

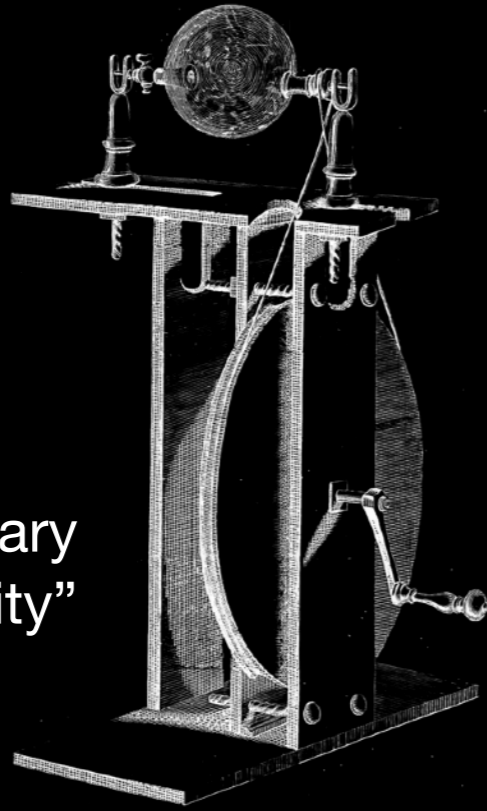


HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

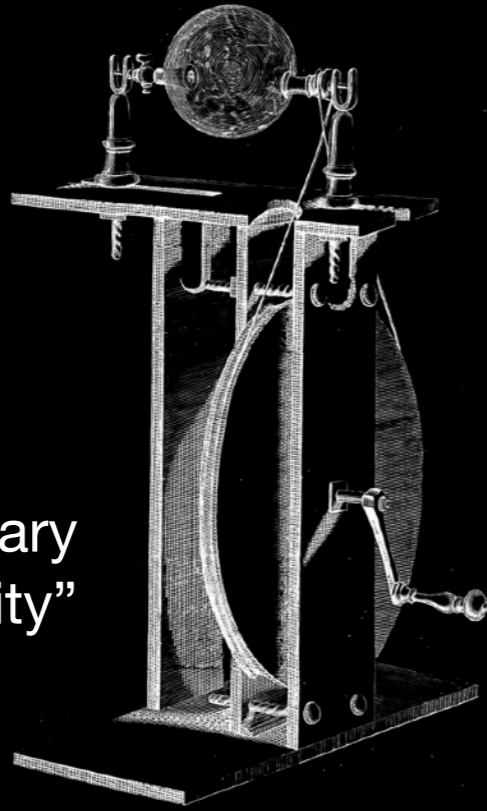
A STORY OF INVENTION AND DISCOVERY

Philipp Windischhofer
November 4, 2023

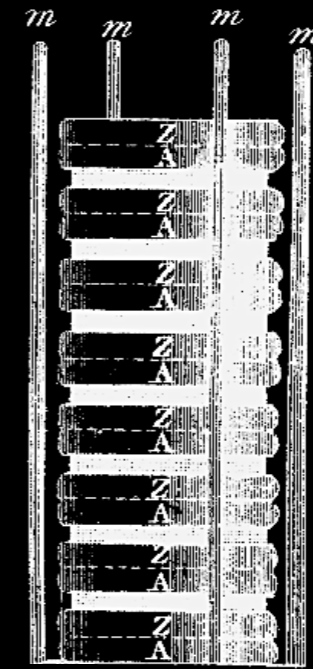
“Ordinary
electricity”



“Ordinary
electricity”

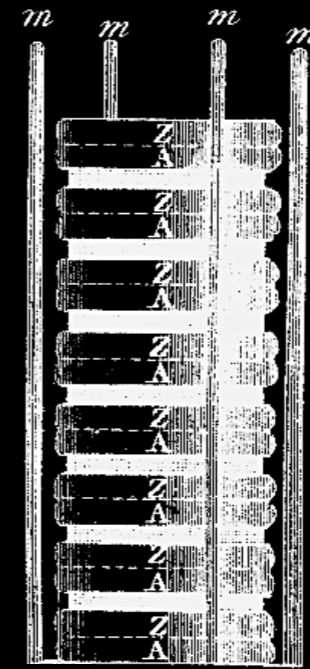
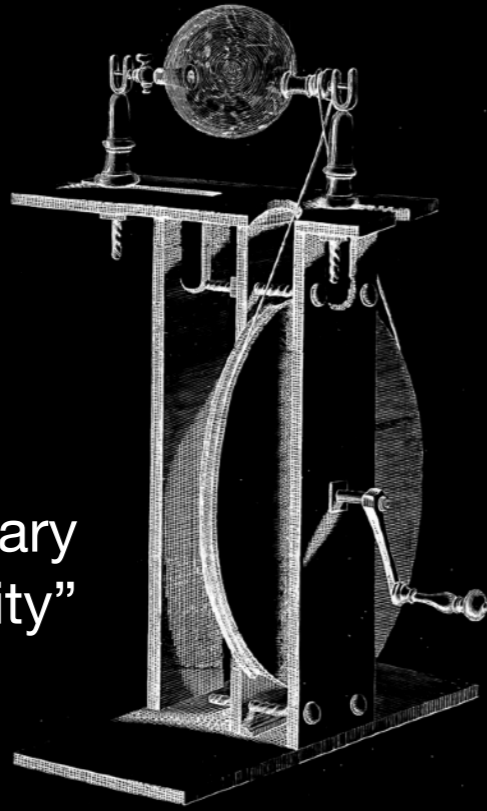


“Voltaic electricity”

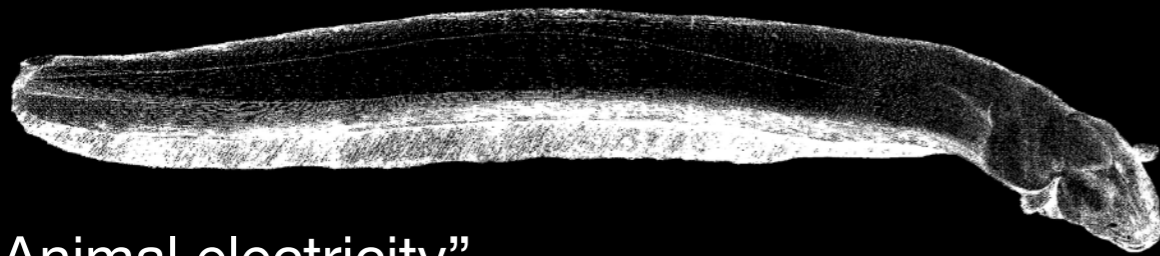


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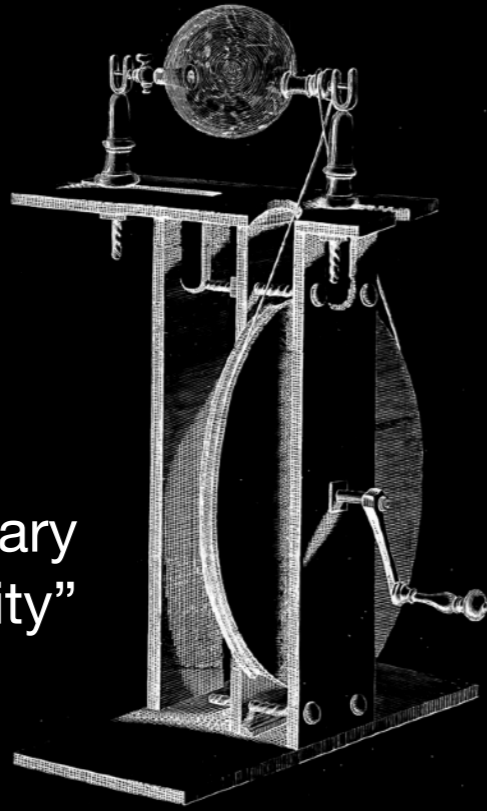
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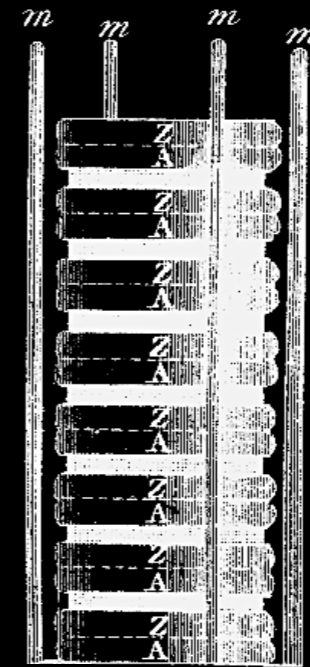
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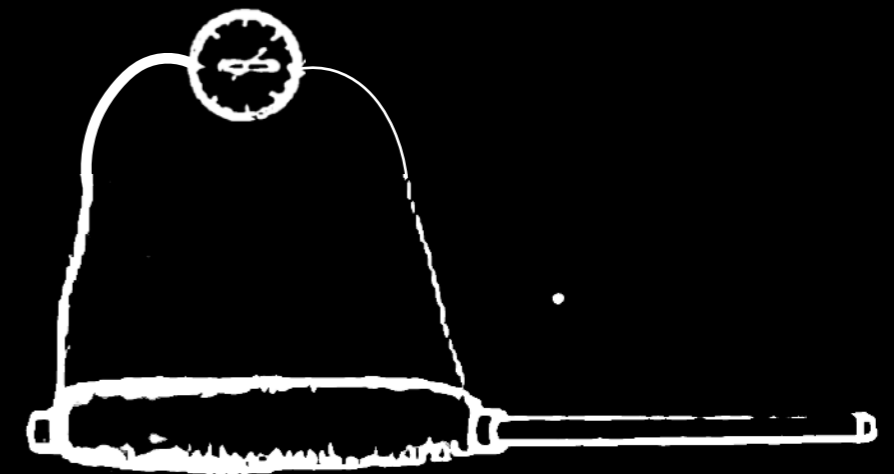
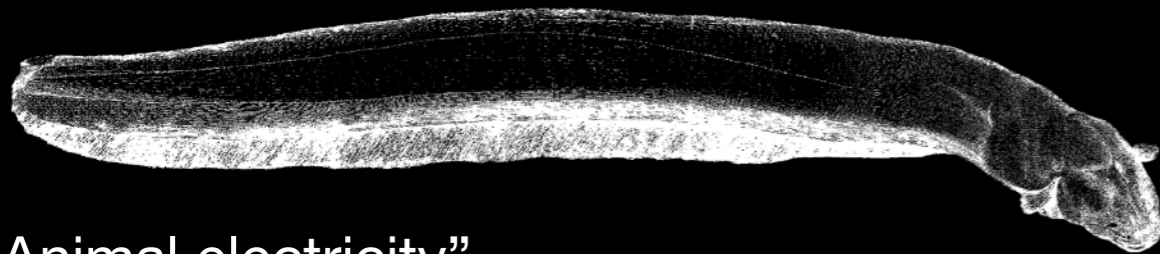
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electricity”



“Voltaic electricity”

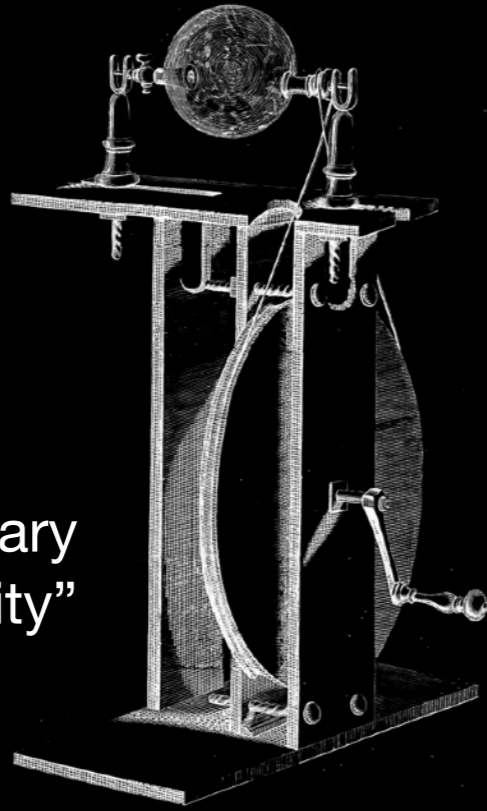


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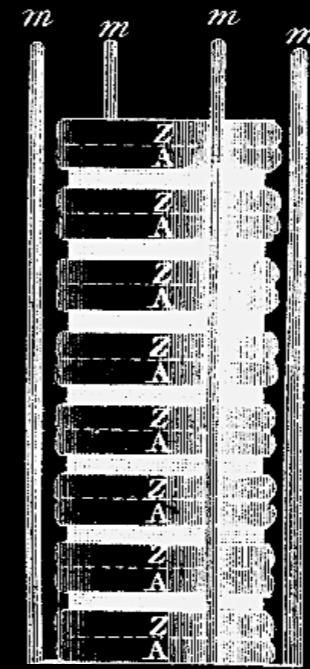


“Magneto-electricity”

“Ordinary
electricity”



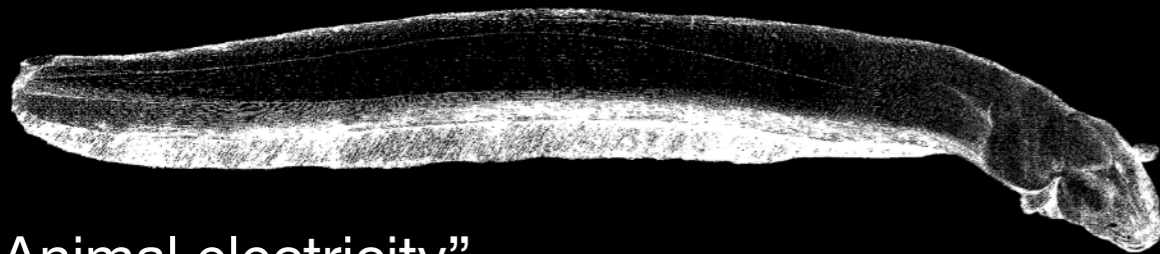
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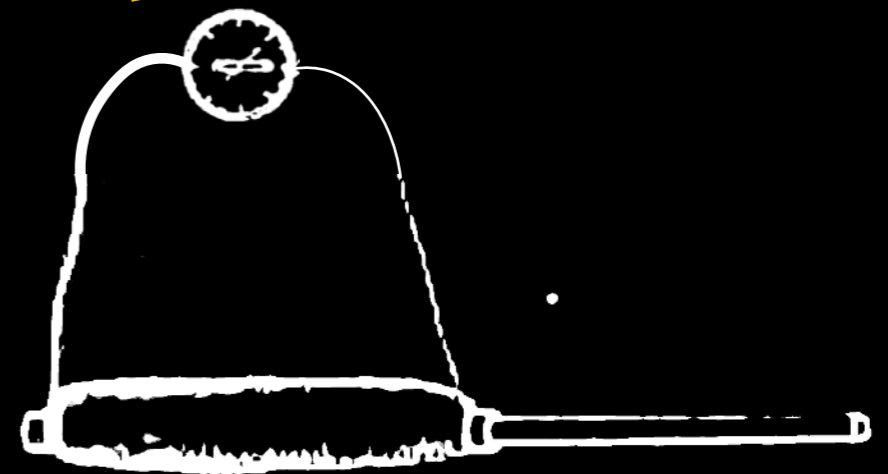
Electricity



“Animal electricity”



“Magneto-electricity”



