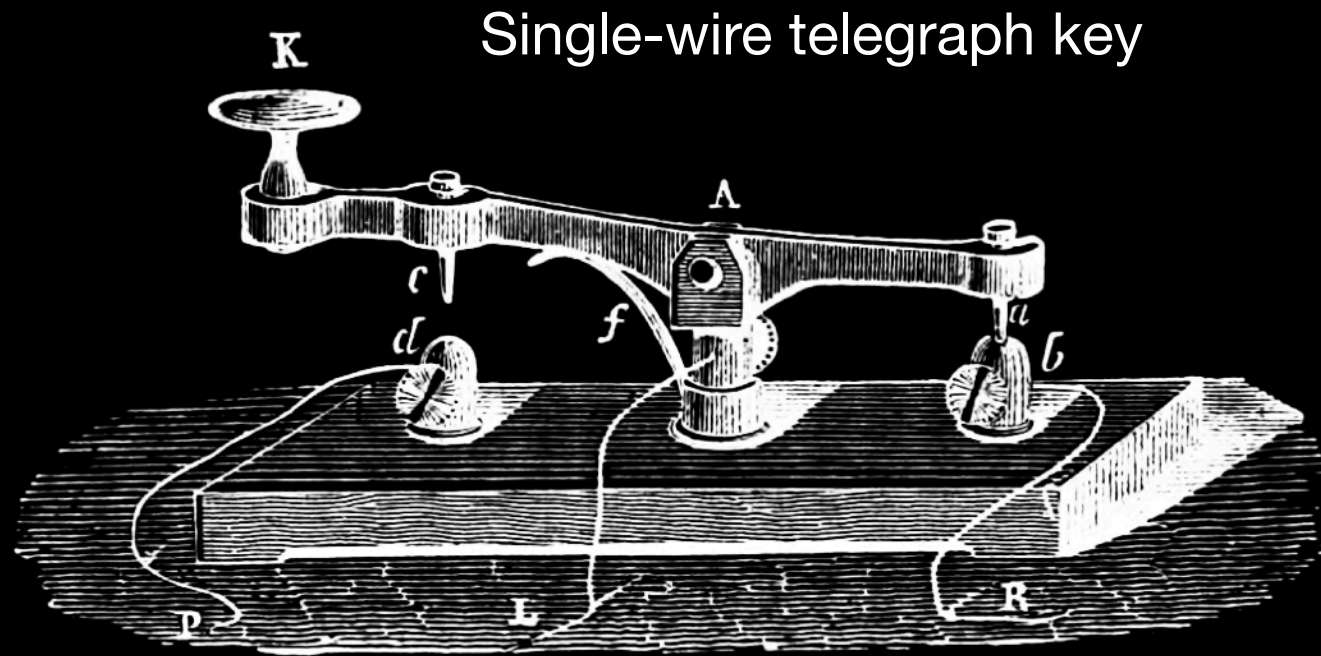
5-wire telegraph cable



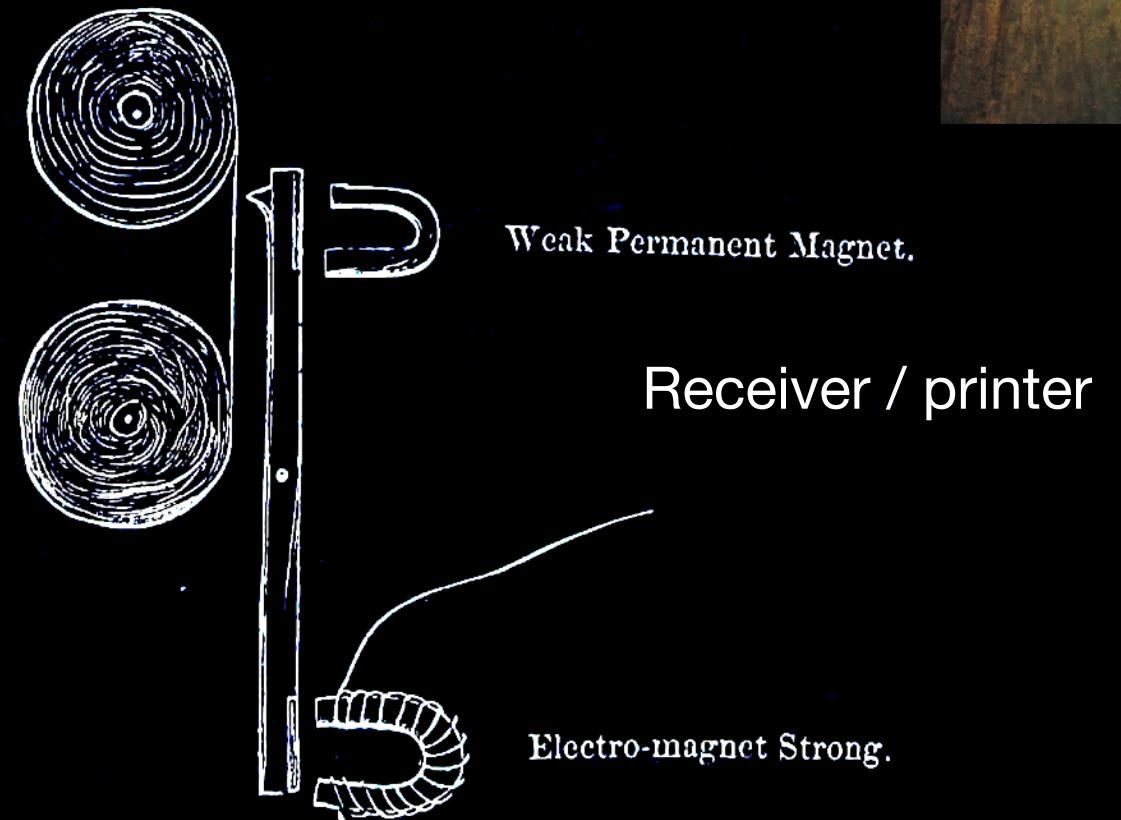
Electricity connects the world



Samuel Morse: How to efficiently cover larger distances?



Single-wire telegraph key

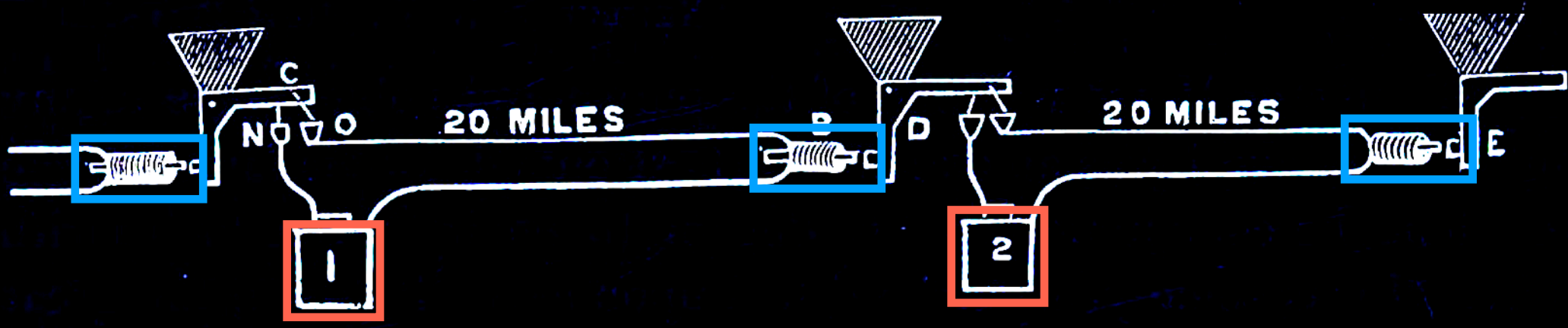


Weak Permanent Magnet.

Receiver / printer

Electro-magnet Strong.

"Relay" stations

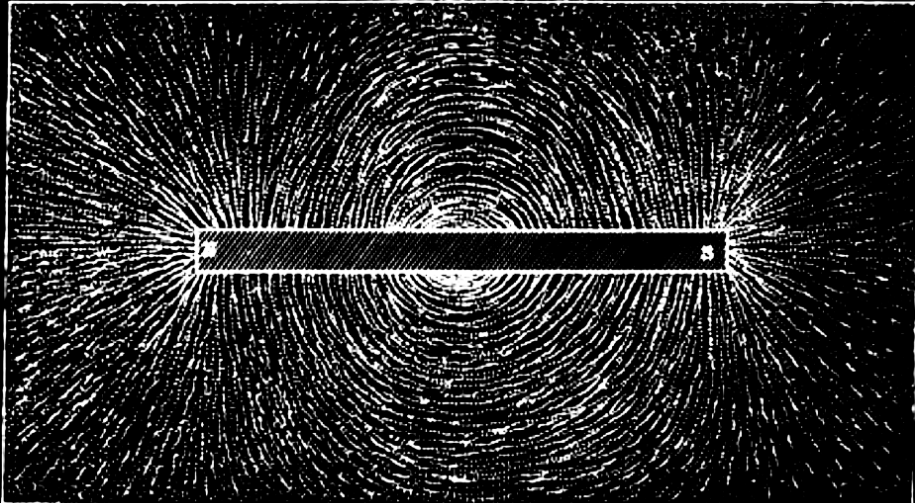


Electromagnet
Battery

Electro-magnetism

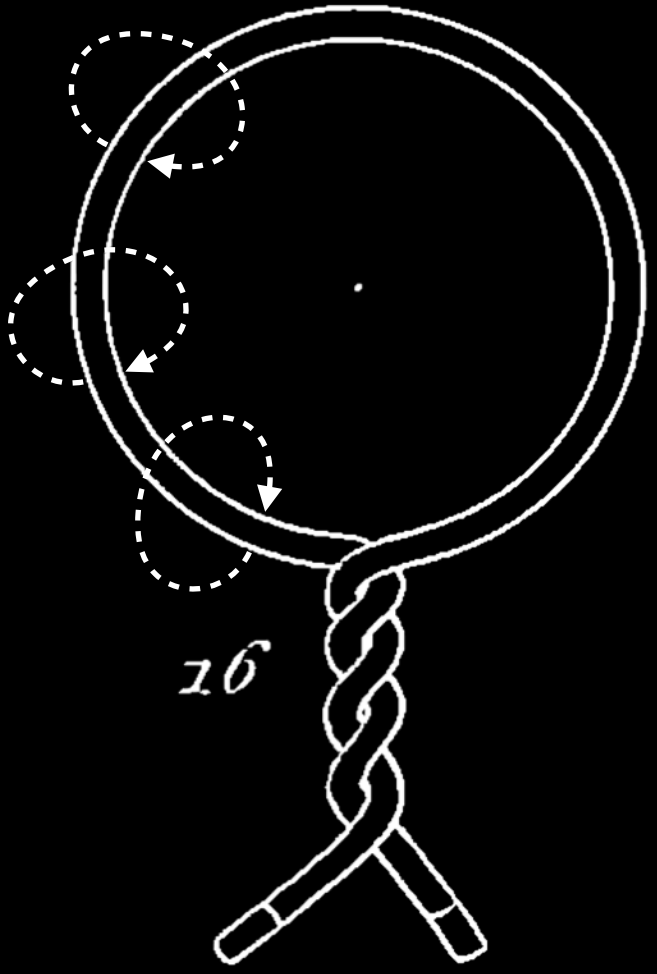
	Physiological Effects.	Magnetic Deflection.	Magnets made.	Spark.	Heating Power.	Attraction and Repulsion.	Discharge by Hot Air.
Voltaic electricity	x	x	x	x	x	x	x
Common electricity...	x	x	x	x	x	x	x
Magneto-Electricity..	x	x	x	x	x	x	
Animal Electricity...	x	x	x	+	+		

“Magnetic lines of force”