Electricity

Electricity



Electricity

Magnetism



Electricity



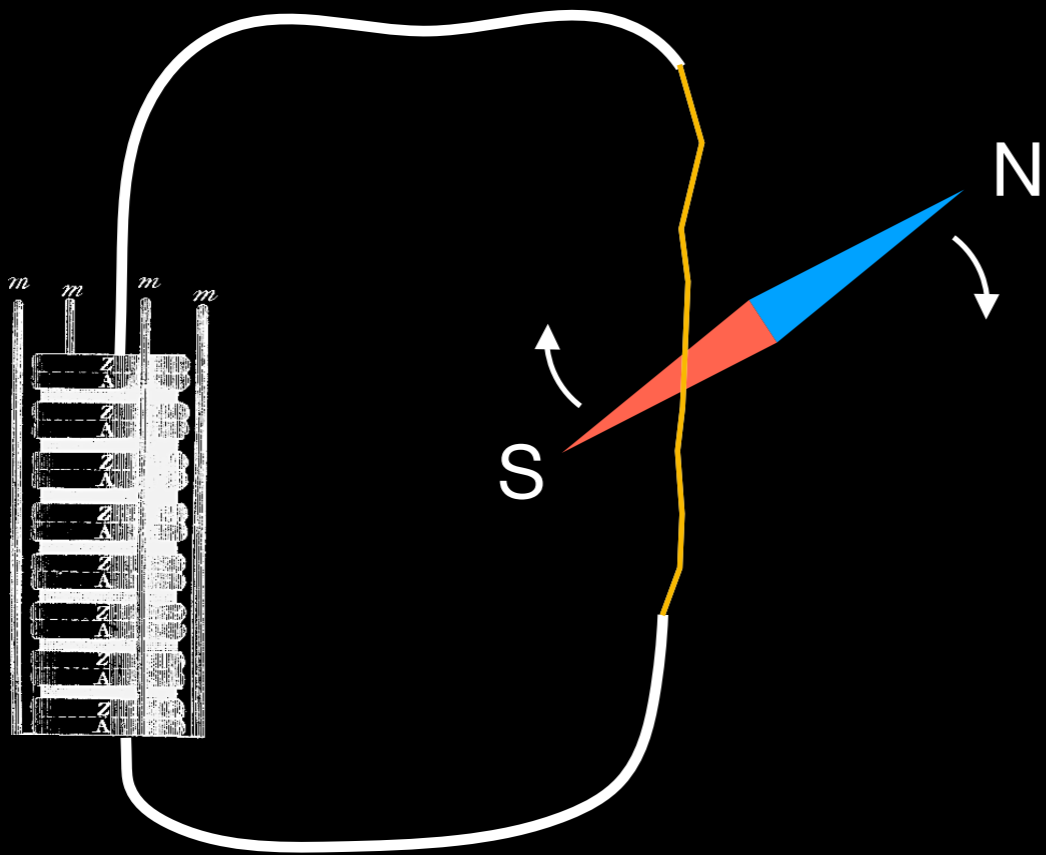
Magnetism



Electricity



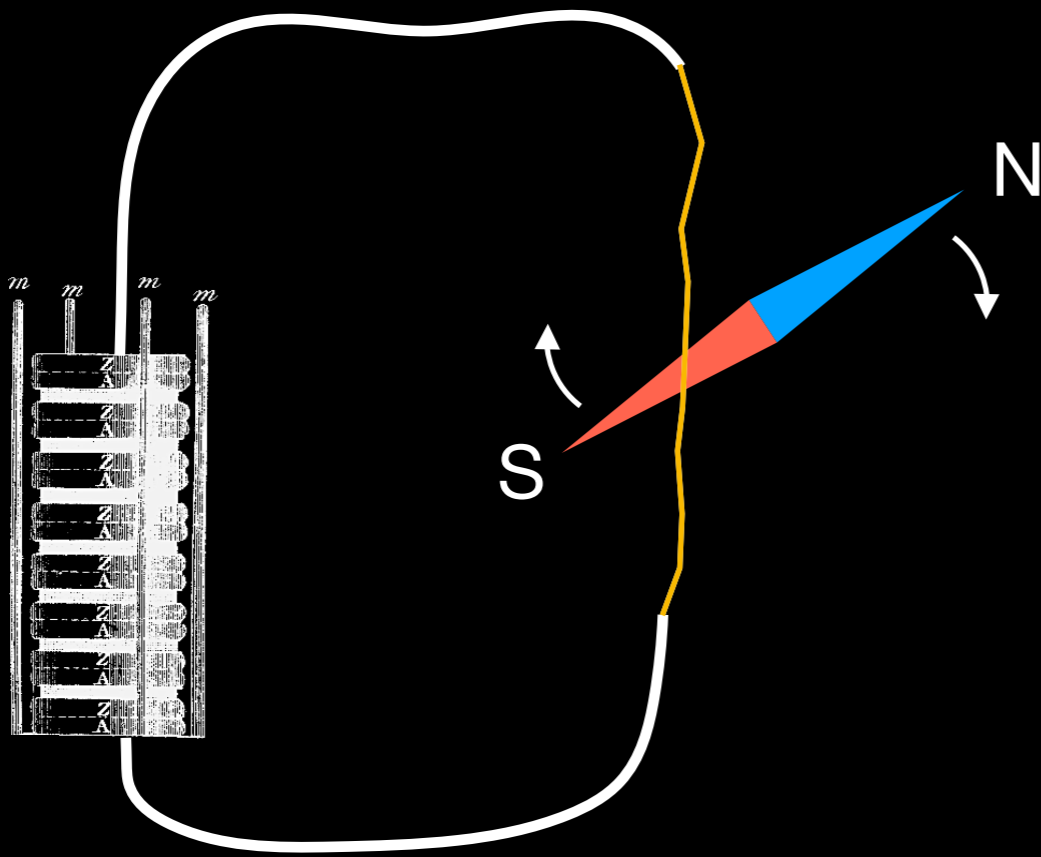
Magnetism



Electricity



Magnetism



Electricity

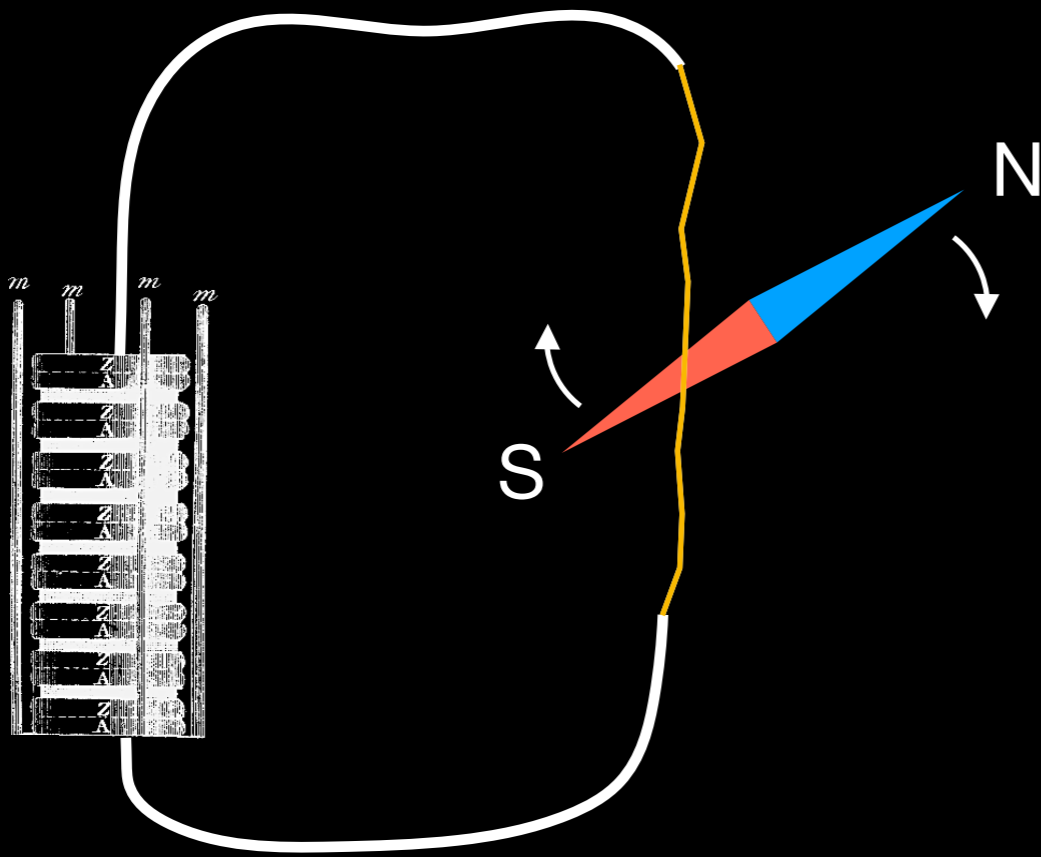


Magnetism

Magnetism



Electricity



Electricity

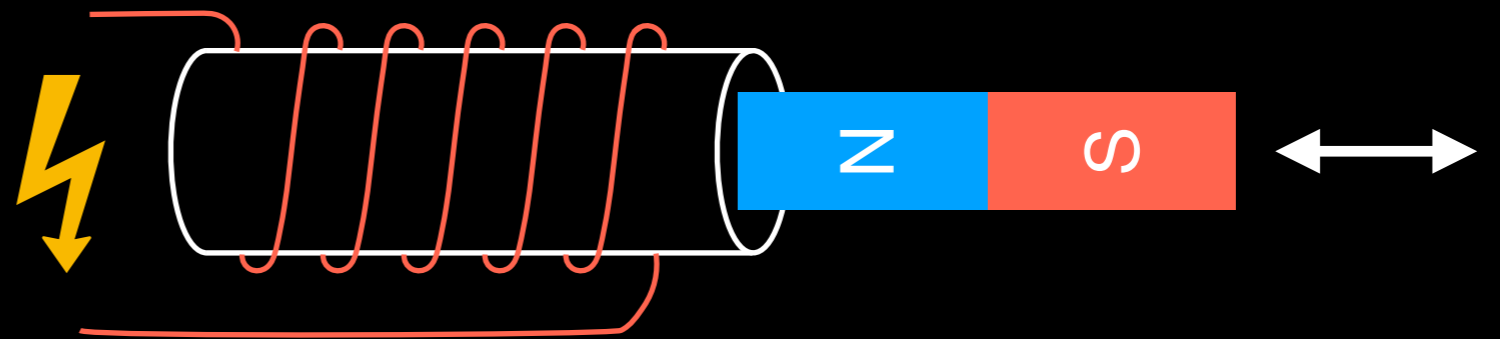


Magnetism

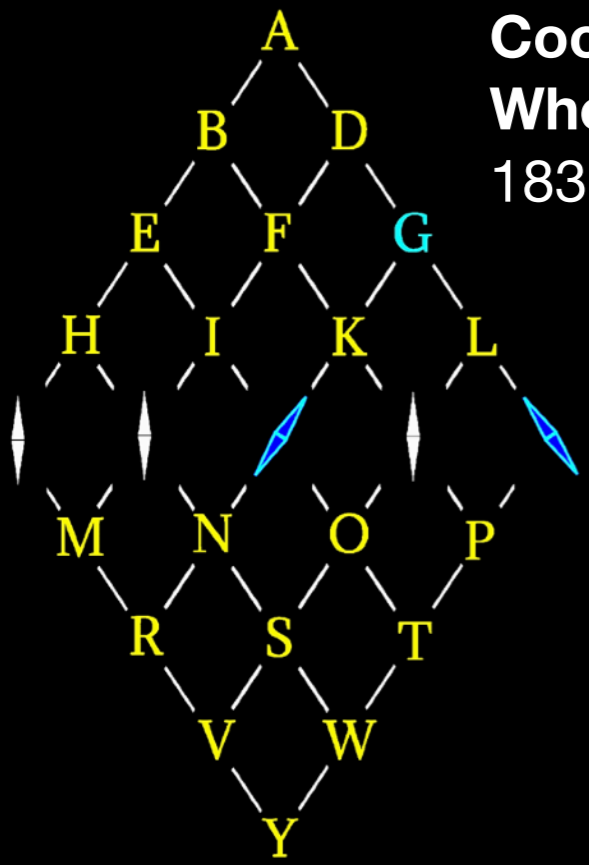
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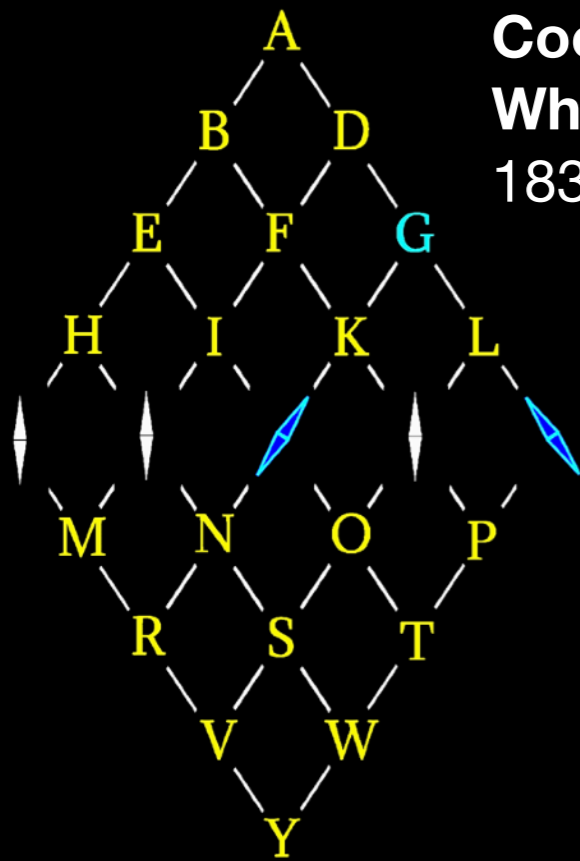


Electricity

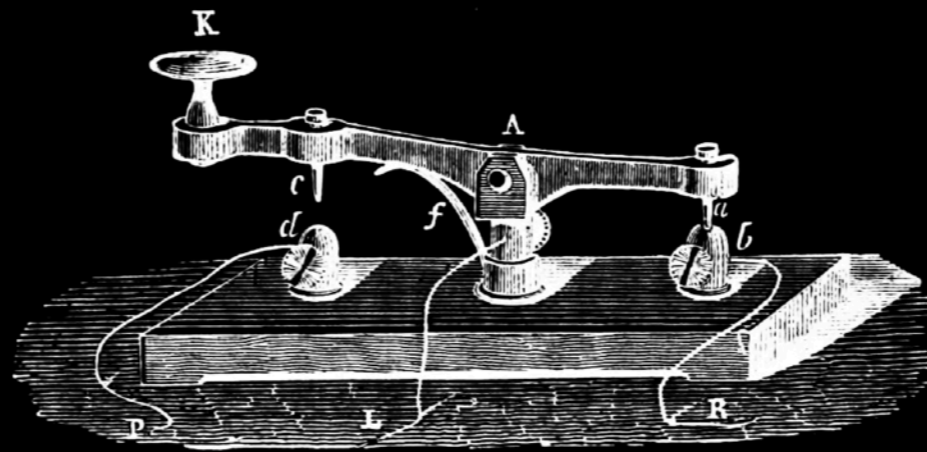


**Cooke &
Wheatstone**
1837

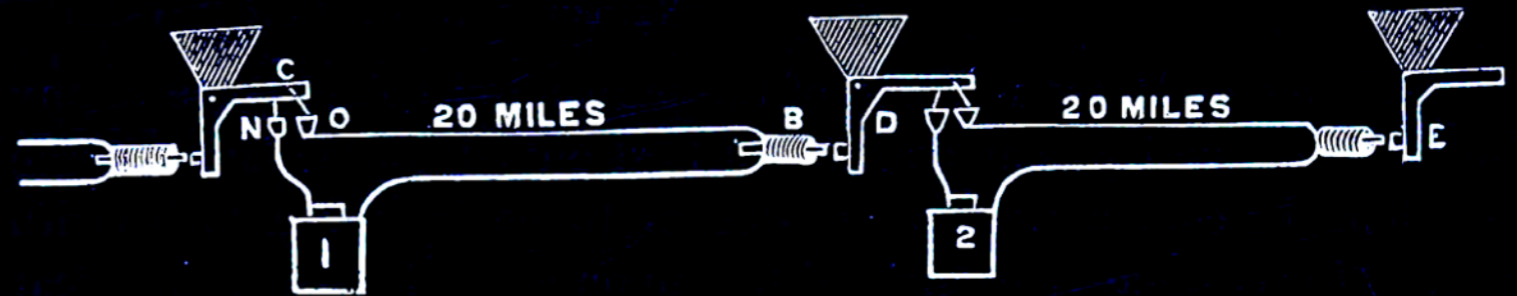


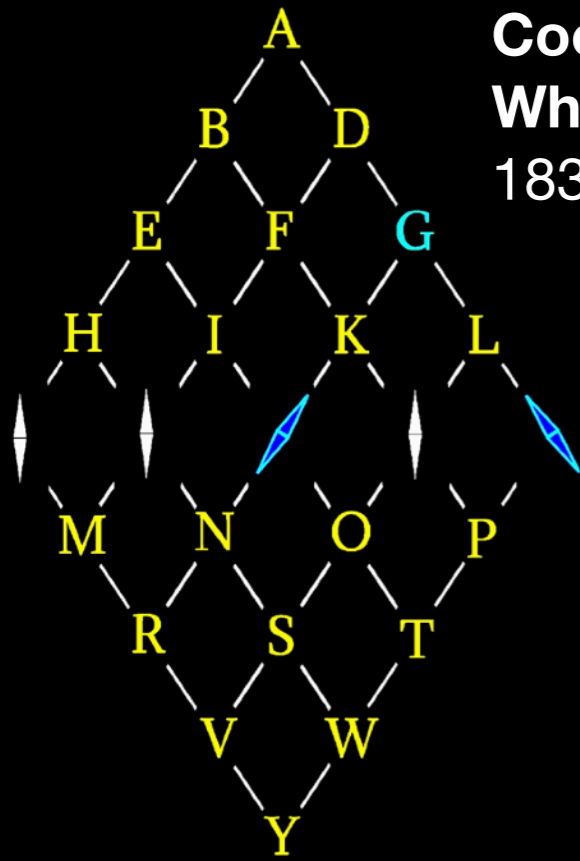


**Cooke &
Wheatstone**
1837

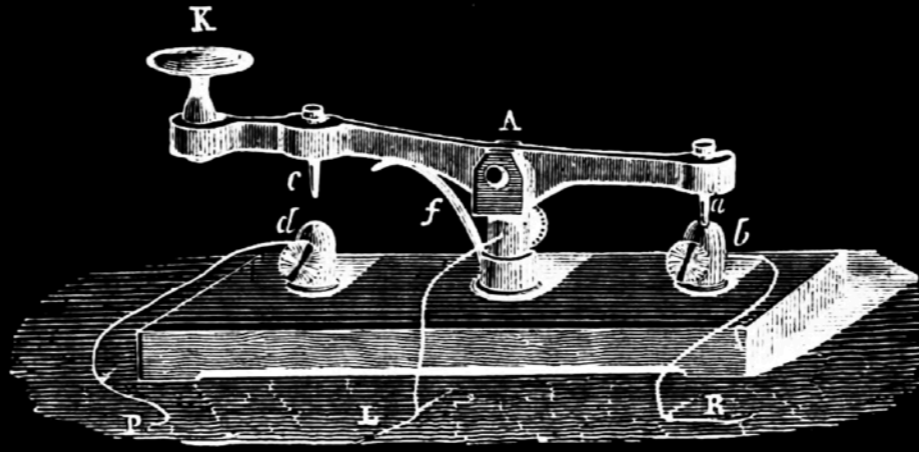


Morse & Vail
1847

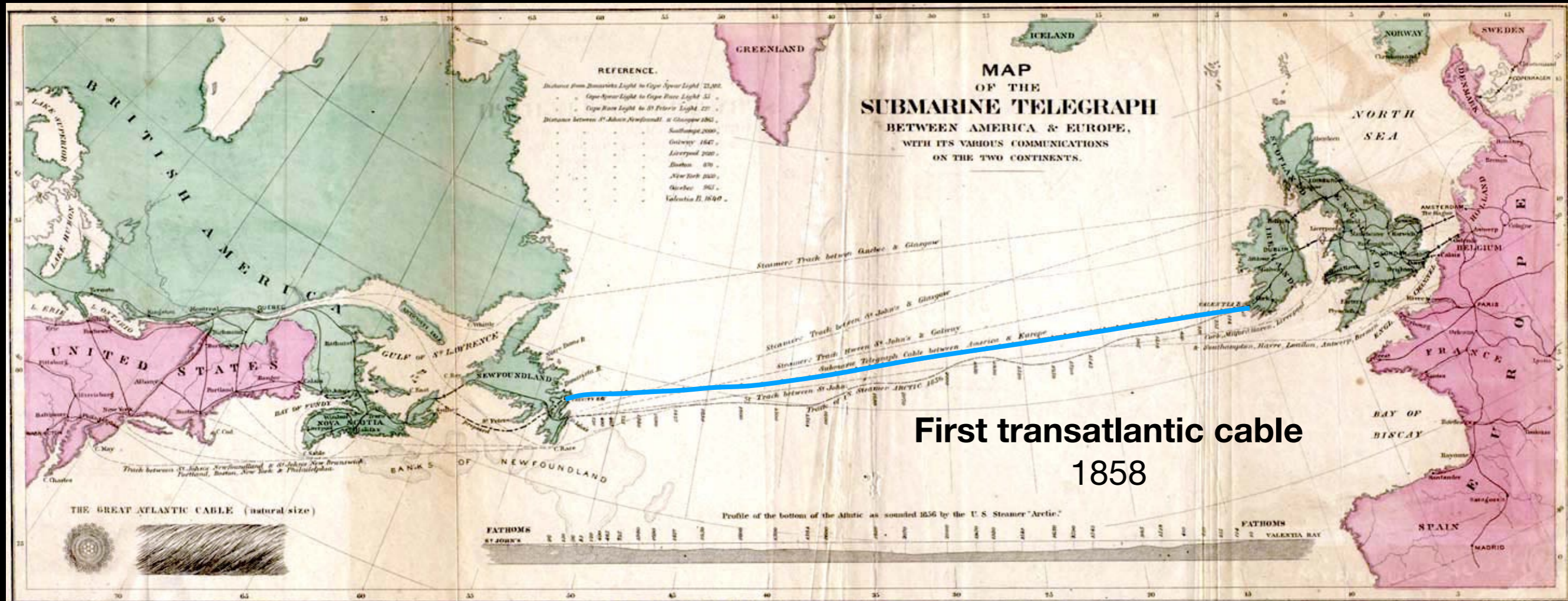
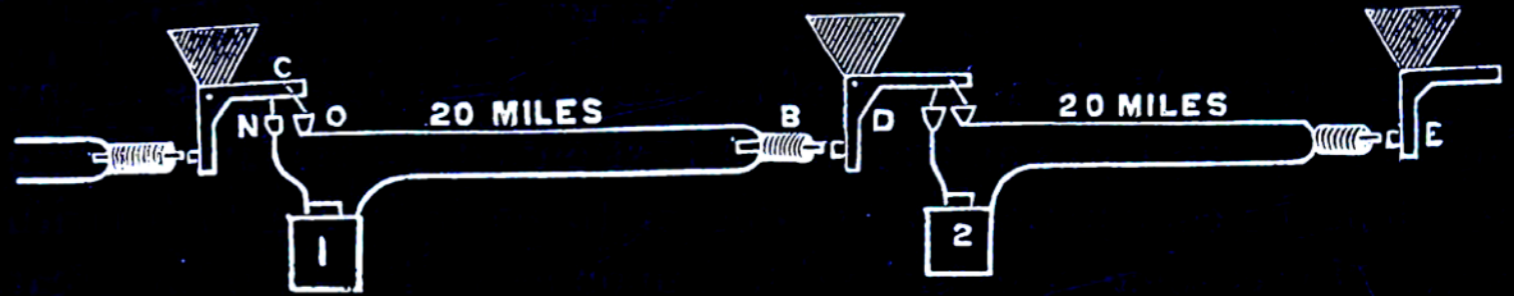




Cooke & Wheatstone
1837



Morse & Vail
1847



First transatlantic cable
1858

“Electric
spiderwebs”

Hauksbee
1709

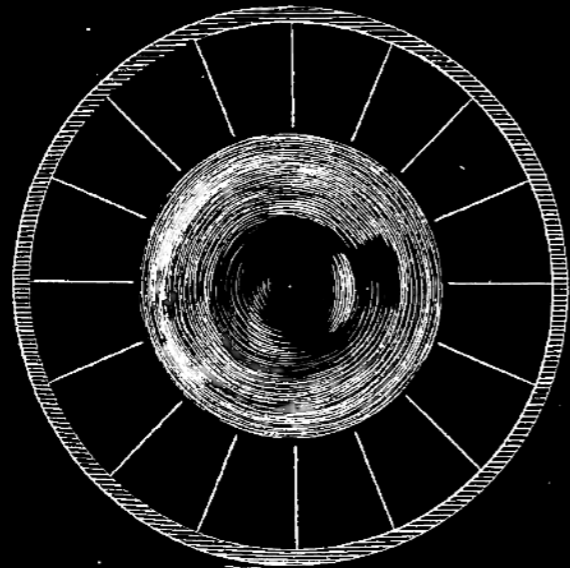


Fig 7.