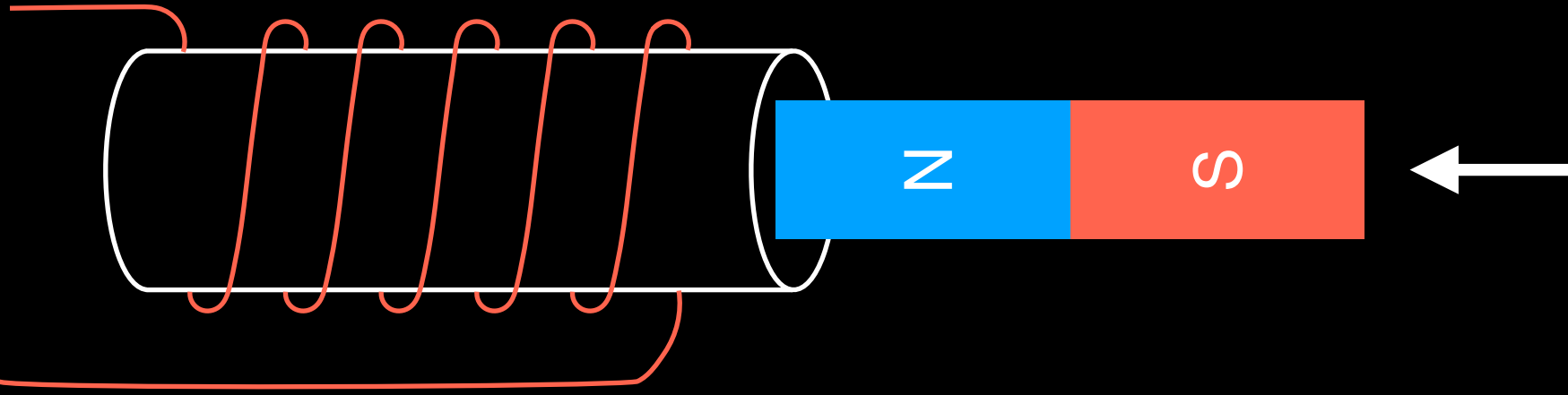


One kind of electricity

Electricity → magnetism

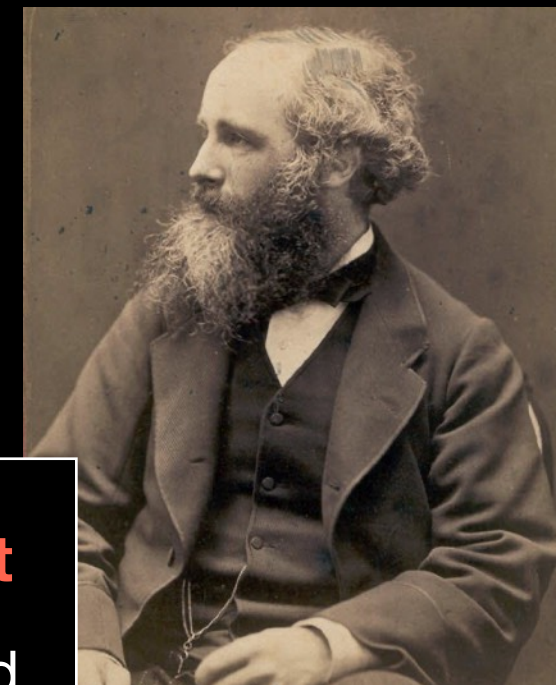


Magnetism → electricity



James Clerk Maxwell

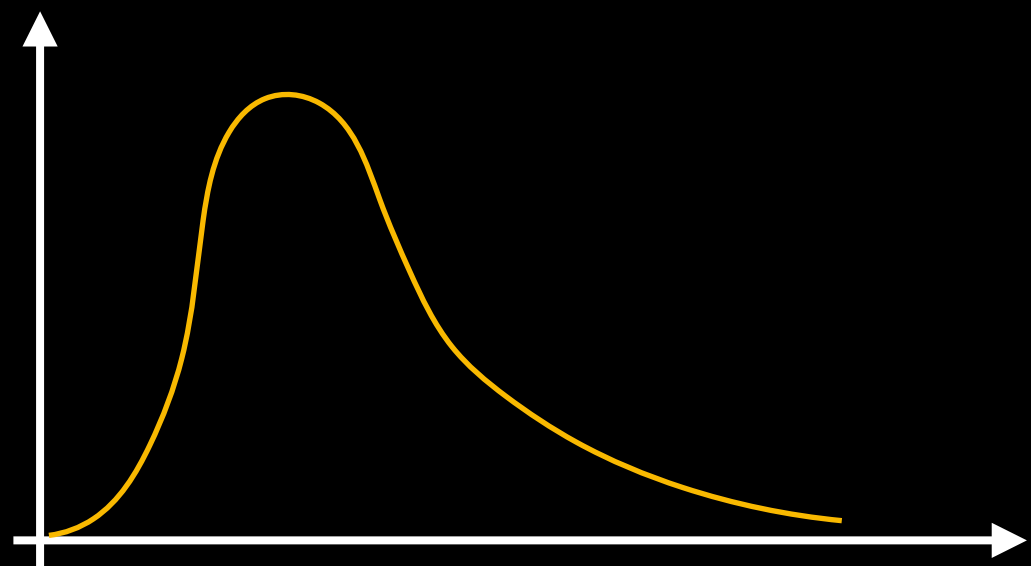
Scottish master physicist



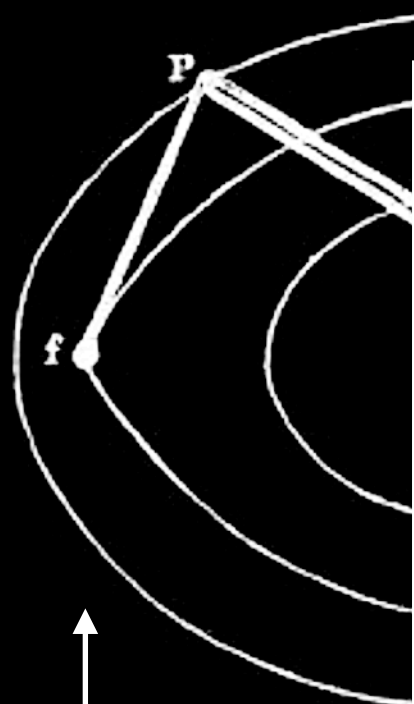
Kinetic theory of heat

Relation between temperature and speed of gas molecules

Number of gas molecules

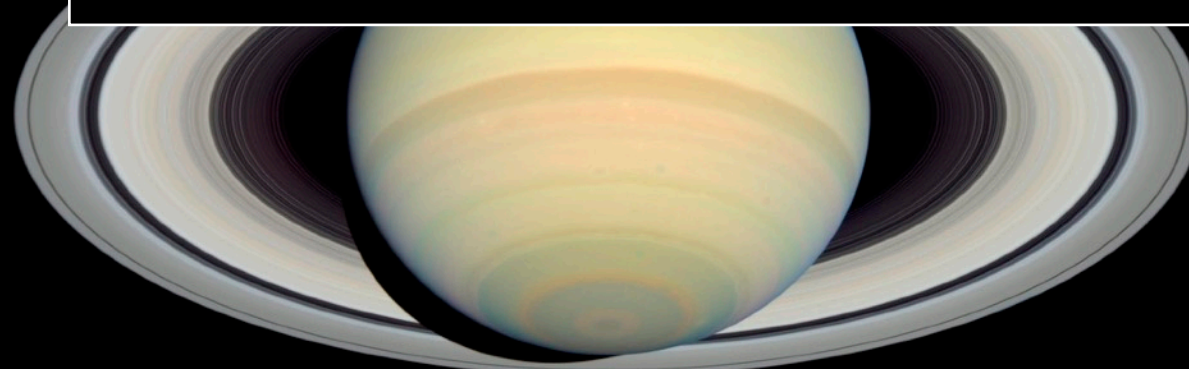


Velocity

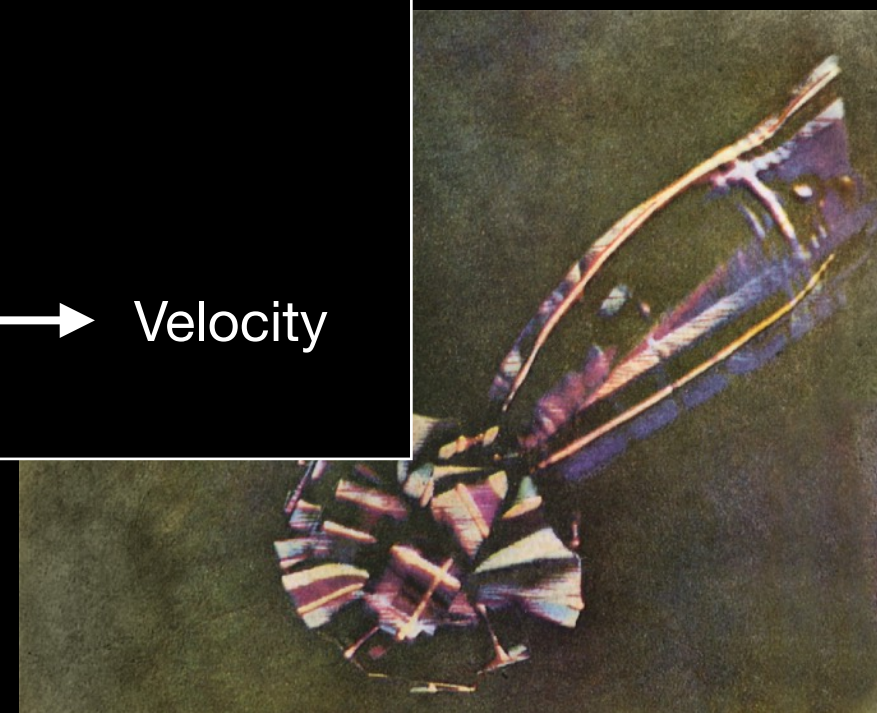


Drawing ovals

Saturn's rings are made of many small particles



Color photography



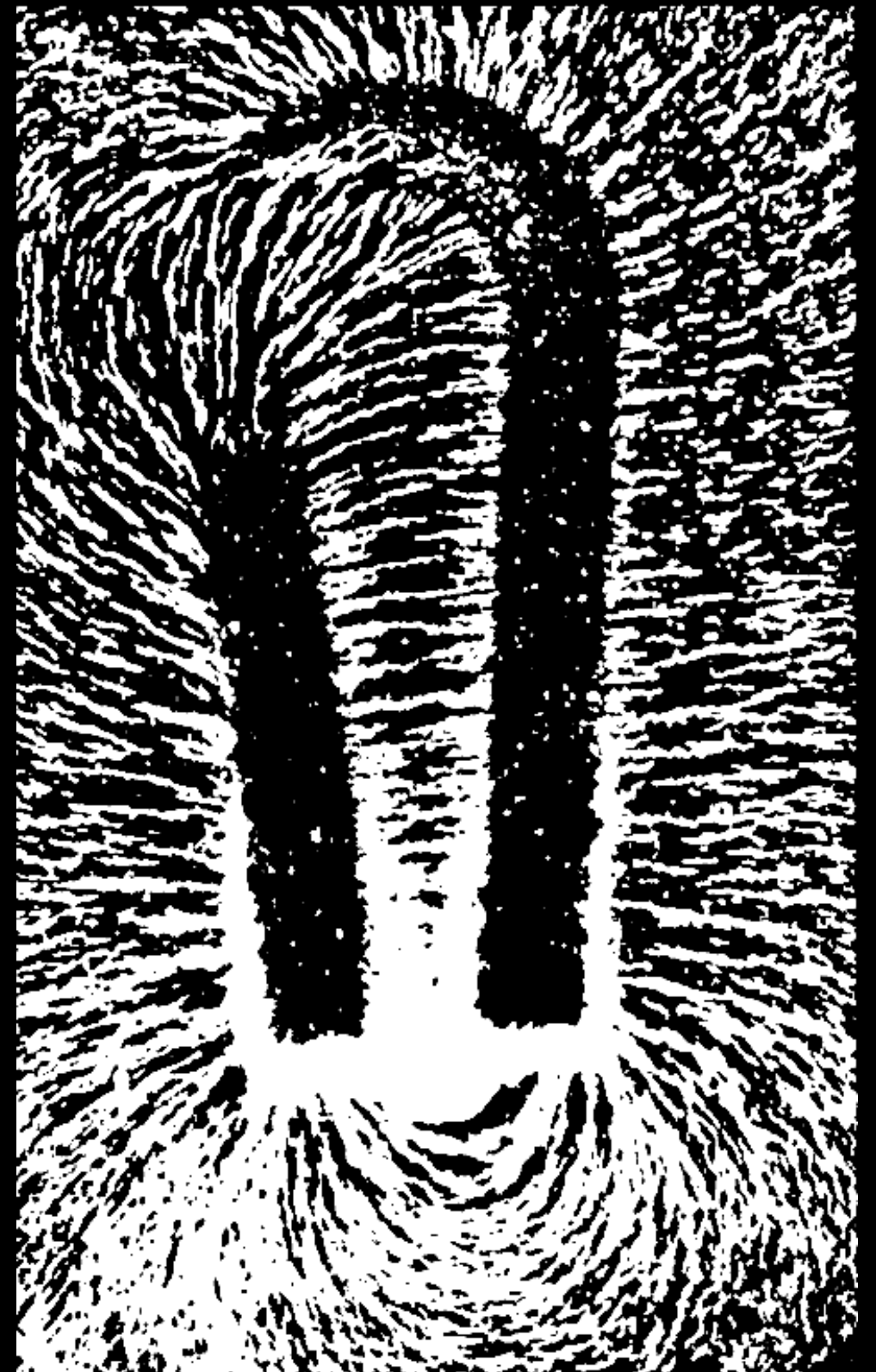
What *really* happens around a magnet?