“Electric spiderwebs”

Hauksbee
1709

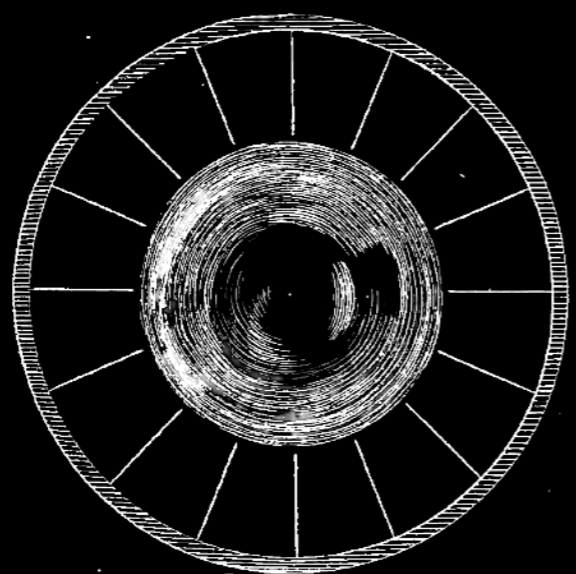
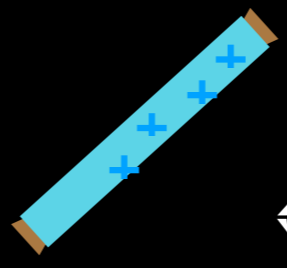


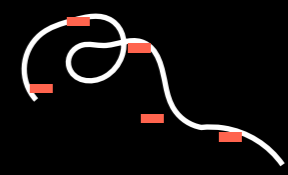
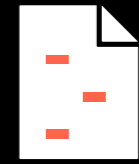
Fig:7.



“Vitreous”



“Resinous”



Du Fay
1733

“Two kinds of electricks”

“Electric spiderwebs”

Hauksbee
1709

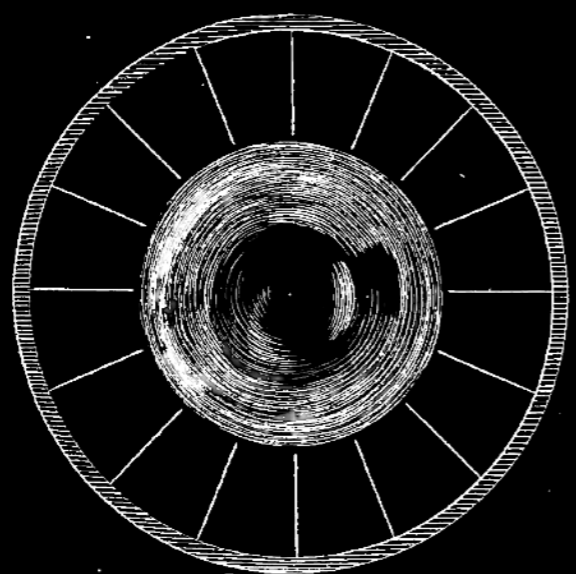
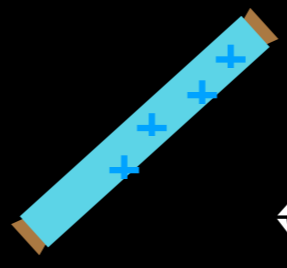
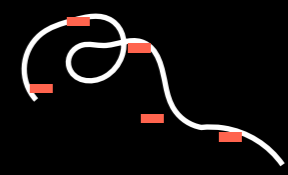
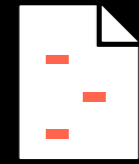


Fig: 7.



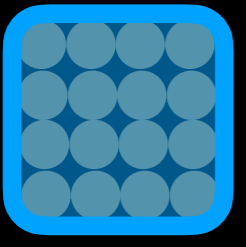
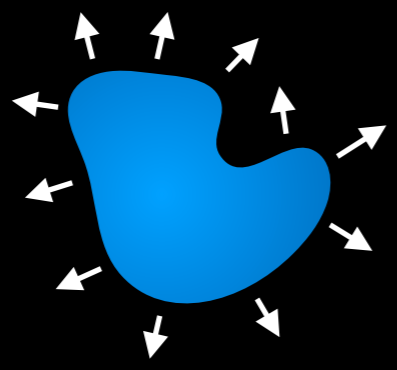
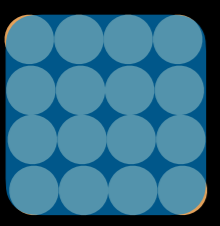
“Vitreous”

“Resinous”



Du Fay
1733

“Two kinds of electricks”

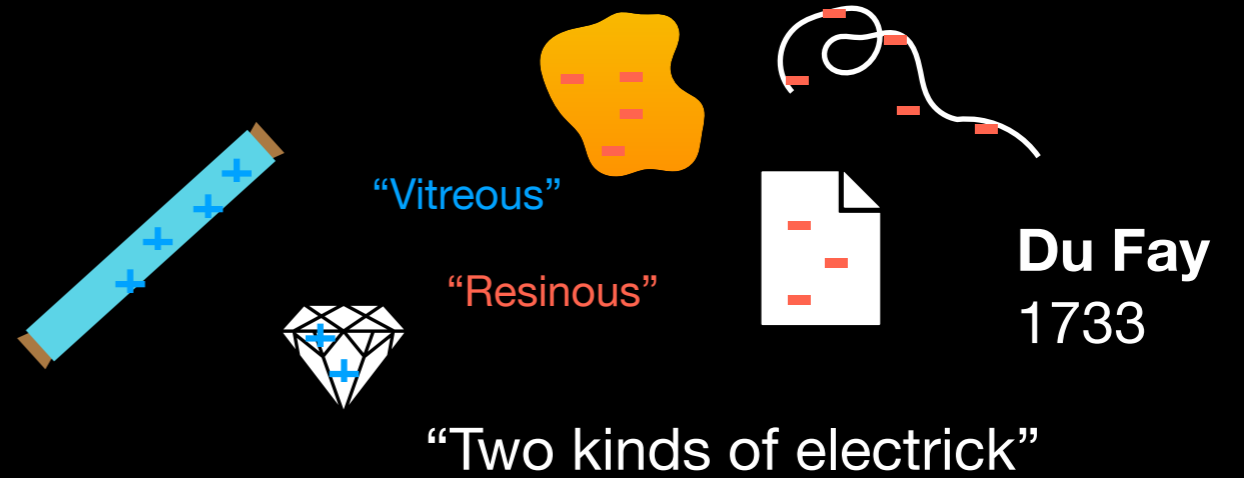
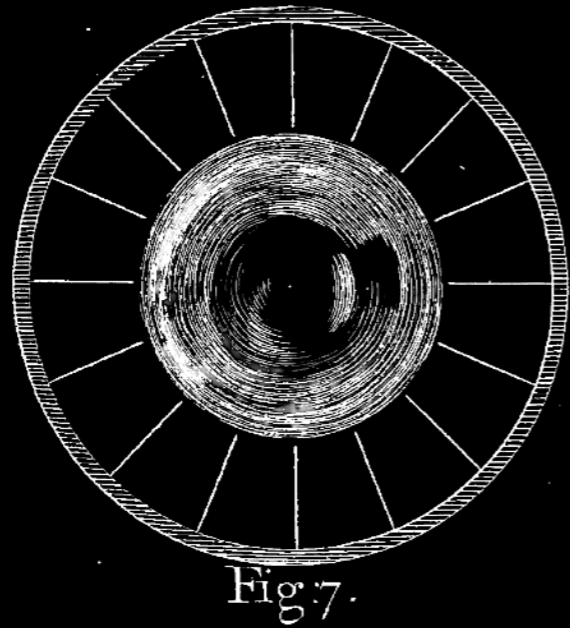


“Electrical atmospheres”

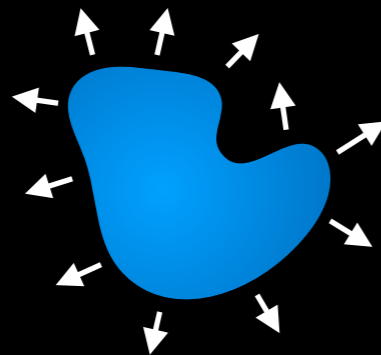
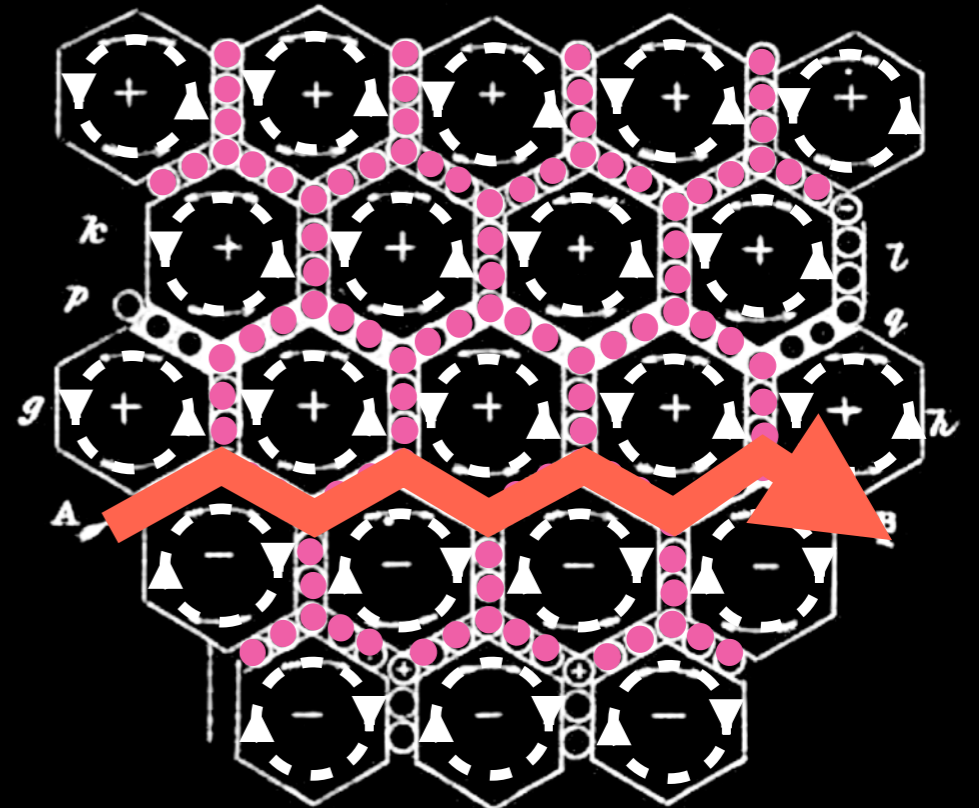
Franklin
1750s

“Electric spiderwebs”

Hauksbee
1709

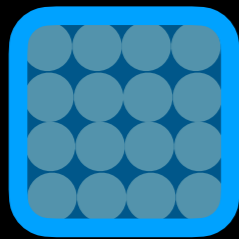


Maxwell's vortices (1860)

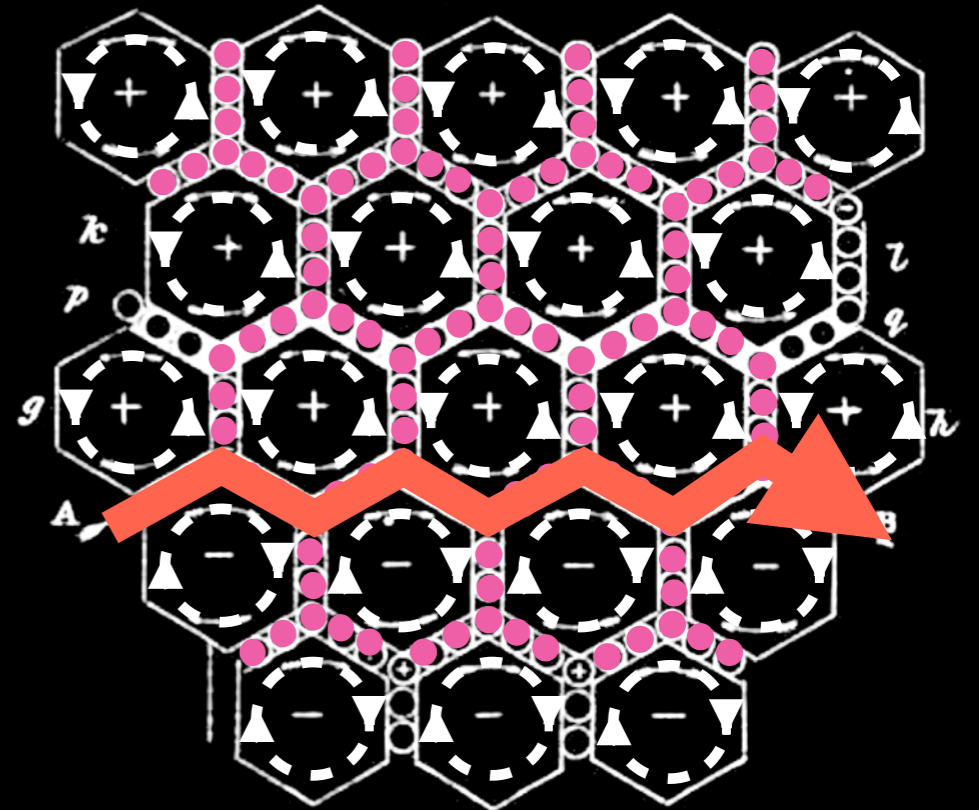


“Electrical atmospheres”

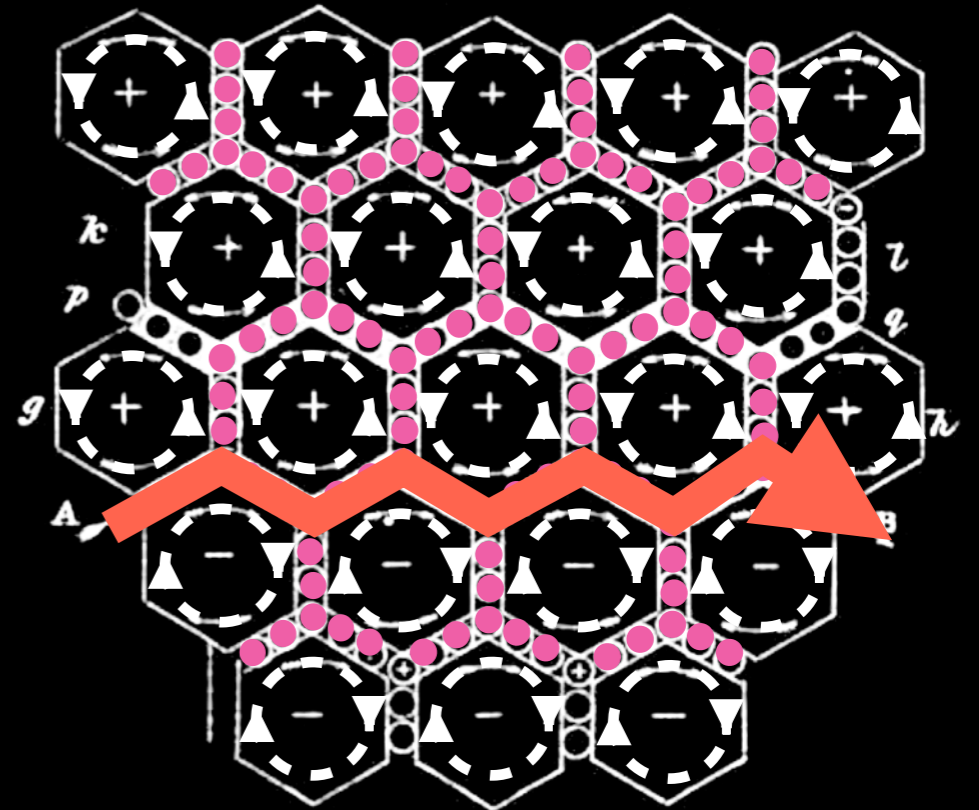
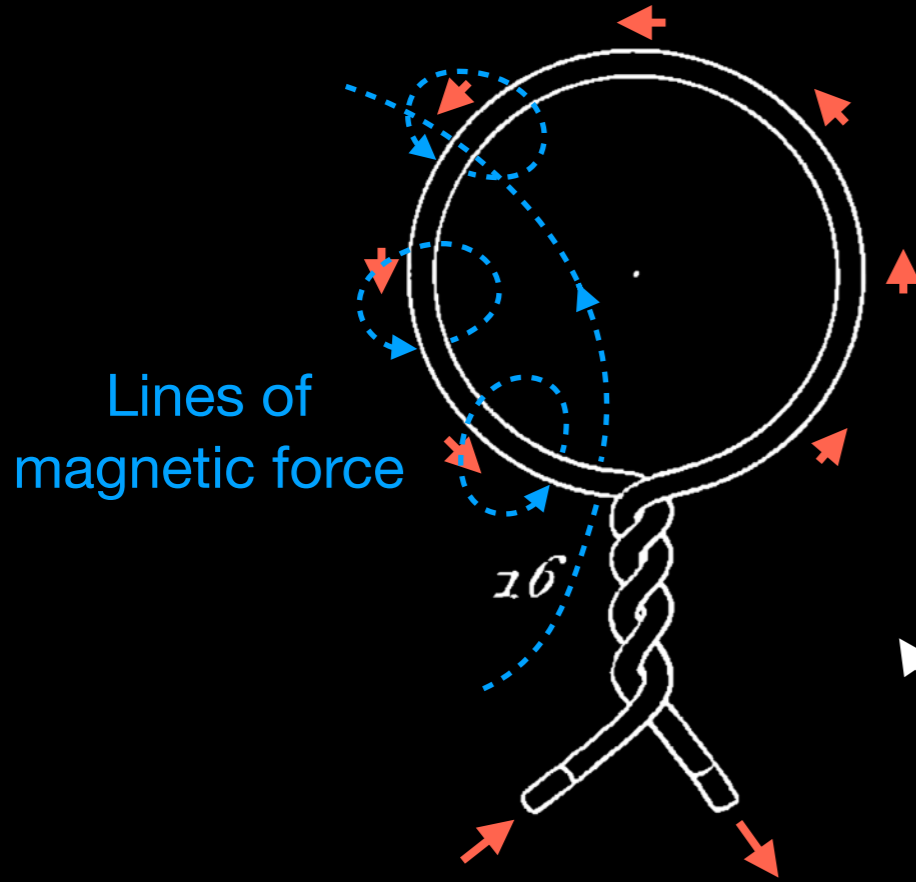
Franklin
1750s



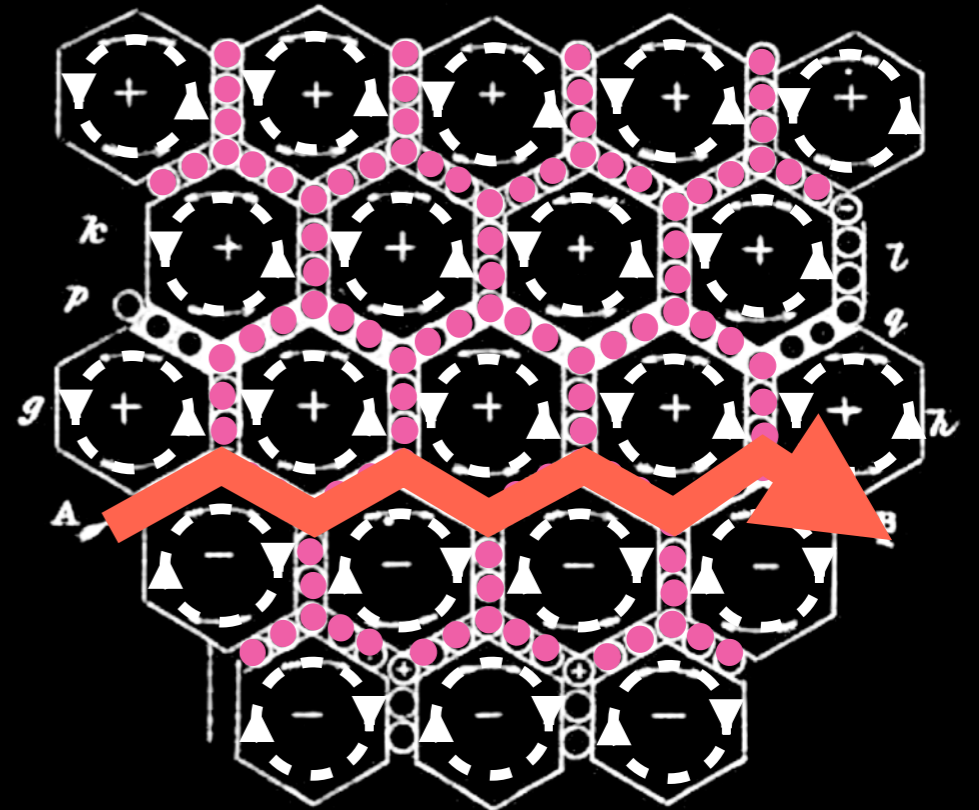
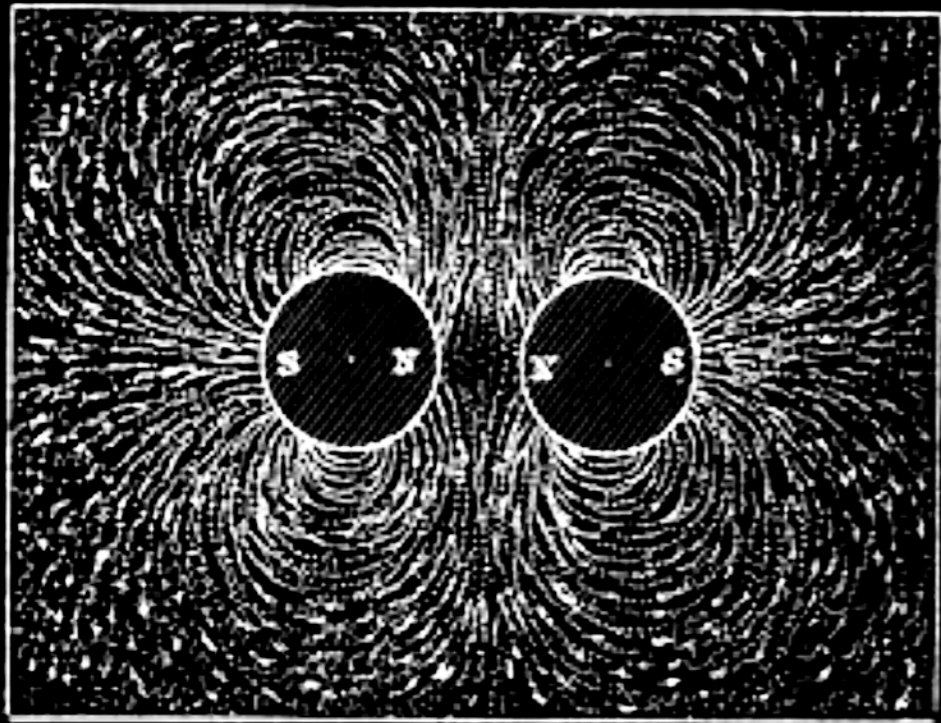
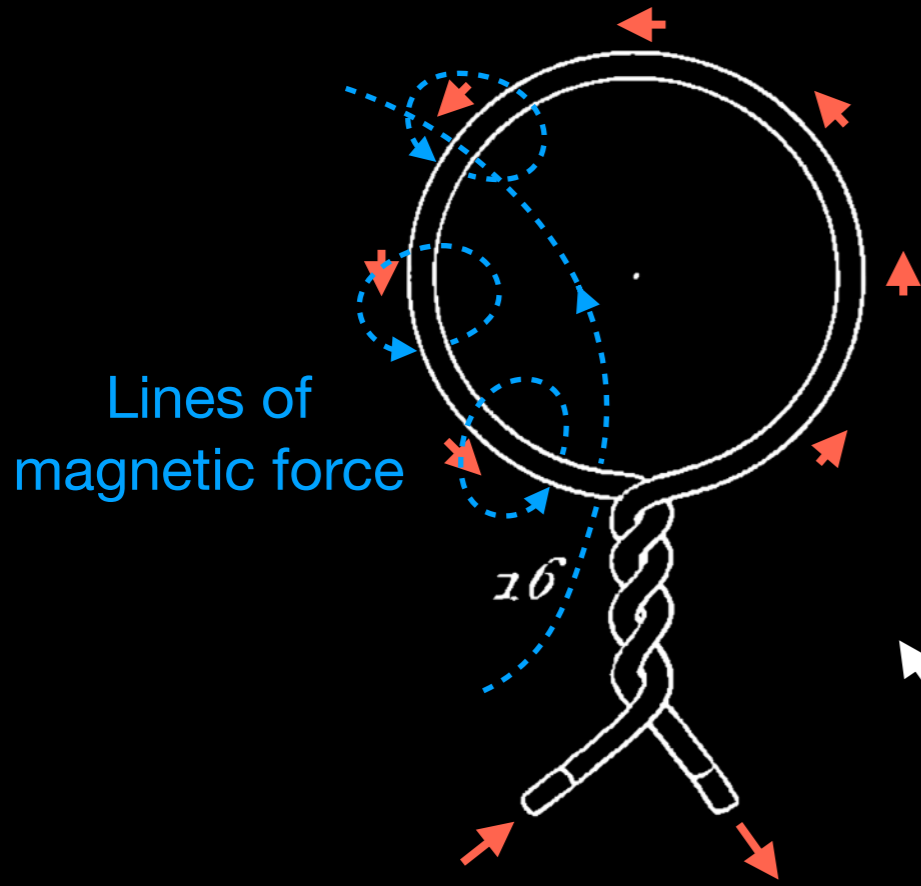
Maxwell's great synthesis



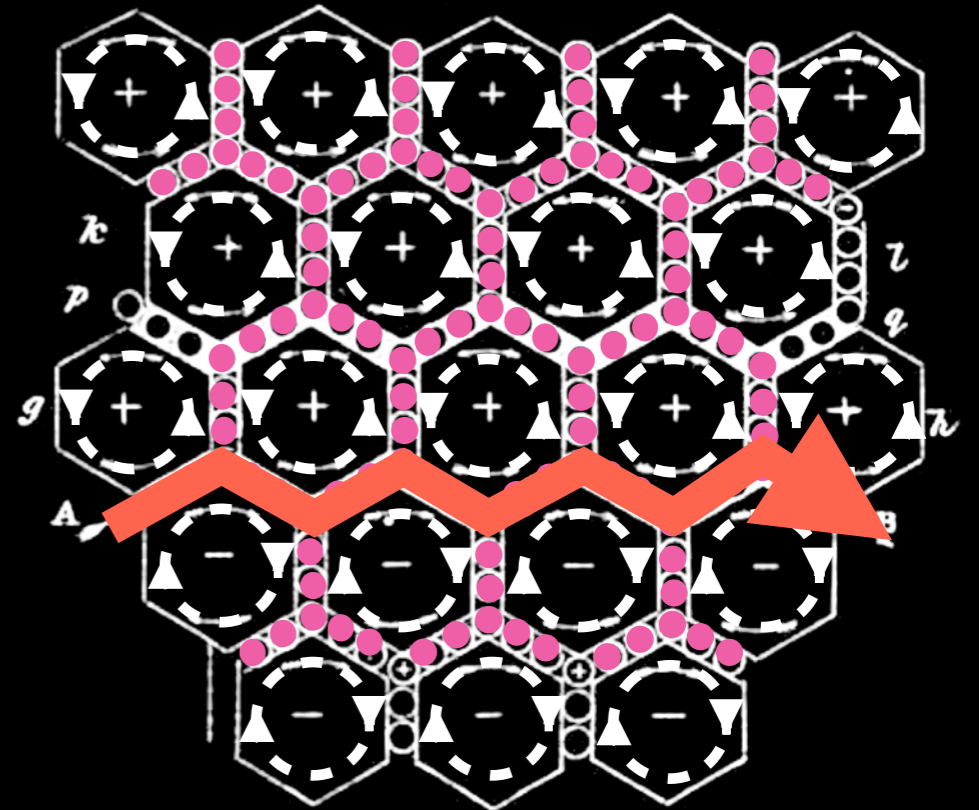
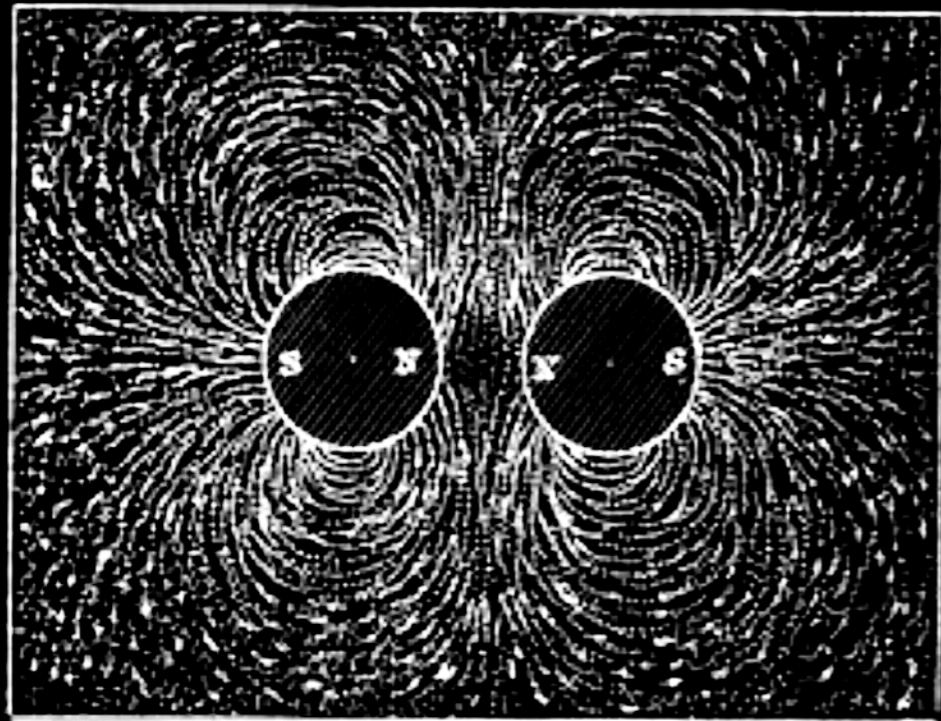
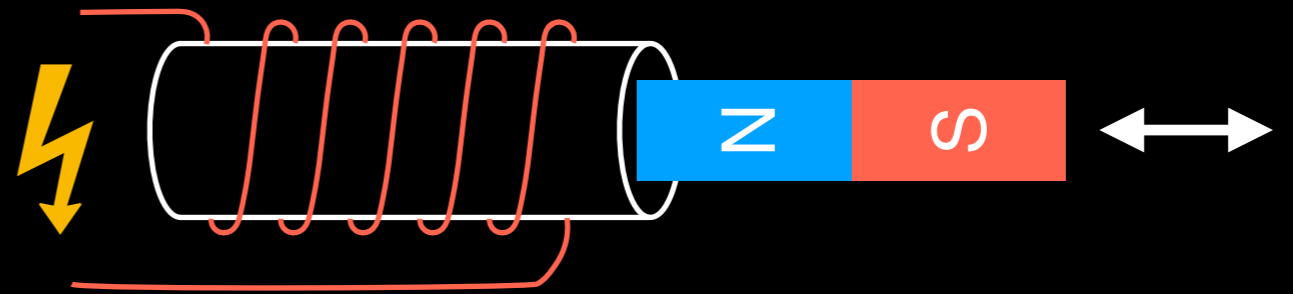
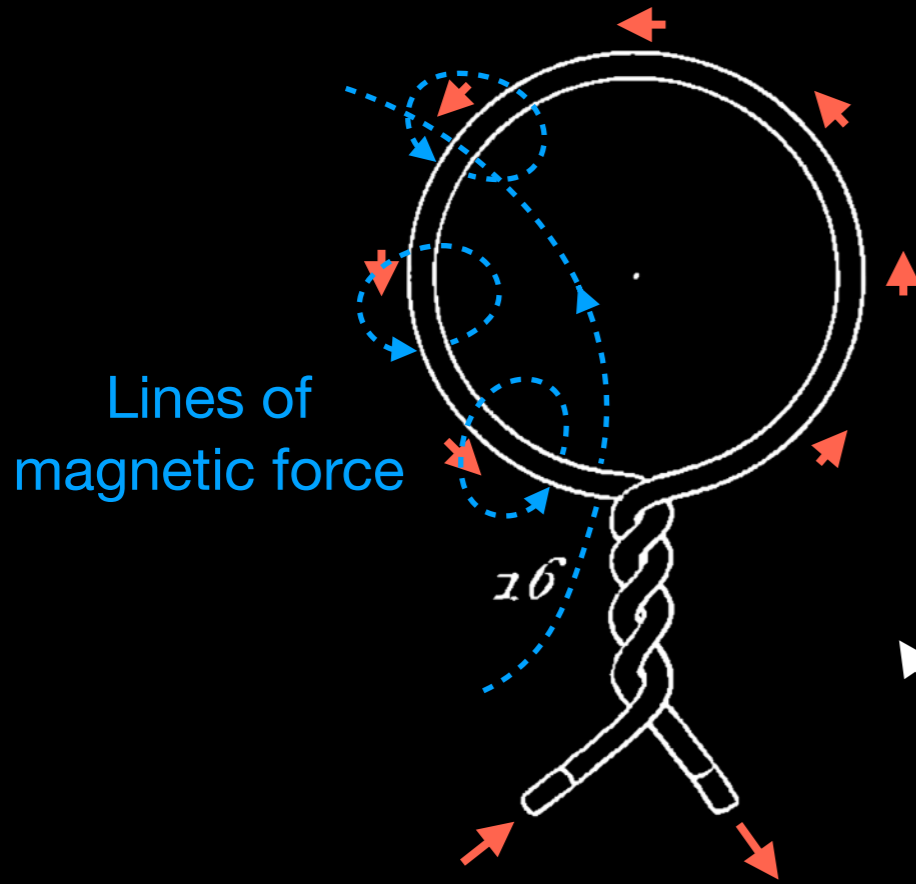
Maxwell's great synthesis



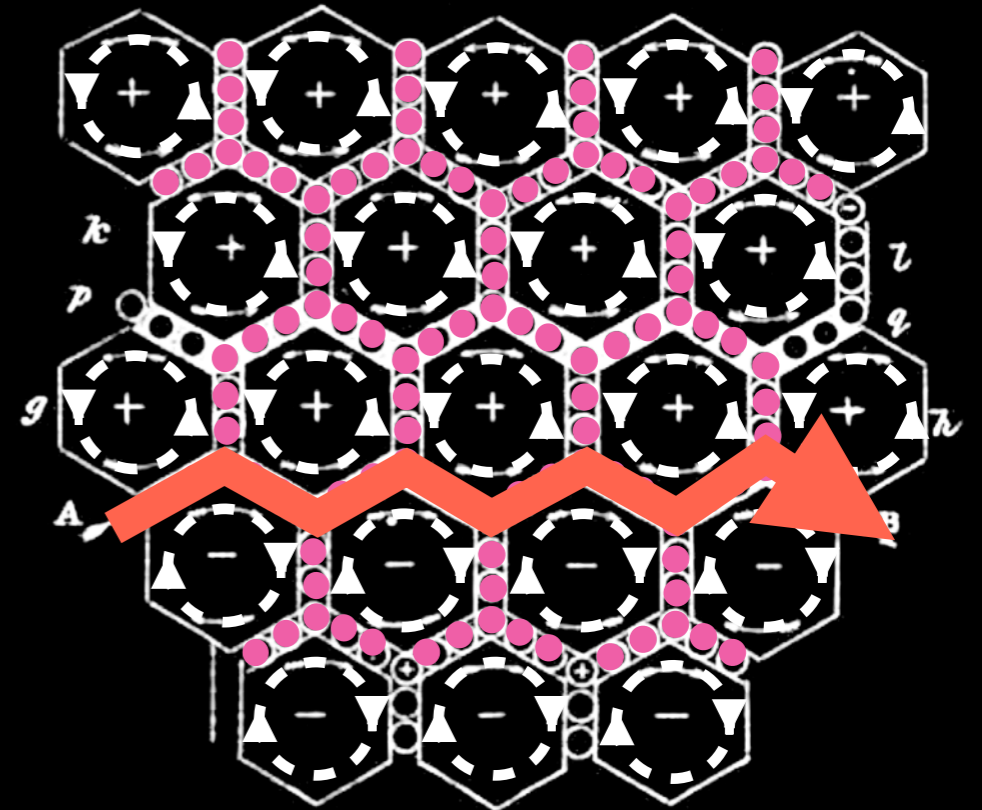
Maxwell's great synthesis



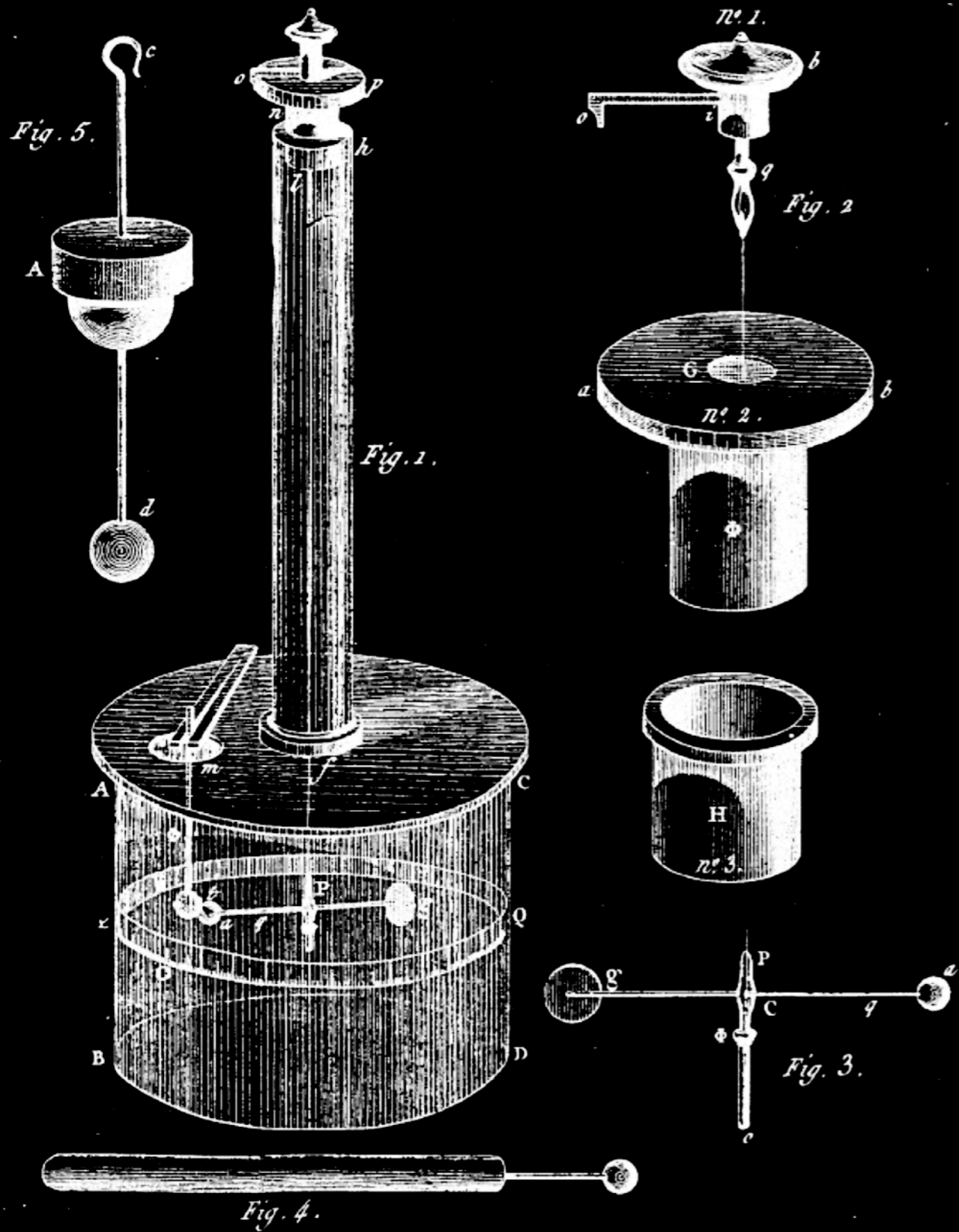
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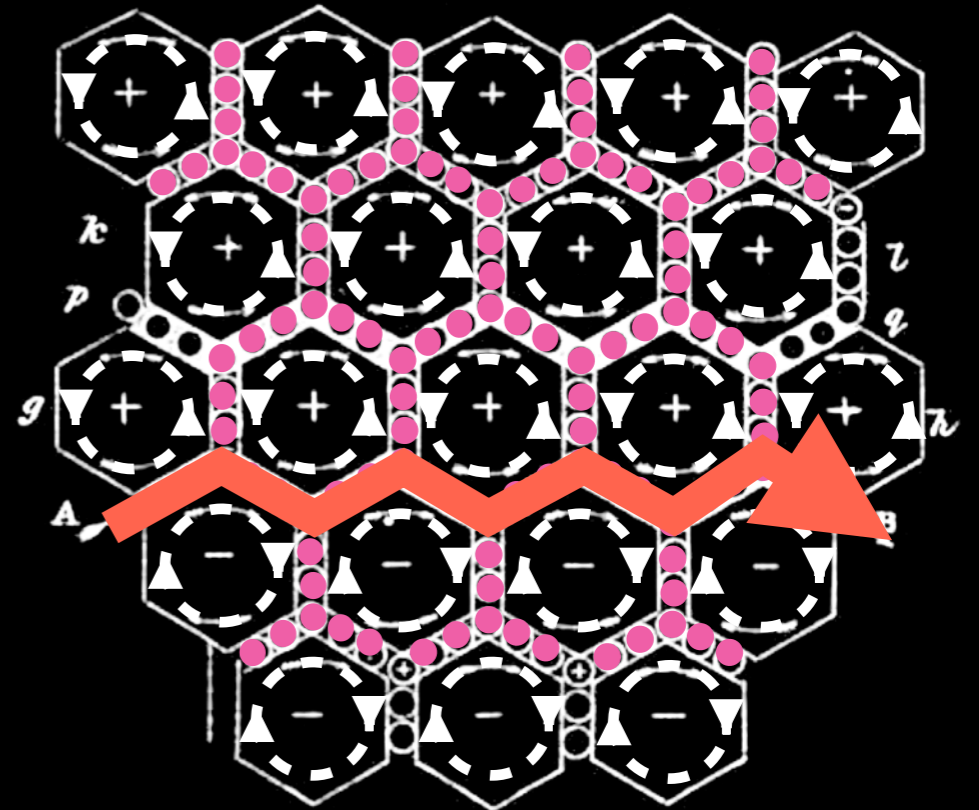
Maxwell's great synthesis