Back to magnetic “lines of force”

“The beautiful illustration of the presence of magnetic force afforded by this experiment, naturally makes us think of the lines of force as something real.”

“We are dissatisfied with the explanation founded on the hypothesis of attractive and repellent forces directed towards the magnetic poles.”

“We cannot help thinking that in every place where we find these lines of force, some physical state or action must exist in sufficient energy to produce the actual phenomena.”

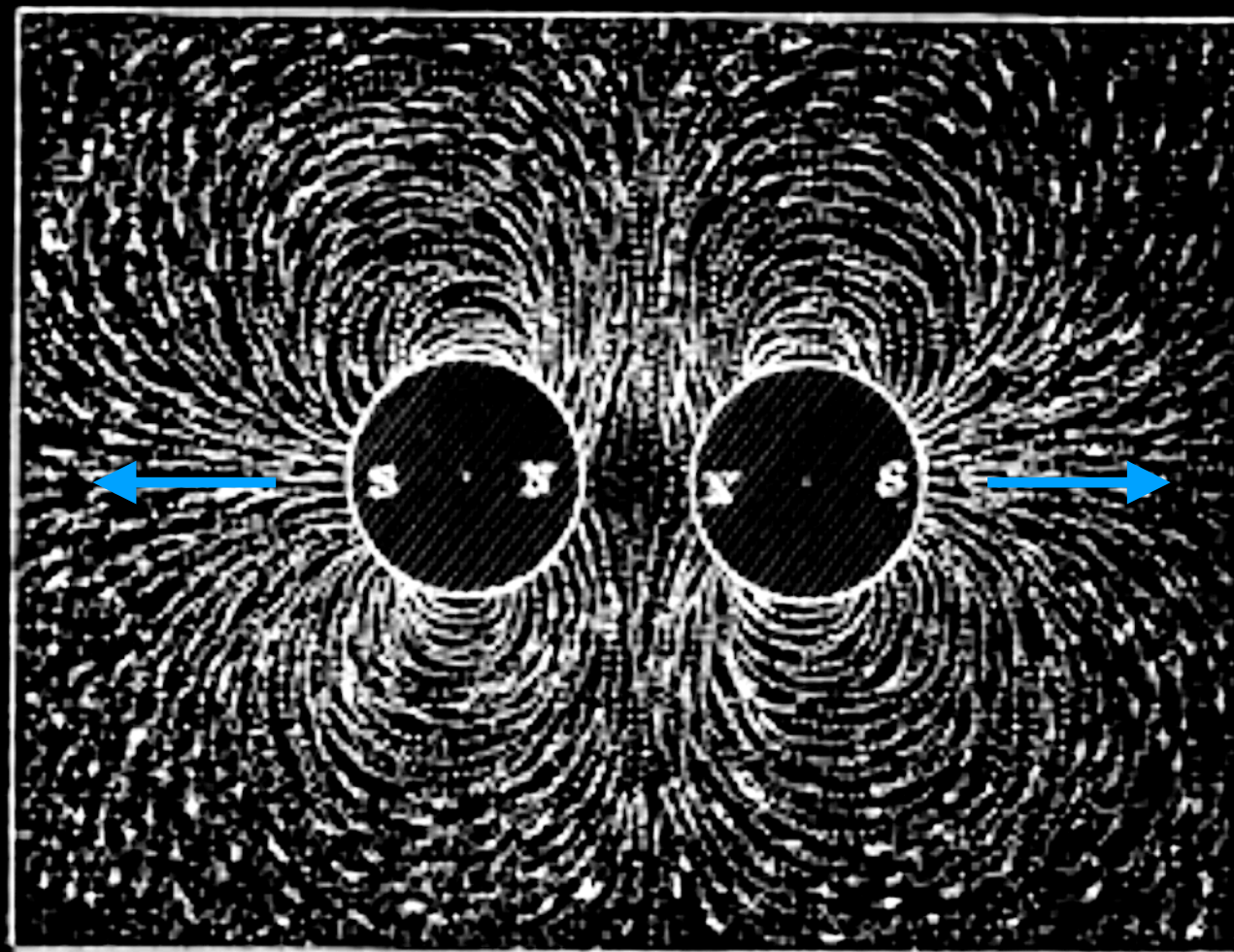


A “magnetic medium” (1861)

“We come to consider the magnetic influence as existing in the form of some kind of pressure or tension in the medium.”

“If we observe the lines of force between two magnets, we observe that where the lines from the poles avoid each other and are dispersed into space, the poles repel each other.”

“It appears that the stress in a line of magnetic force is a tension, like that of a rope.”