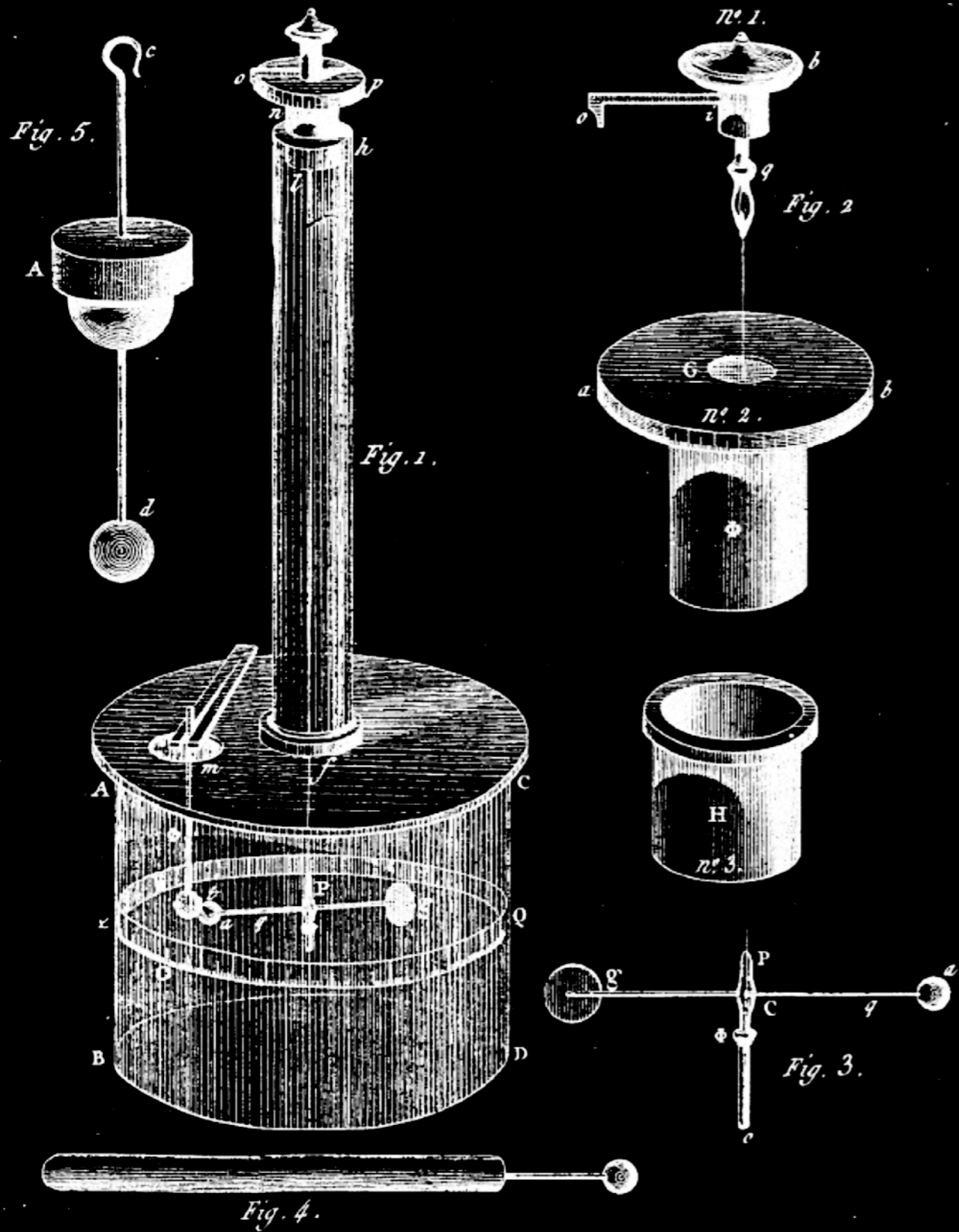
Maxwell's great synthesis



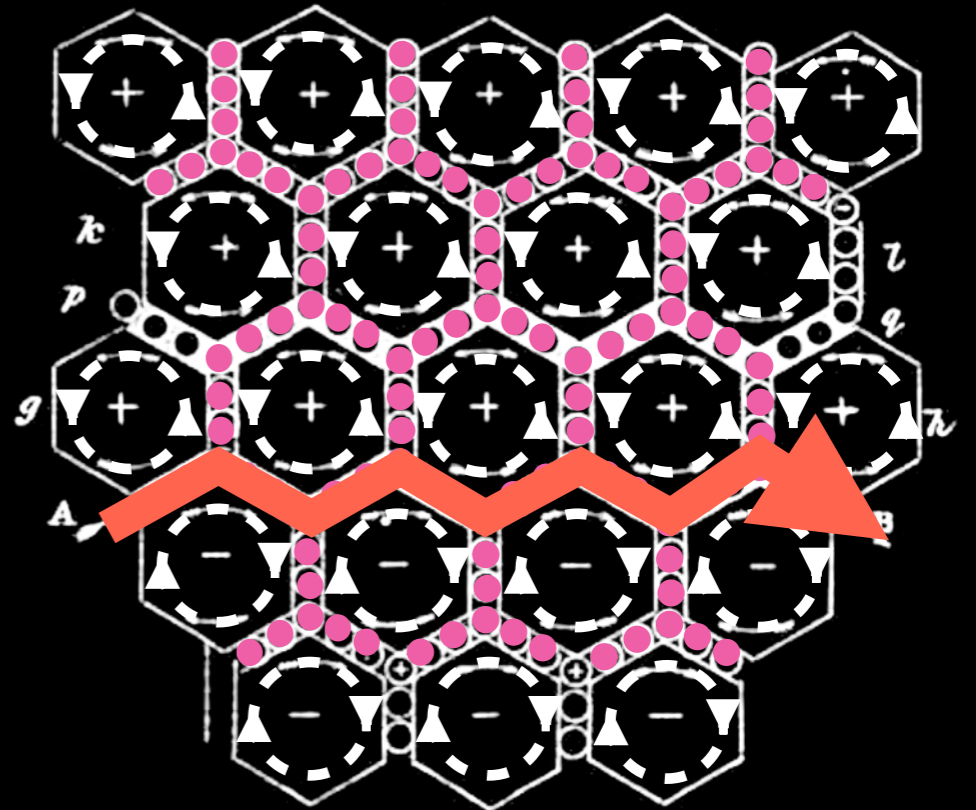
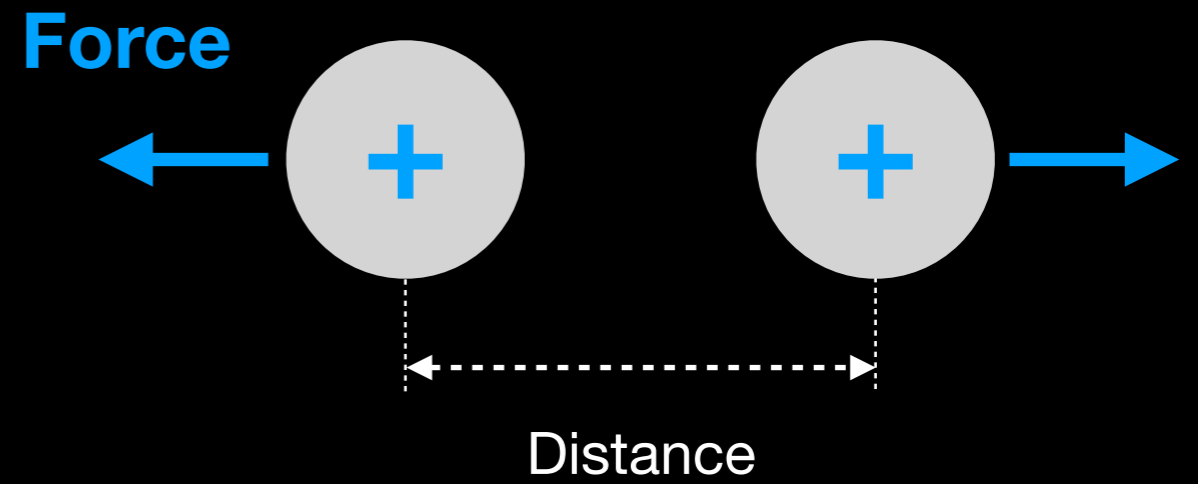
Charles Coulomb (1785)



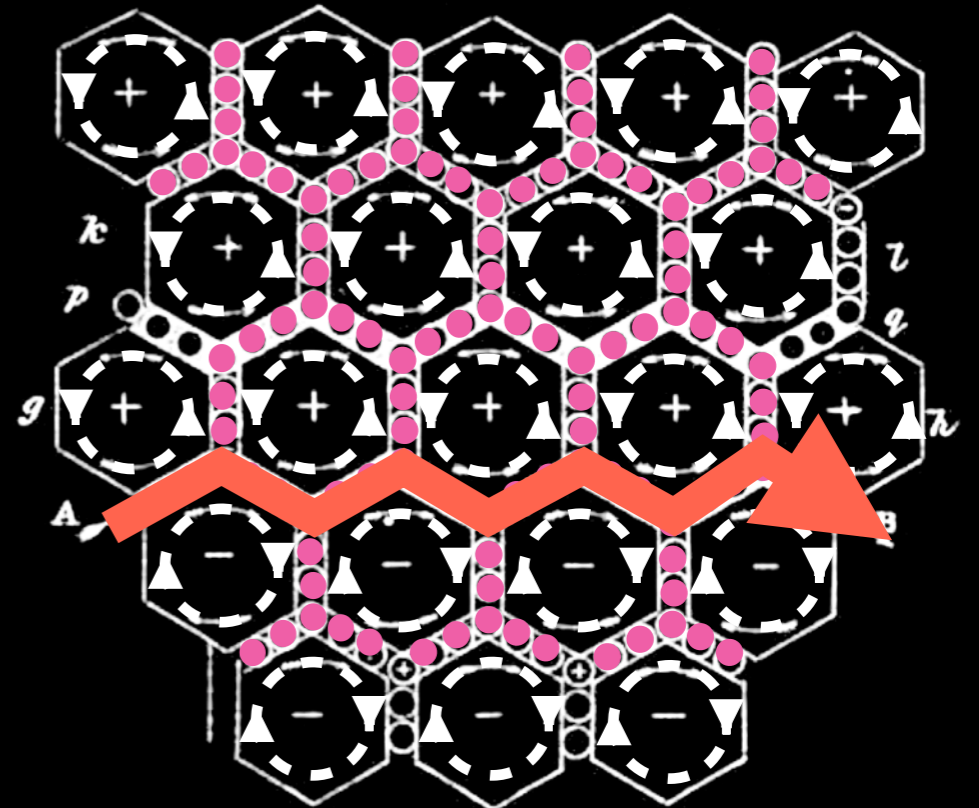
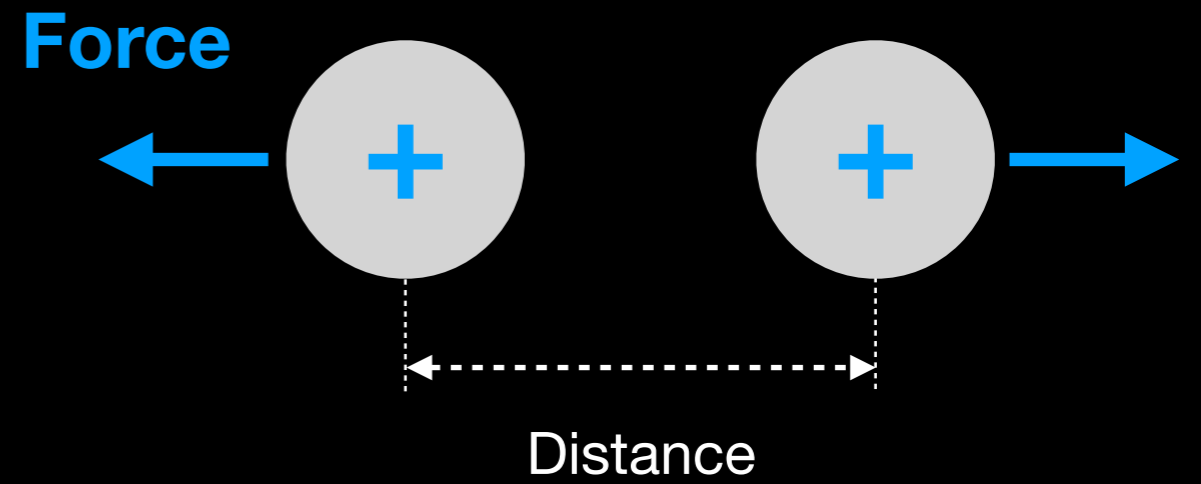
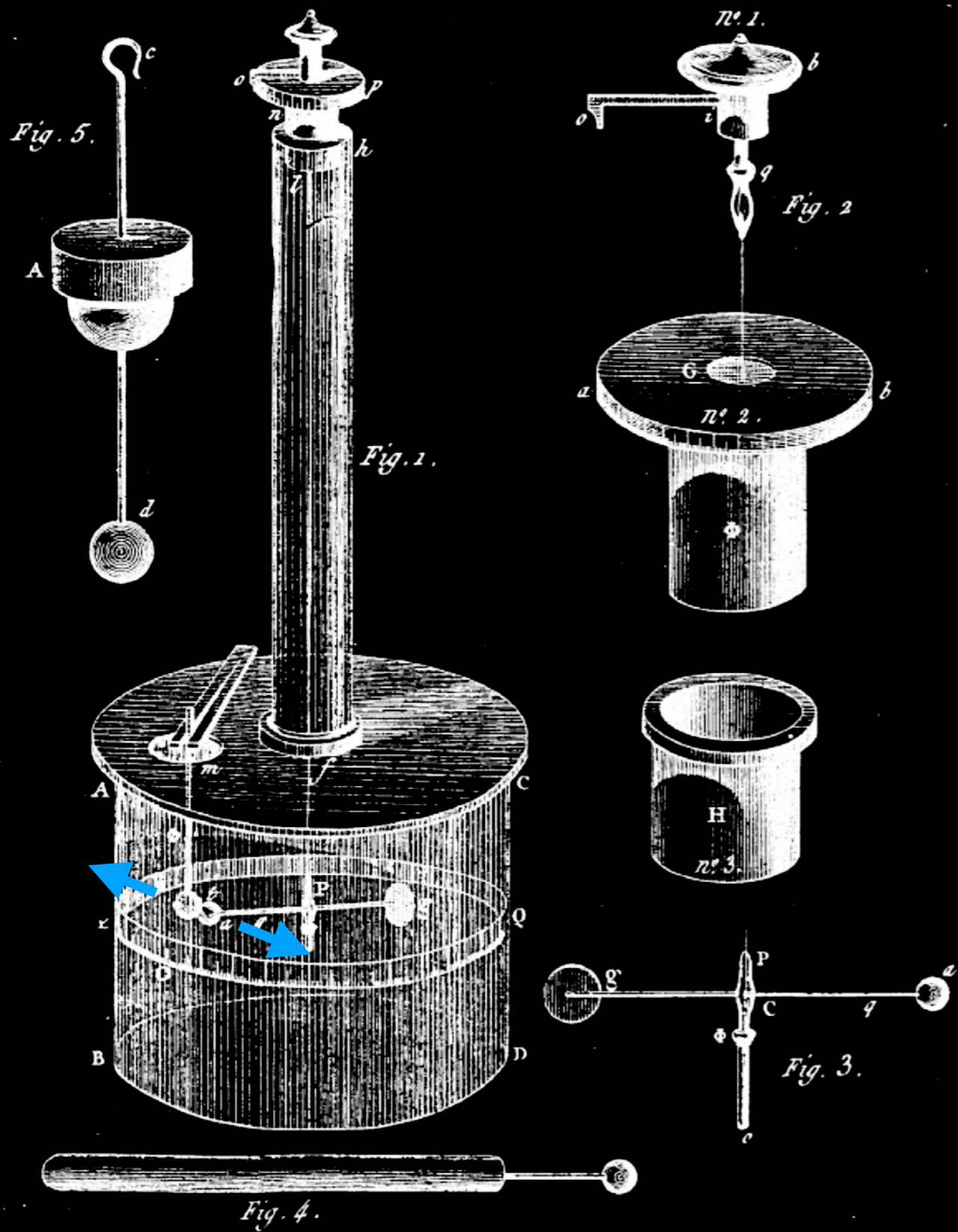
Maxwell's great synthesis



Charles Coulomb (1785)