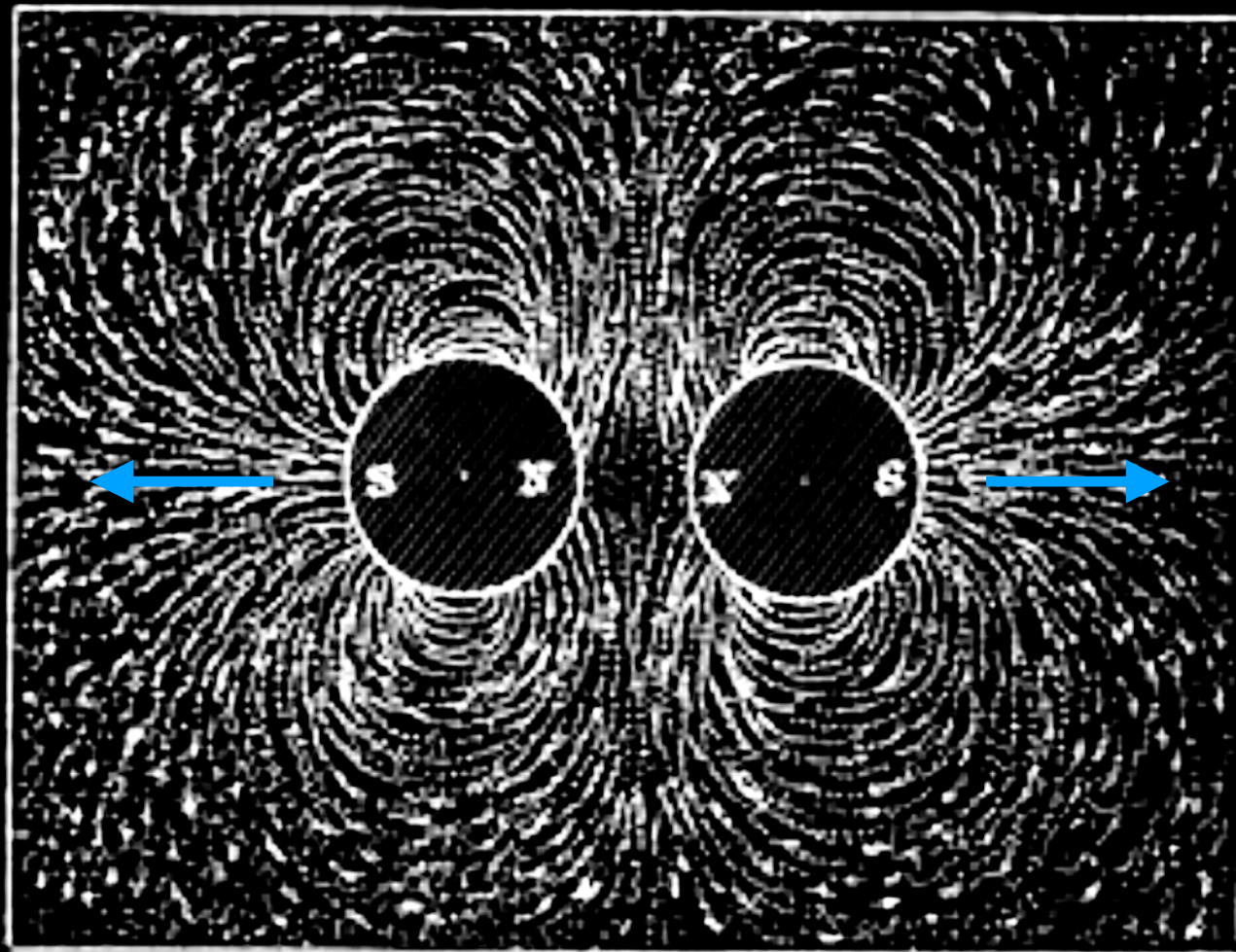
**Two repelling
magnets**



A mechanical model of magnetism

“I propose to examine magnetic phenomena from a mechanical point of view, to determine what tensions in a medium are capable of producing the mechanical phenomena observed.”

**A successful microscopic explanation of magnetism
“will greatly enlarge our knowledge of this part of physics”.**

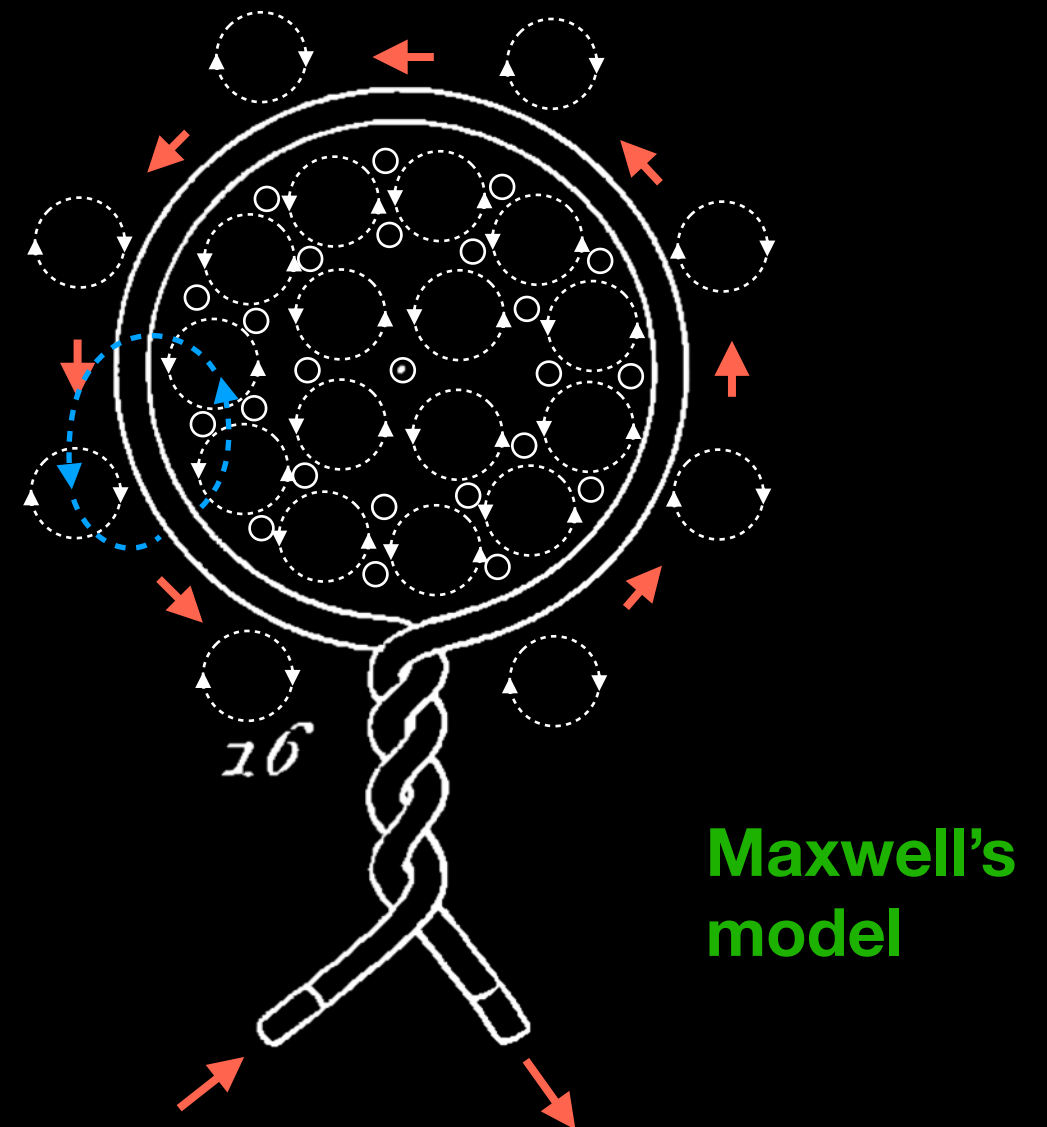
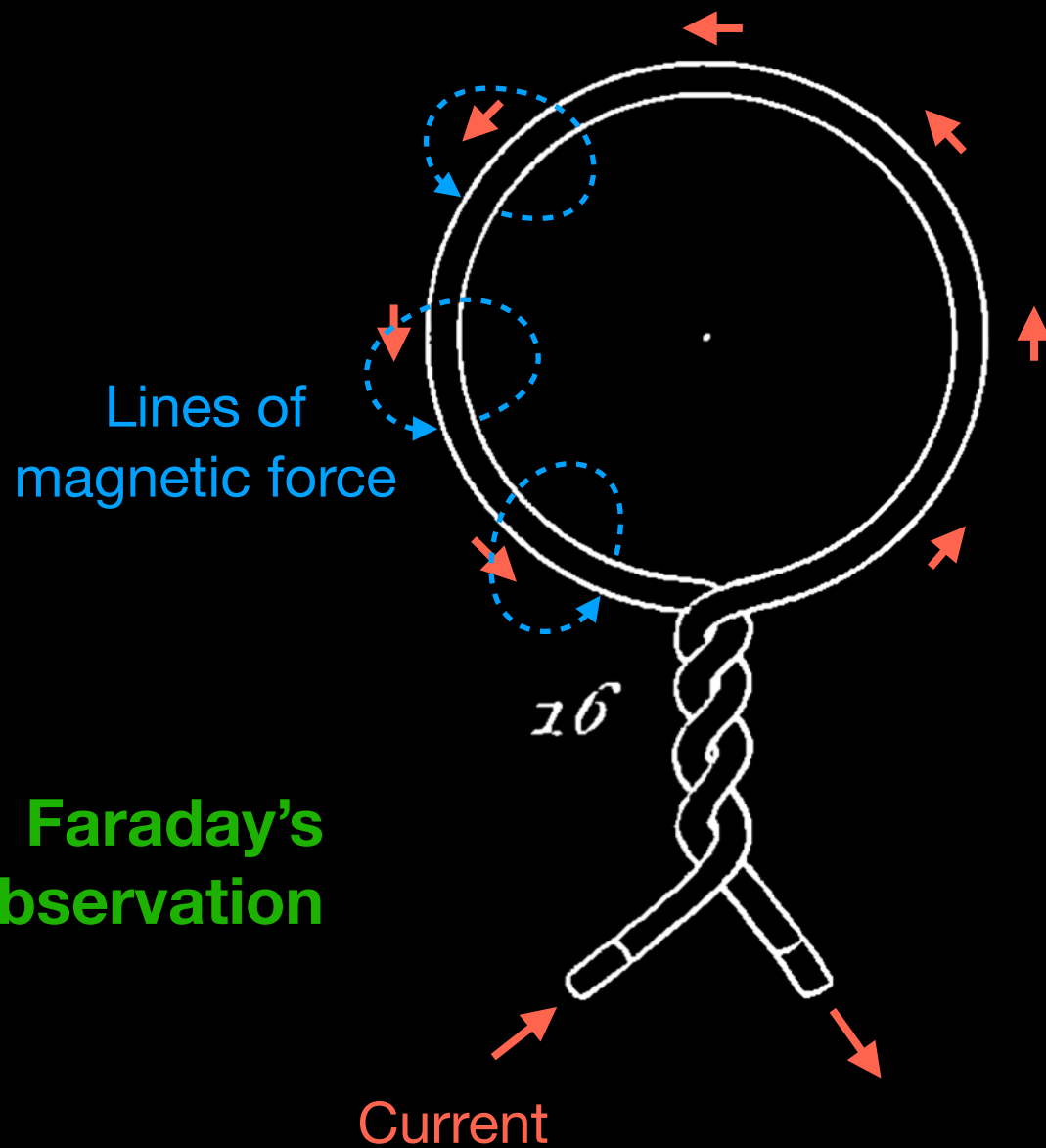
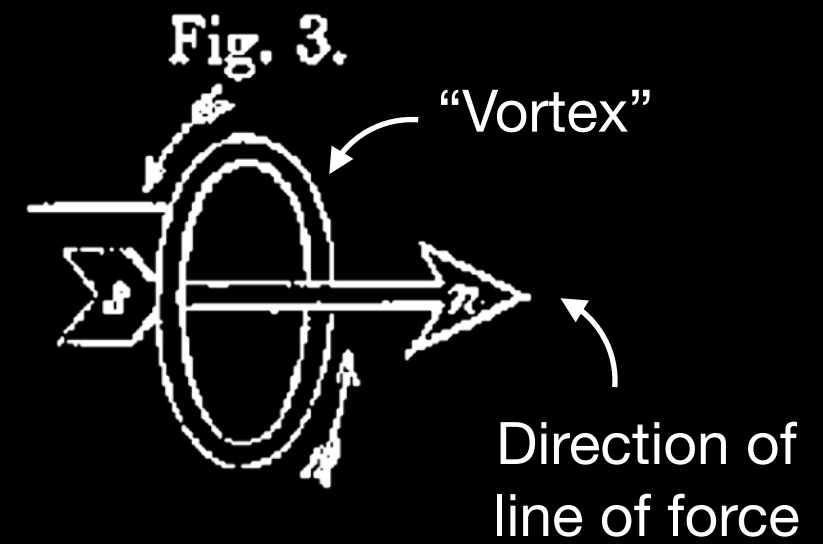