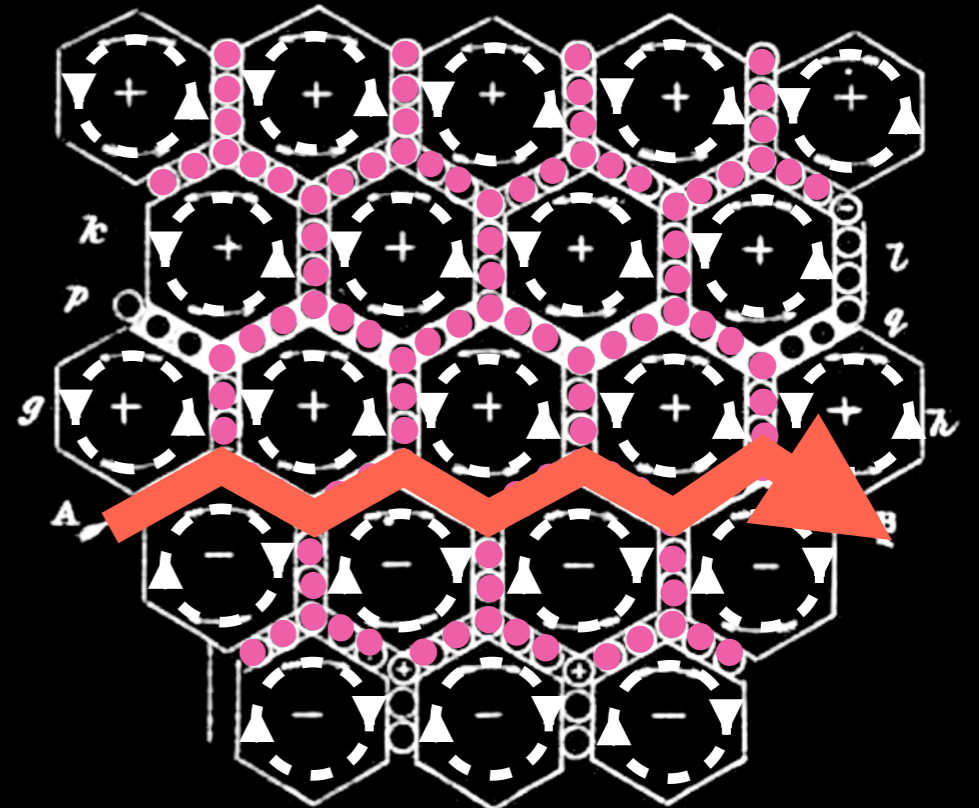
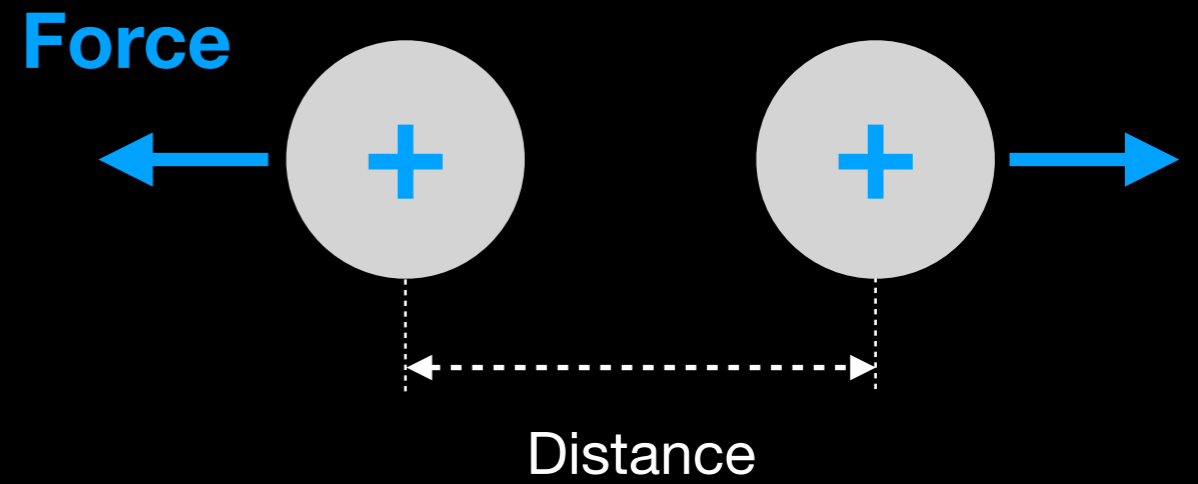
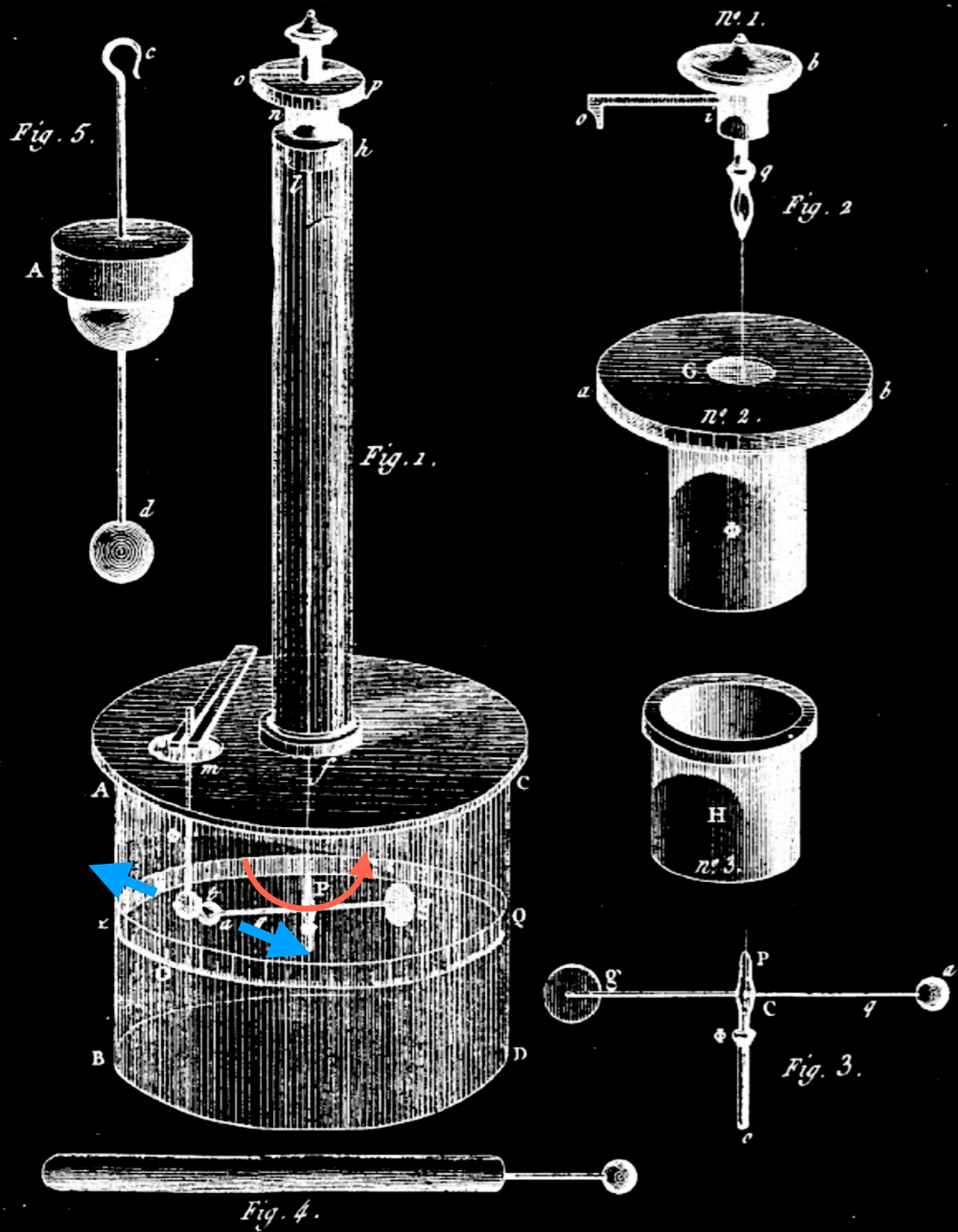


Maxwell's great synthesis



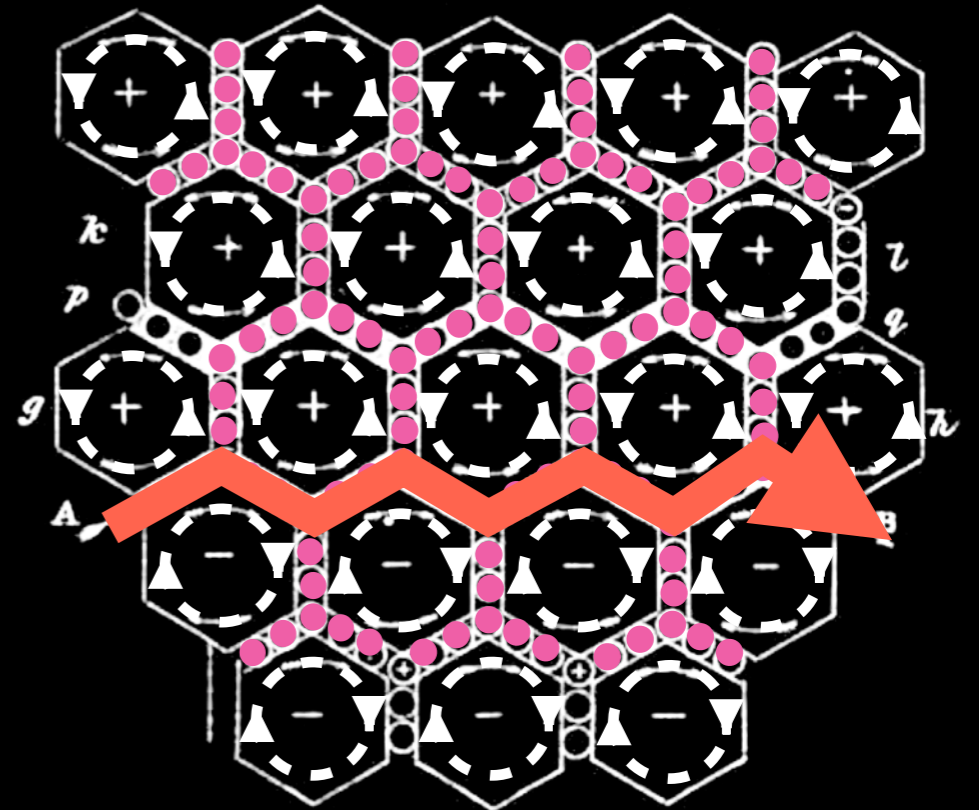
Charles Coulomb (1785)

Maxwell's great synthesis



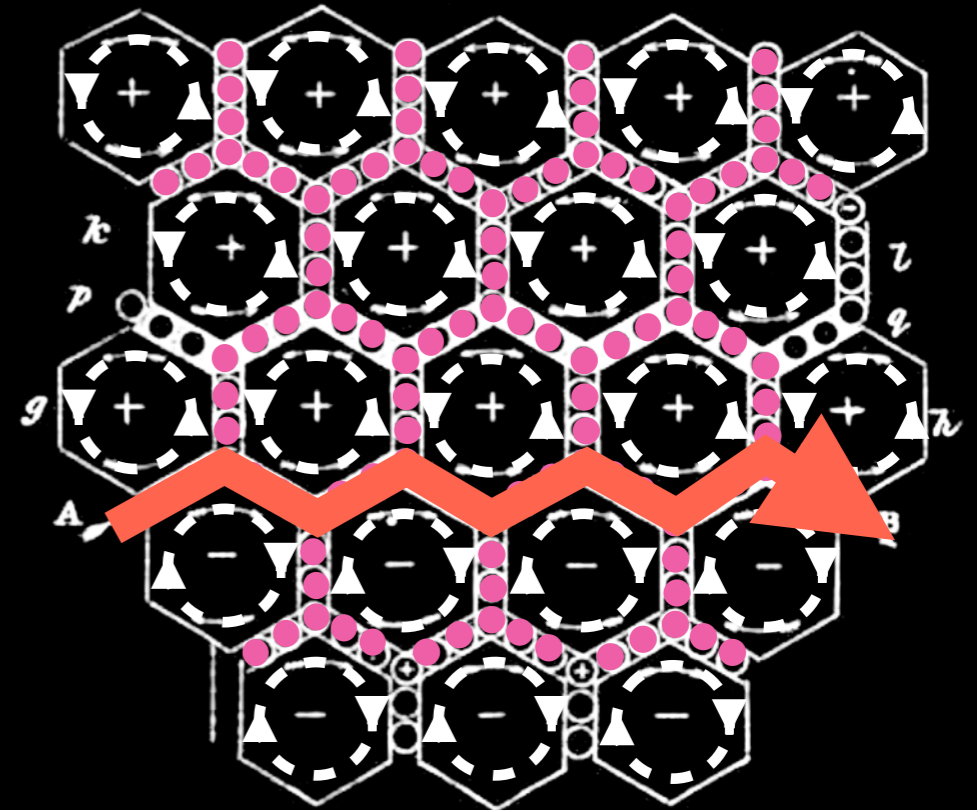
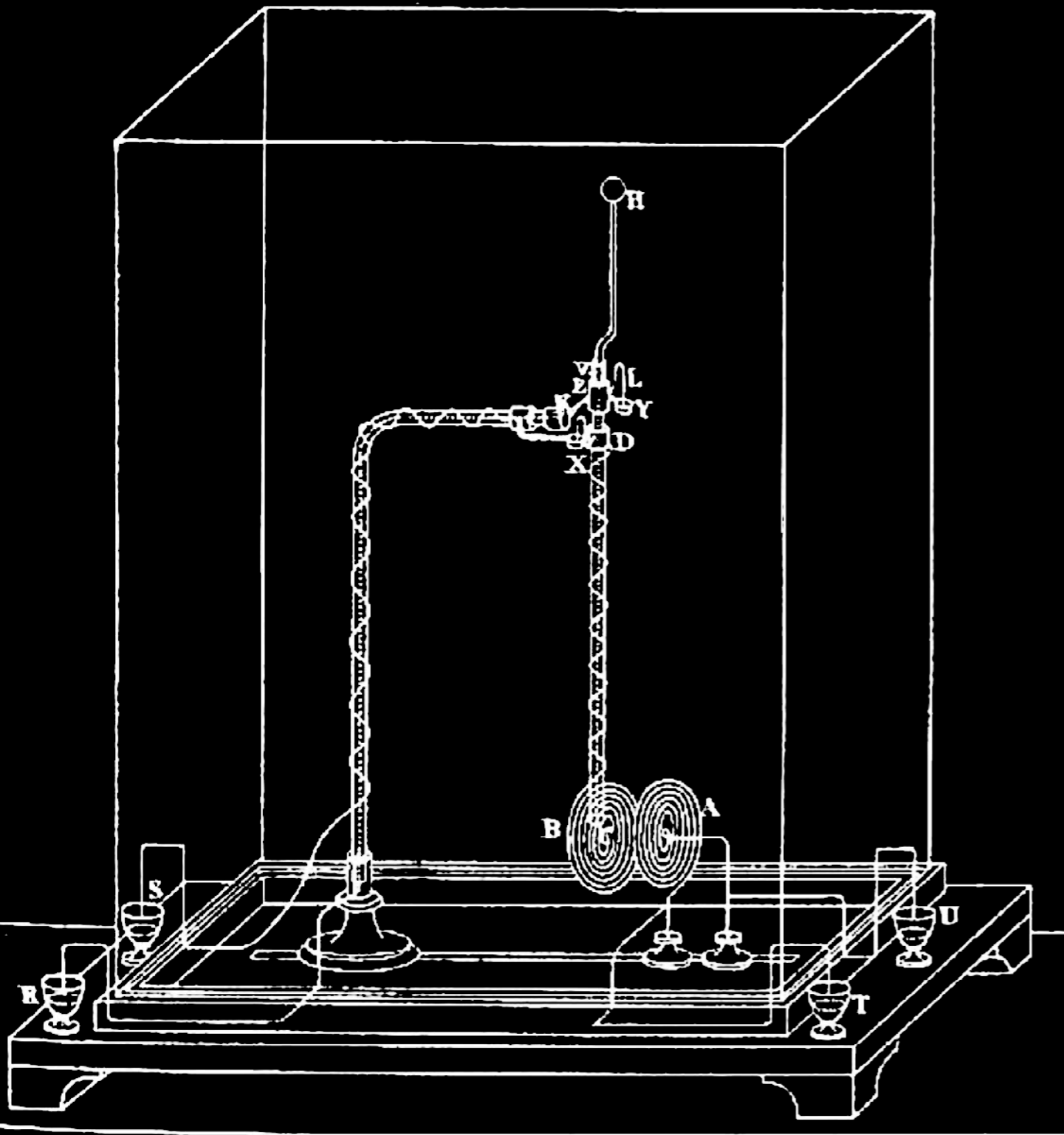
Charles Coulomb (1785)

Maxwell's great synthesis



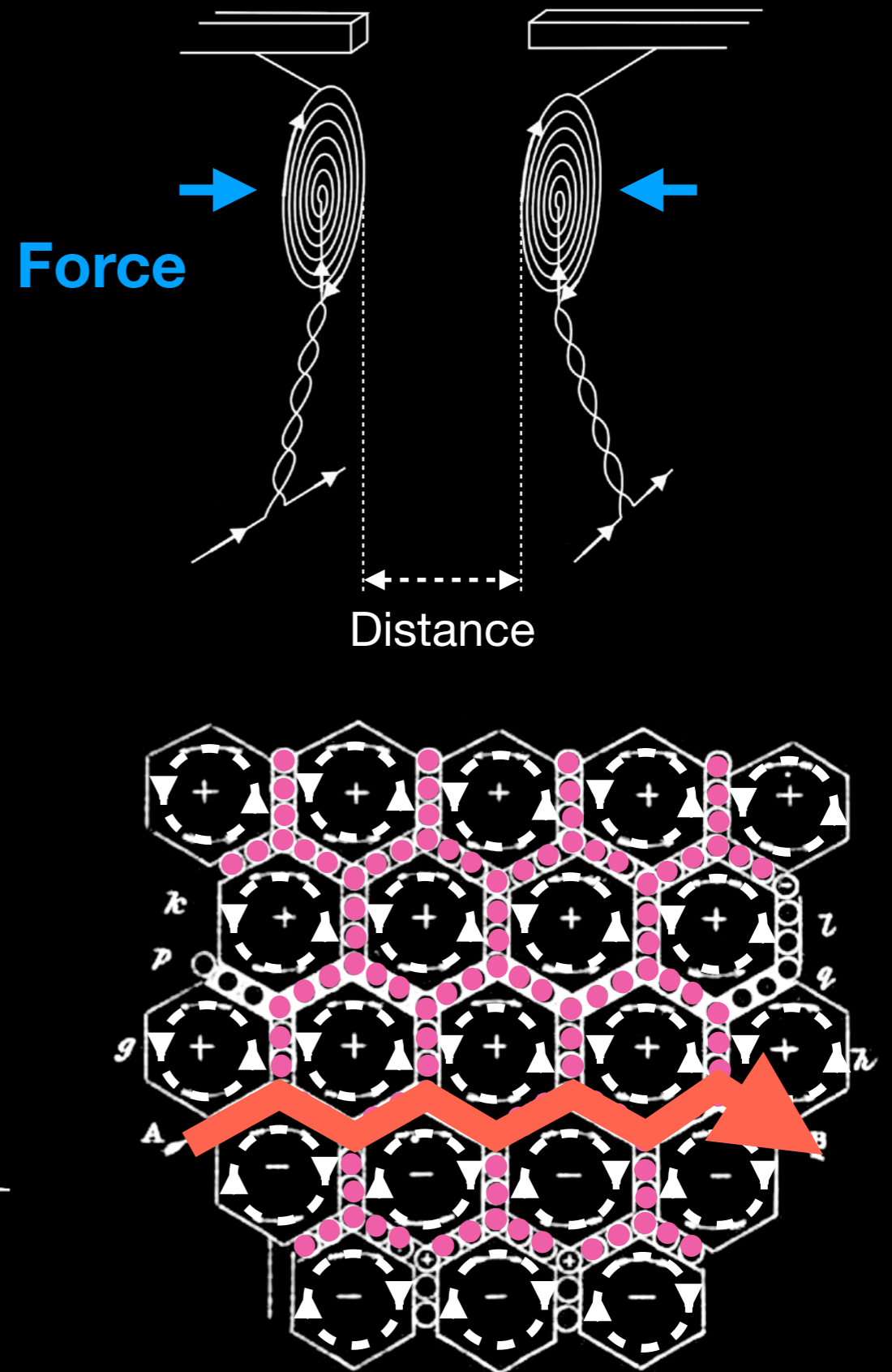
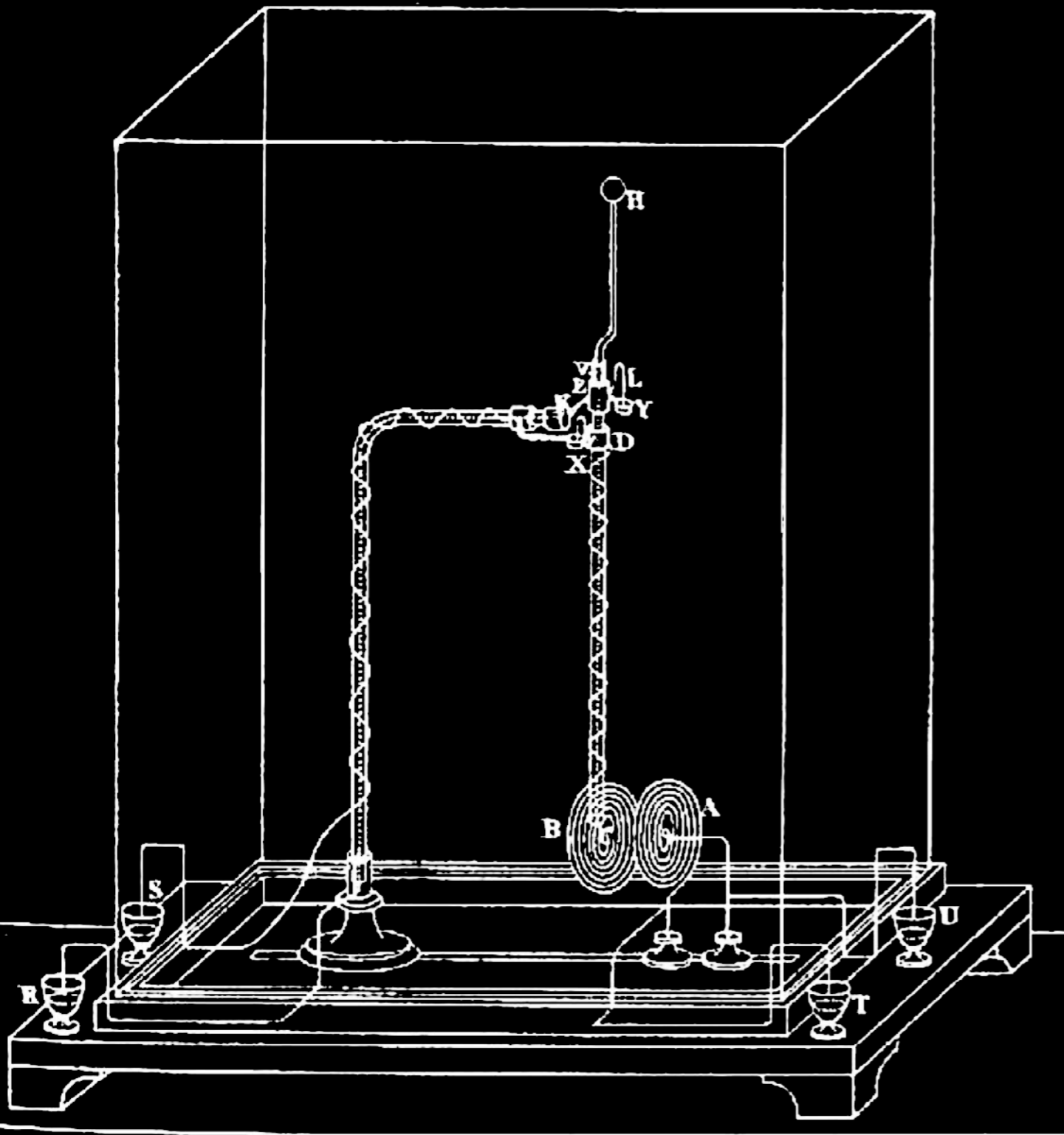
Maxwell's great synthesis

André-Marie Ampère (1820)



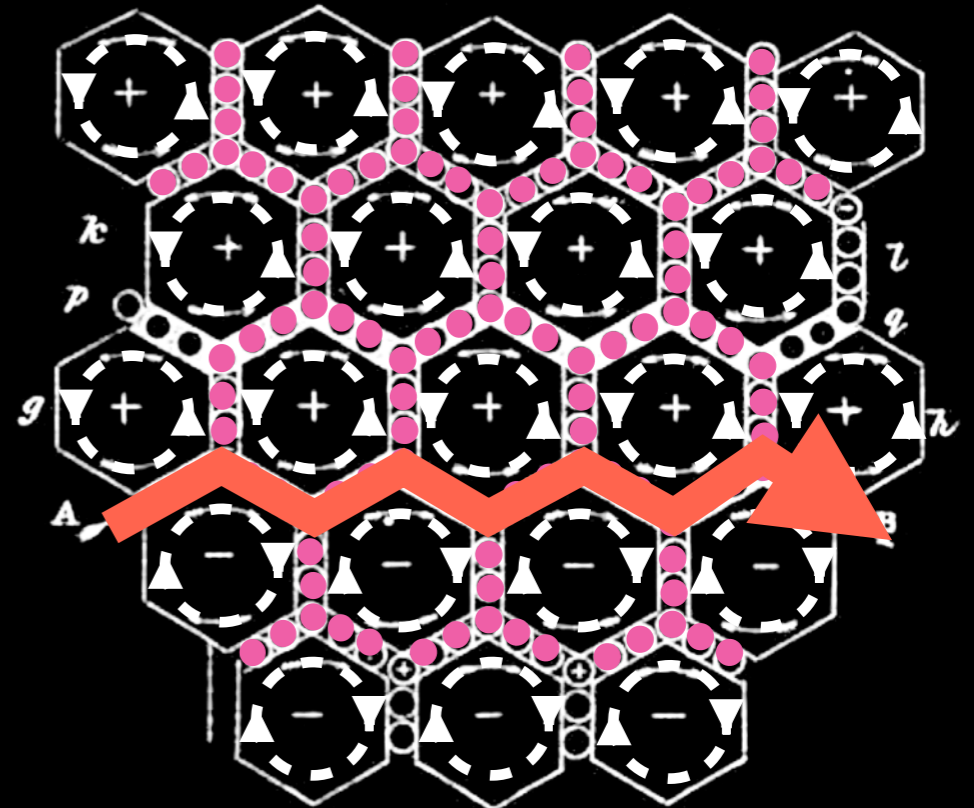
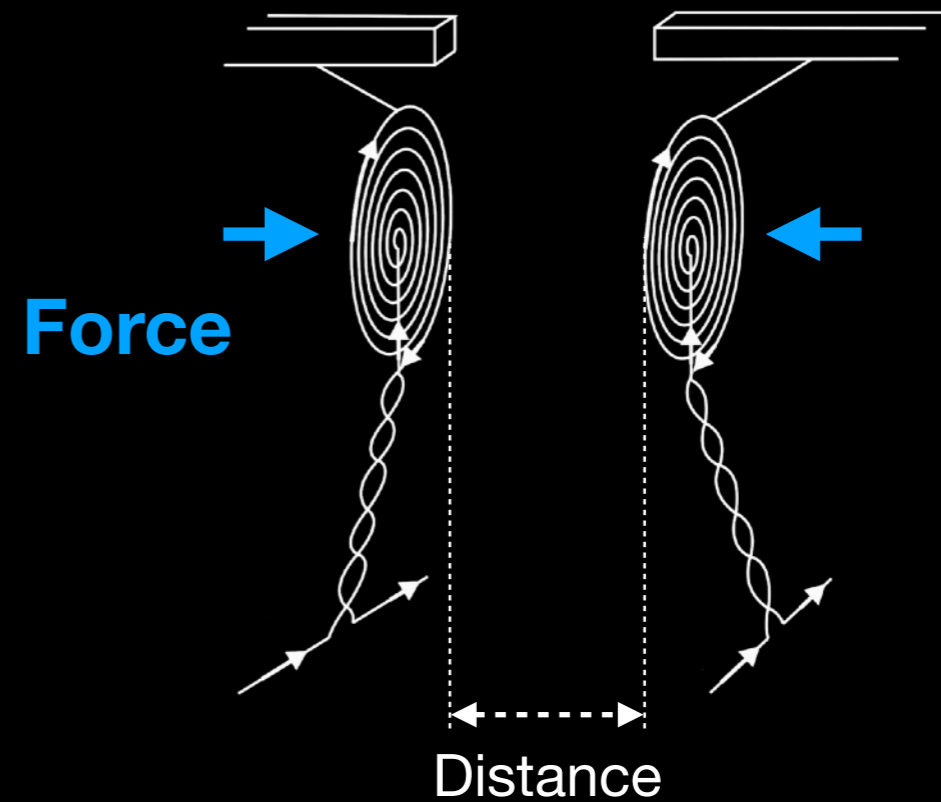
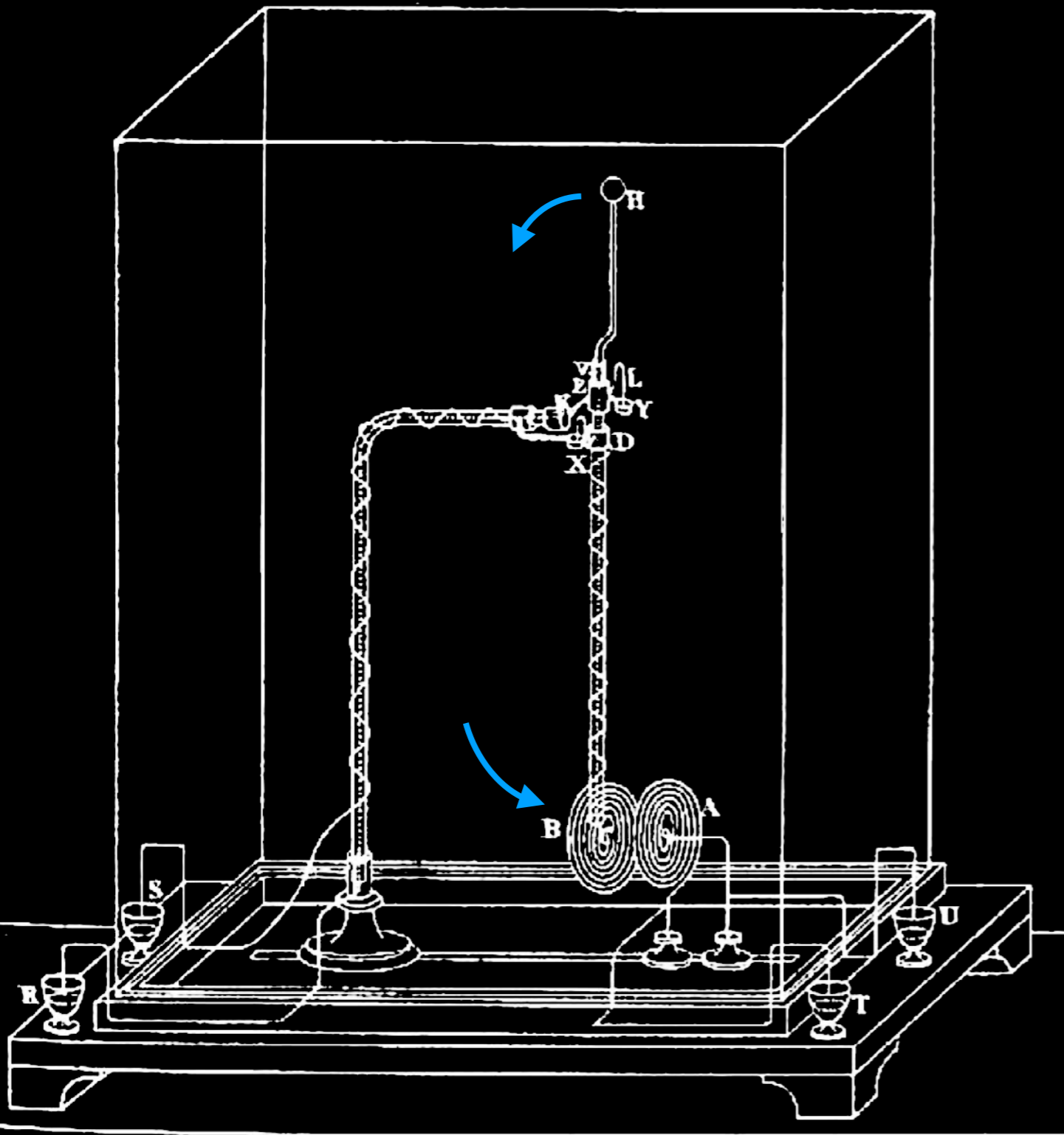
Maxwell's great synthesis

André-Marie Ampère (1820)

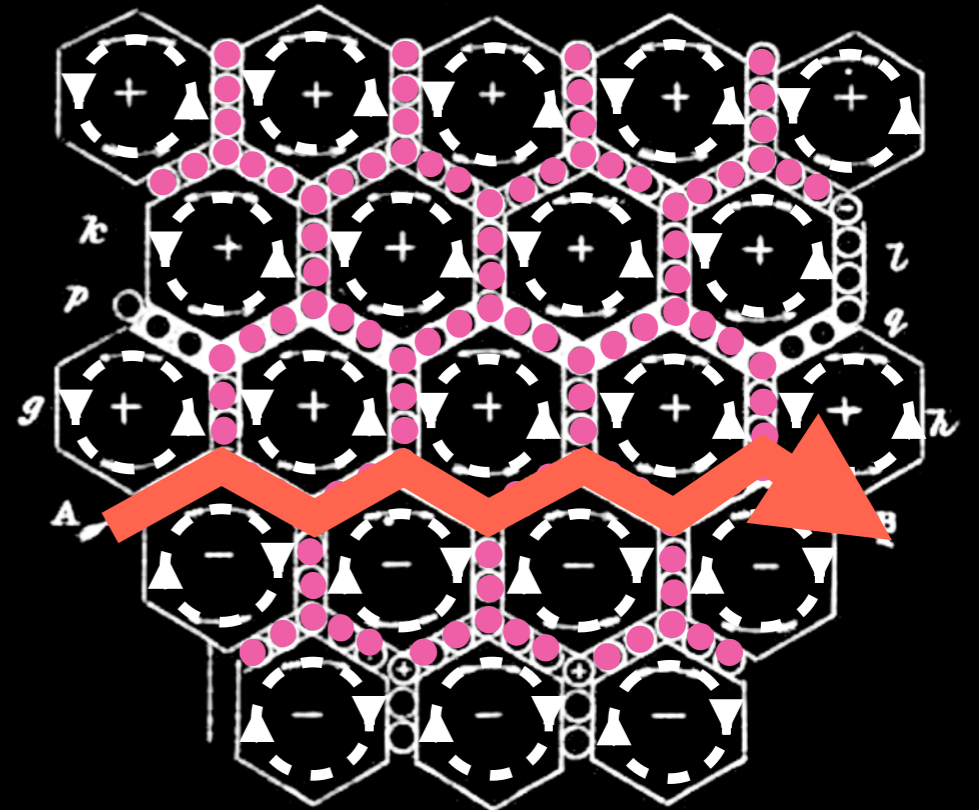


Maxwell's great synthesis

André-Marie Ampère (1820)



Maxwell's great synthesis



Maxwell's great synthesis

168 Prof. Maxwell on the Theory of Molecular Vortices

We have in general, for the force in the direction of x per unit of volume by the law of equilibrium of stresses*,

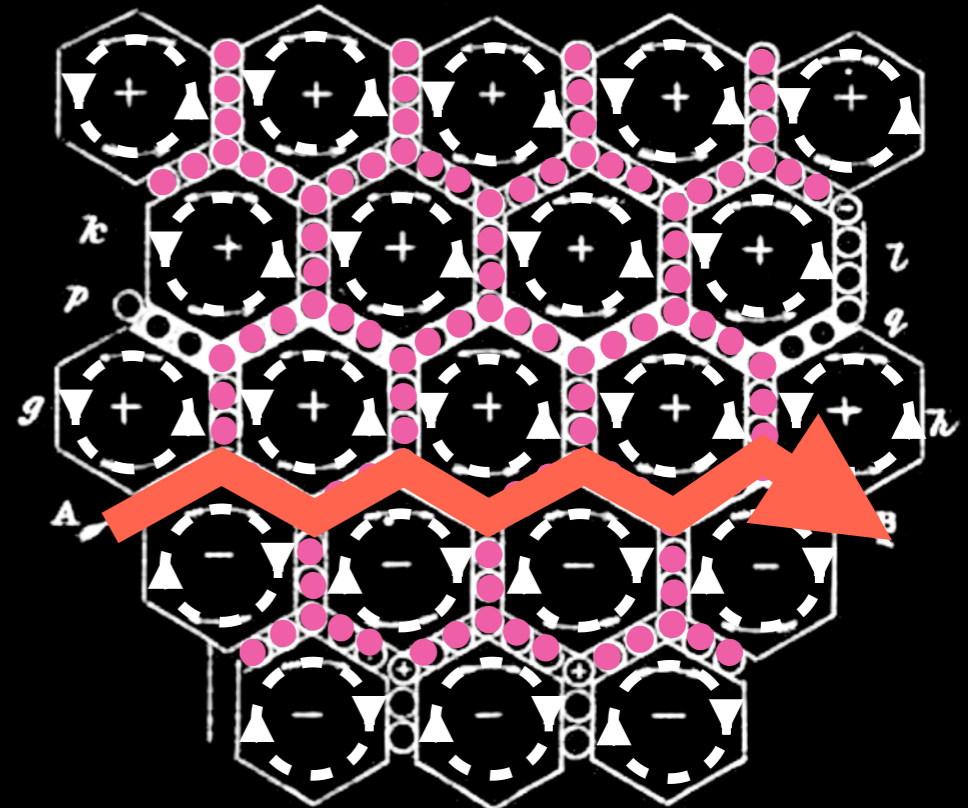
$$\mathbf{X} = \frac{d}{dx} p_{xx} + \frac{d}{dy} p_{xy} + \frac{d}{dz} p_{xz} \dots \dots \dots (3)$$

In this case the expression may be written

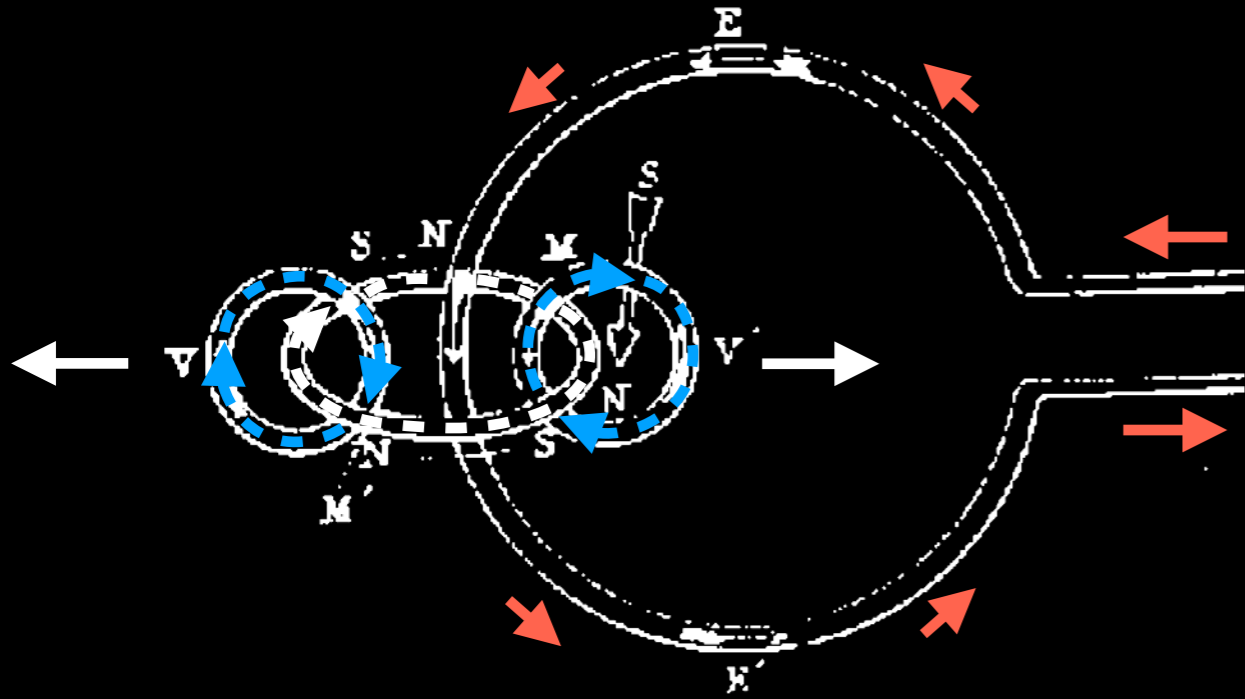
$$\mathbf{X} = \frac{1}{4\pi} \left\{ \frac{d(\mu\alpha)}{dx} \alpha + \mu\alpha \frac{d\alpha}{dx} - 4\pi \frac{dp_1}{dx} + \frac{d(\mu\beta)}{dy} \alpha + \mu\beta \frac{d\alpha}{dy} + \frac{d(\mu\gamma)}{dz} \alpha + \mu\gamma \frac{d\alpha}{dz} \right\} \dots \dots \dots (4)$$

Remembering that $\alpha \frac{d\alpha}{dx} + \beta \frac{d\beta}{dx} + \gamma \frac{d\gamma}{dx} = \frac{1}{2} \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$, this becomes

$$\mathbf{X} = \alpha \frac{1}{4\pi} \left(\frac{d}{dx} (\mu\alpha) + \frac{d}{dy} (\mu\beta) + \frac{d}{dz} (\mu\gamma) \right) + \frac{1}{8\pi} \mu \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$$



Maxwell's great synthesis



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

168 Prof. Maxwell on the *Theory of Molecular Vortices*

We have in general, for the force in the direction of x per unit of volume by the law of equilibrium of stresses*,

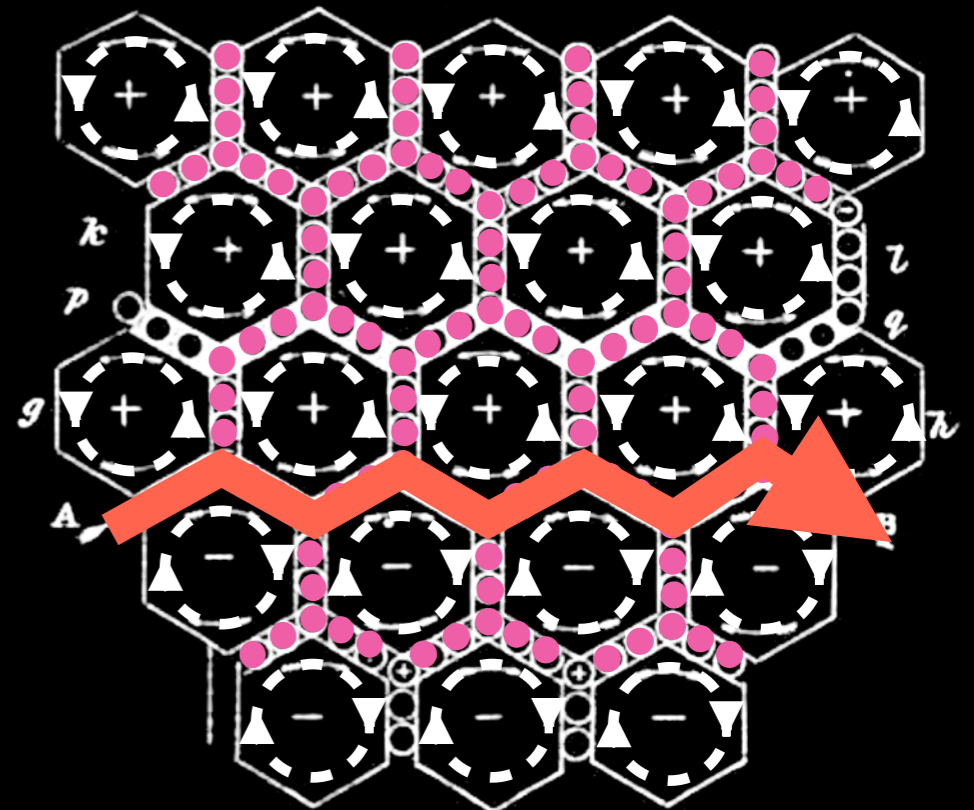
$$\mathbf{X} = \frac{d}{dx} p_{xx} + \frac{d}{dy} p_{xy} + \frac{d}{dz} p_{xz} \dots \dots \dots (3)$$