**Two repelling
magnets**

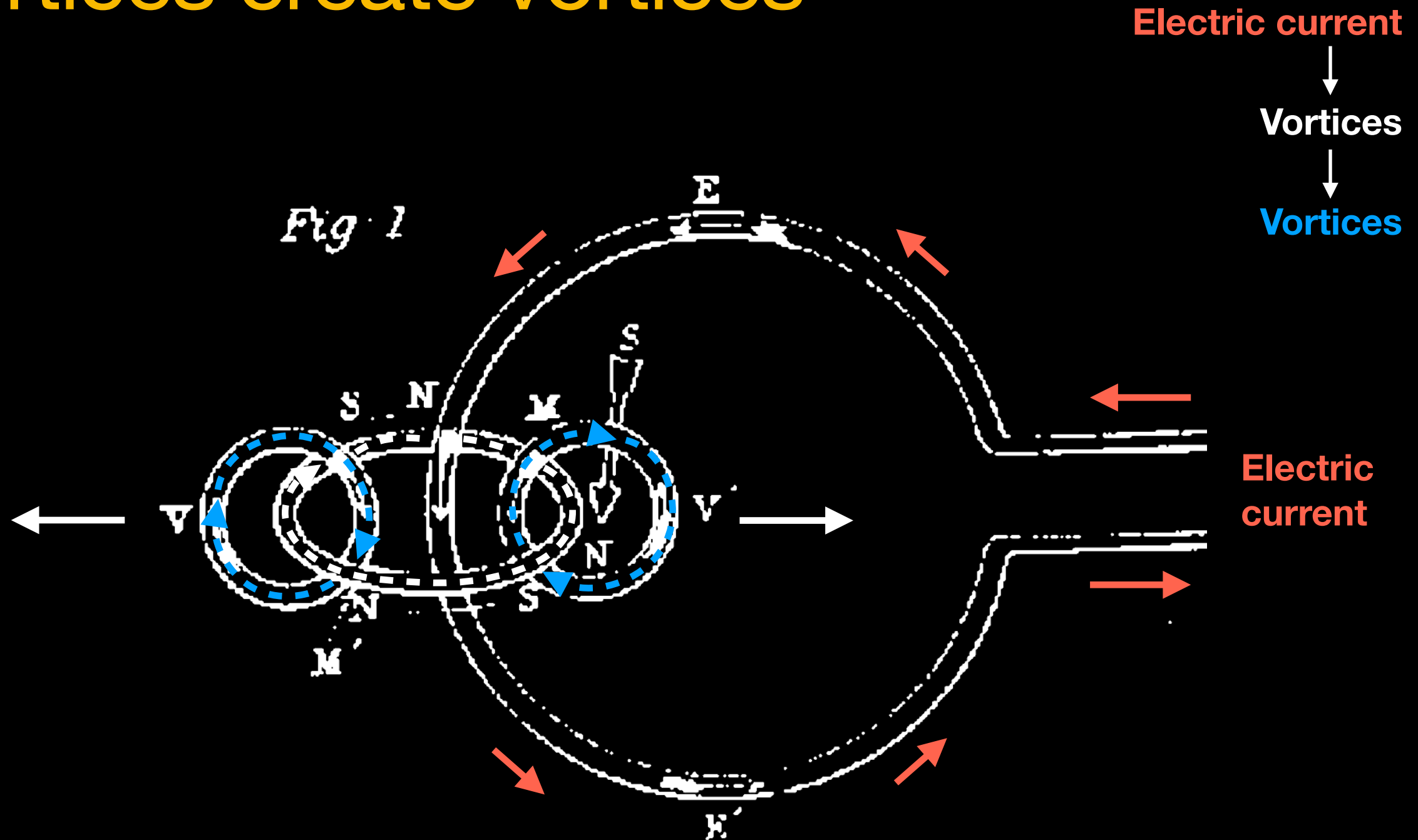


Magnetic “vortices”

“We know that when electricity circulates in a conductor, it produces lines of magnetic force passing through the circuit [...]”



Vortices create vortices



Maxwell: under the right conditions, vortices *themselves* create vortices

“Disturbance” in the magnetic medium can propagate far away from the current

Electromagnetic “waves”

In air or vacuum $\mu=1$, and therefore

$$\left. \begin{aligned} V &= E, \\ &= 310,740,000,000 \text{ millimetres per second,} \\ &= 193,088 \text{ miles per second.} \end{aligned} \right\} \cdot (136)$$

The velocity of light in air, as determined by M. Fizeau*, is 70,843 leagues per second (25 leagues to a degree) which gives

$$\begin{aligned} V &= 314,858,000,000 \text{ millimetres} \\ &= 195,647 \text{ miles per second.} \quad \cdot \cdot \cdot \cdot (137) \end{aligned}$$

“The velocity of undulations in our hypothetical medium agrees so exactly with the velocity of light that we can scarcely avoid the inference that light consists in the undulations of the same medium which is the cause of electric and magnetic phenomena.”

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