In this case the expression may be written

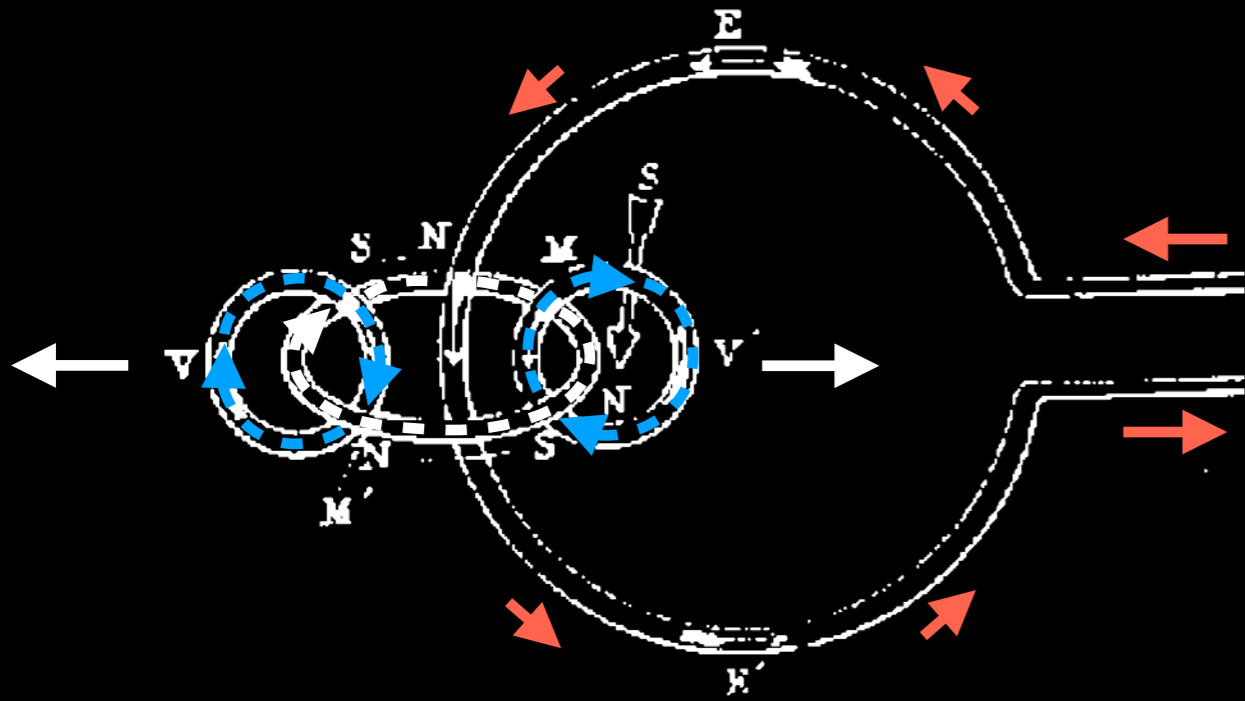
$$\mathbf{X} = \frac{1}{4\pi} \left\{ \frac{d(\mu\alpha)}{dx} \alpha + \mu\alpha \frac{d\alpha}{dx} - 4\pi \frac{dp_1}{dx} + \frac{d(\mu\beta)}{dy} \alpha + \mu\beta \frac{d\alpha}{dy} + \frac{d(\mu\gamma)}{dz} \alpha + \mu\gamma \frac{d\alpha}{dz} \right\} \dots \dots \dots (4)$$

Remembering that $\alpha \frac{d\alpha}{dx} + \beta \frac{d\beta}{dx} + \gamma \frac{d\gamma}{dx} = \frac{1}{2} \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$, this becomes

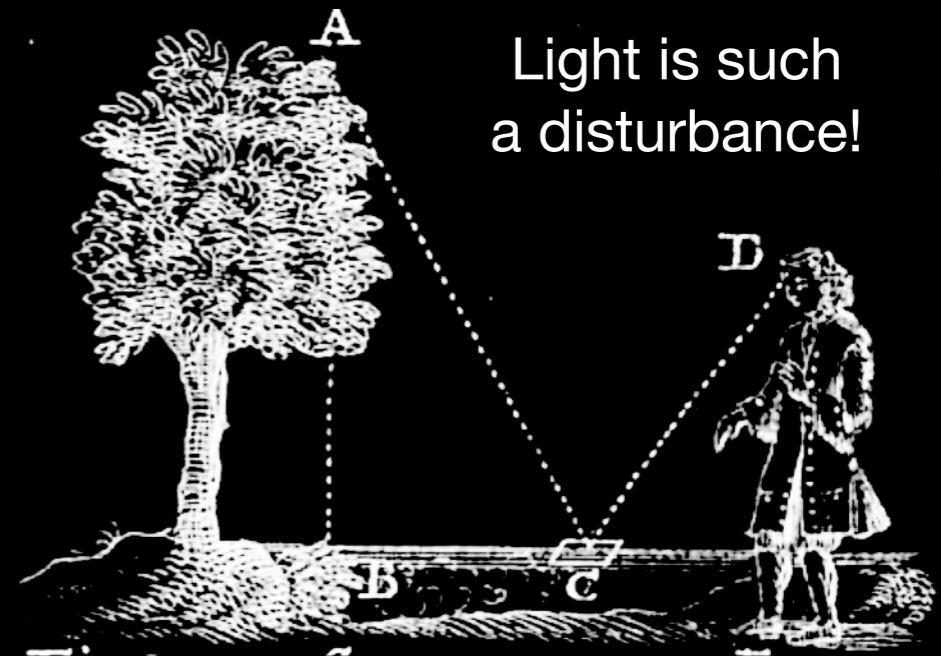
$$\mathbf{X} = \alpha \frac{1}{4\pi} \left(\frac{d}{dx} (\mu\alpha) + \frac{d}{dy} (\mu\beta) + \frac{d}{dz} (\mu\gamma) \right) + \frac{1}{8\pi} \mu \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$$



Maxwell's great synthesis



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



Light is such a disturbance!

168 Prof. Maxwell on the Theory of Molecular Vortices

We have in general, for the force in the direction of x per unit of volume by the law of equilibrium of stresses*,

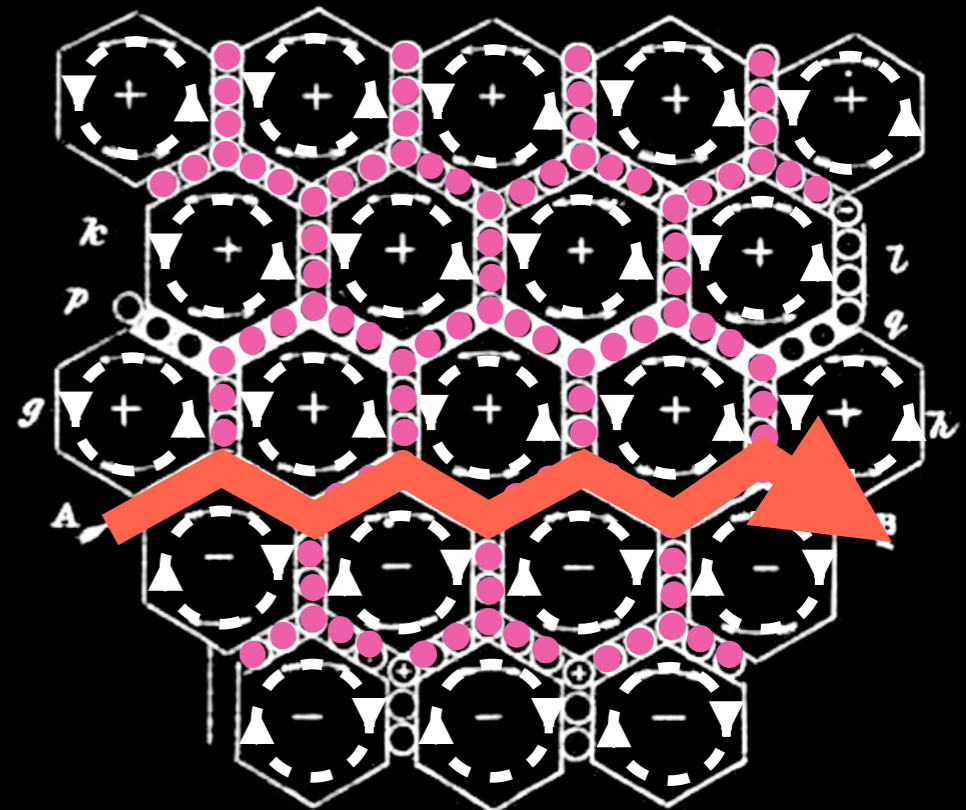
$$X = \frac{d}{dx} p_{xx} + \frac{d}{dy} p_{xy} + \frac{d}{dz} p_{xz} \dots \dots \dots (3)$$

In this case the expression may be written

$$X = \frac{1}{4\pi} \left\{ \frac{d(\mu\alpha)}{dx} \alpha + \mu\alpha \frac{d\alpha}{dx} - 4\pi \frac{dp_1}{dx} + \frac{d(\mu\beta)}{dy} \alpha + \mu\beta \frac{d\alpha}{dy} + \frac{d(\mu\gamma)}{dz} \alpha + \mu\gamma \frac{d\alpha}{dz} \right\} \dots \dots \dots (4)$$

Remembering that $\alpha \frac{d\alpha}{dx} + \beta \frac{d\beta}{dx} + \gamma \frac{d\gamma}{dx} = \frac{1}{2} \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$, this becomes

$$X = \alpha \frac{1}{4\pi} \left(\frac{d}{dx} (\mu\alpha) + \frac{d}{dy} (\mu\beta) + \frac{d}{dz} (\mu\gamma) \right) + \frac{1}{8\pi} \mu \frac{d}{dx} (\alpha^2 + \beta^2 + \gamma^2)$$



“Ordinary
electricity”

“Voltaic
electricity”

“Ordinary
electricity”

“Voltaic
electricity”

“Animal
electricity”

“Ordinary
electricity”

“Voltaic
electricity”

“Animal
electricity”

“Ordinary
electricity”

“Magneto-
electricity”

“Voltaic
electricity”

“Animal
electricity”

“Ordinary
electricity”

“Magneto-
electricity”

Electricity

“Voltaic
electricity”

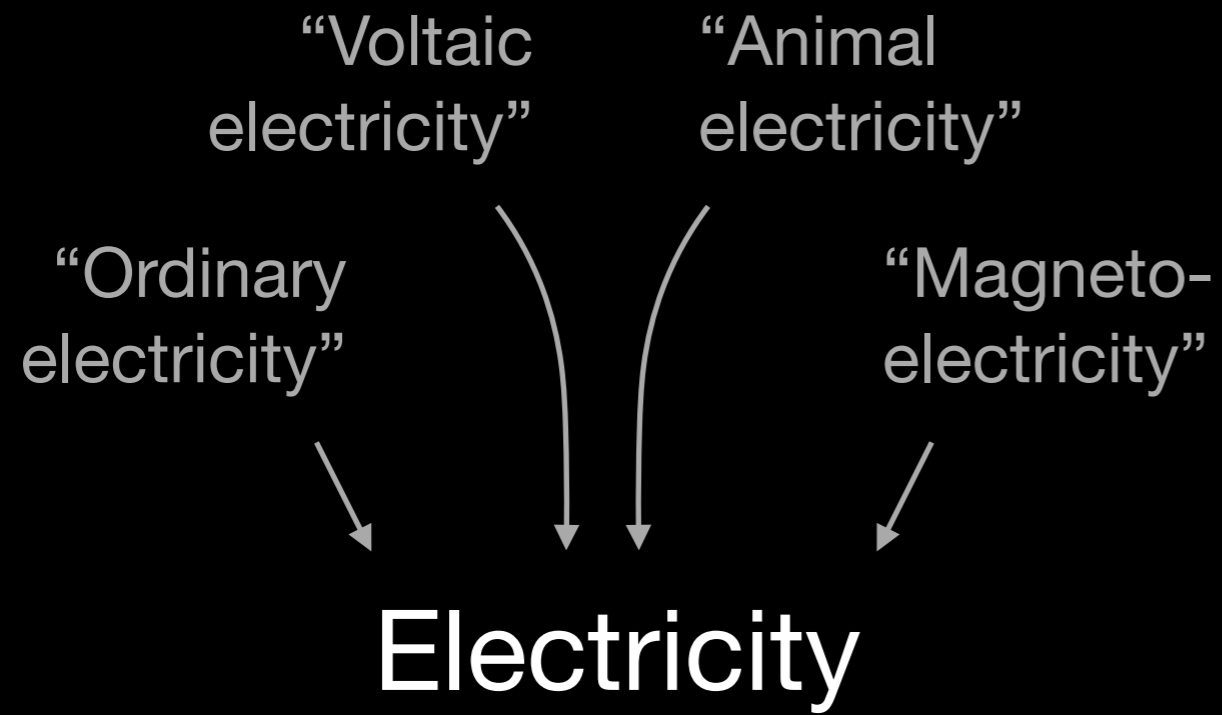
“Animal
electricity”

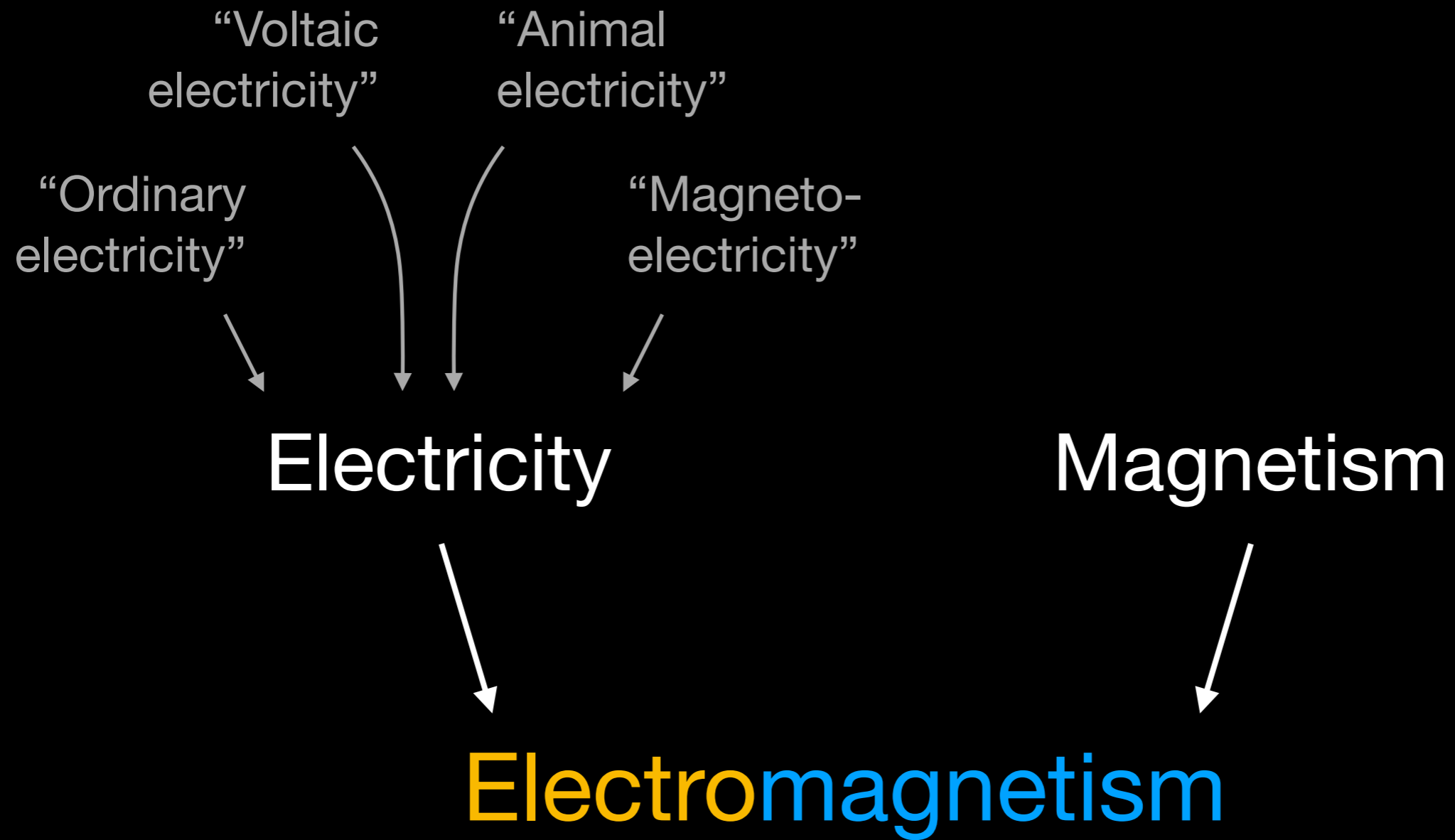
“Ordinary
electricity”

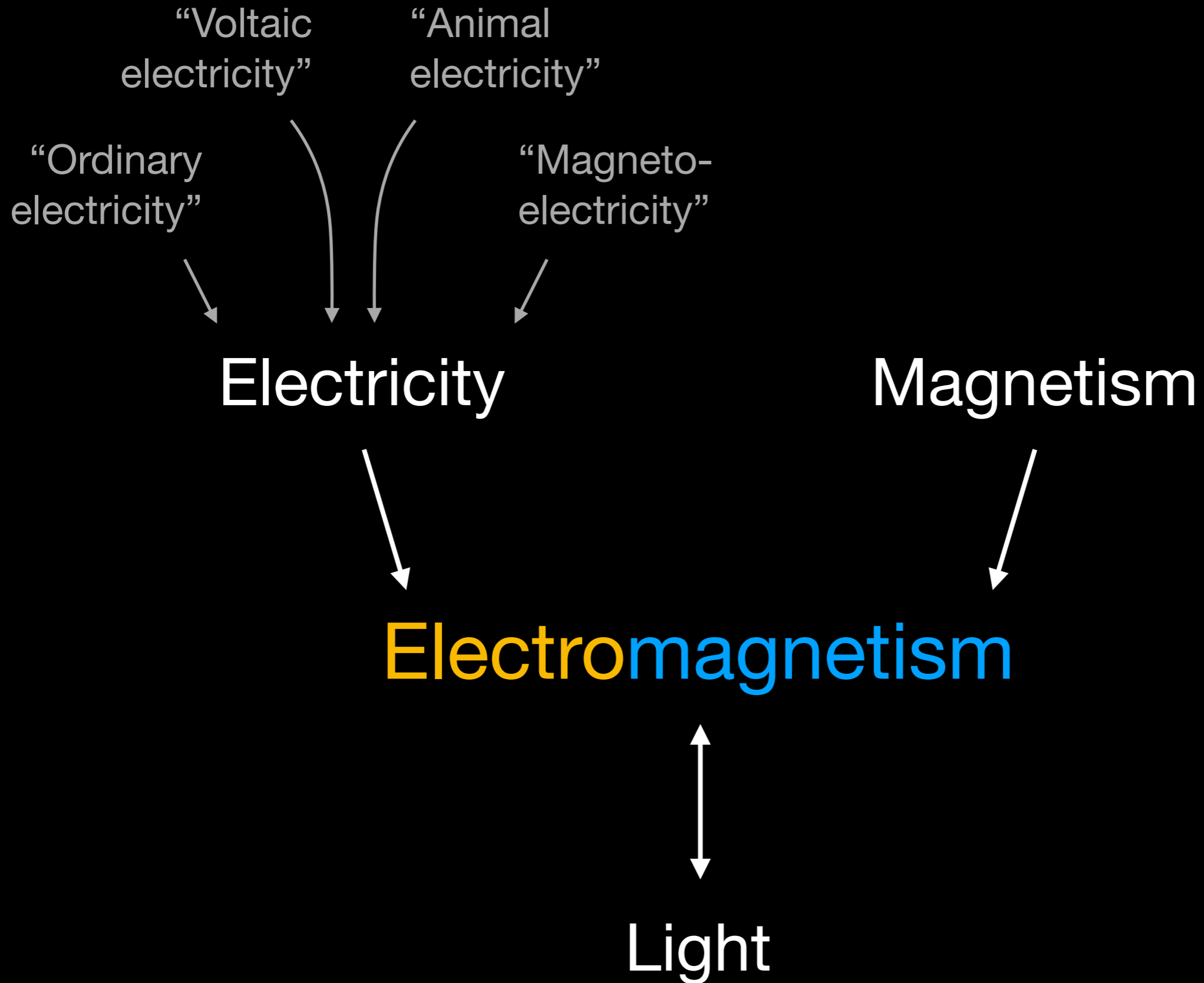
“Magneto-
electricity”

Electricity

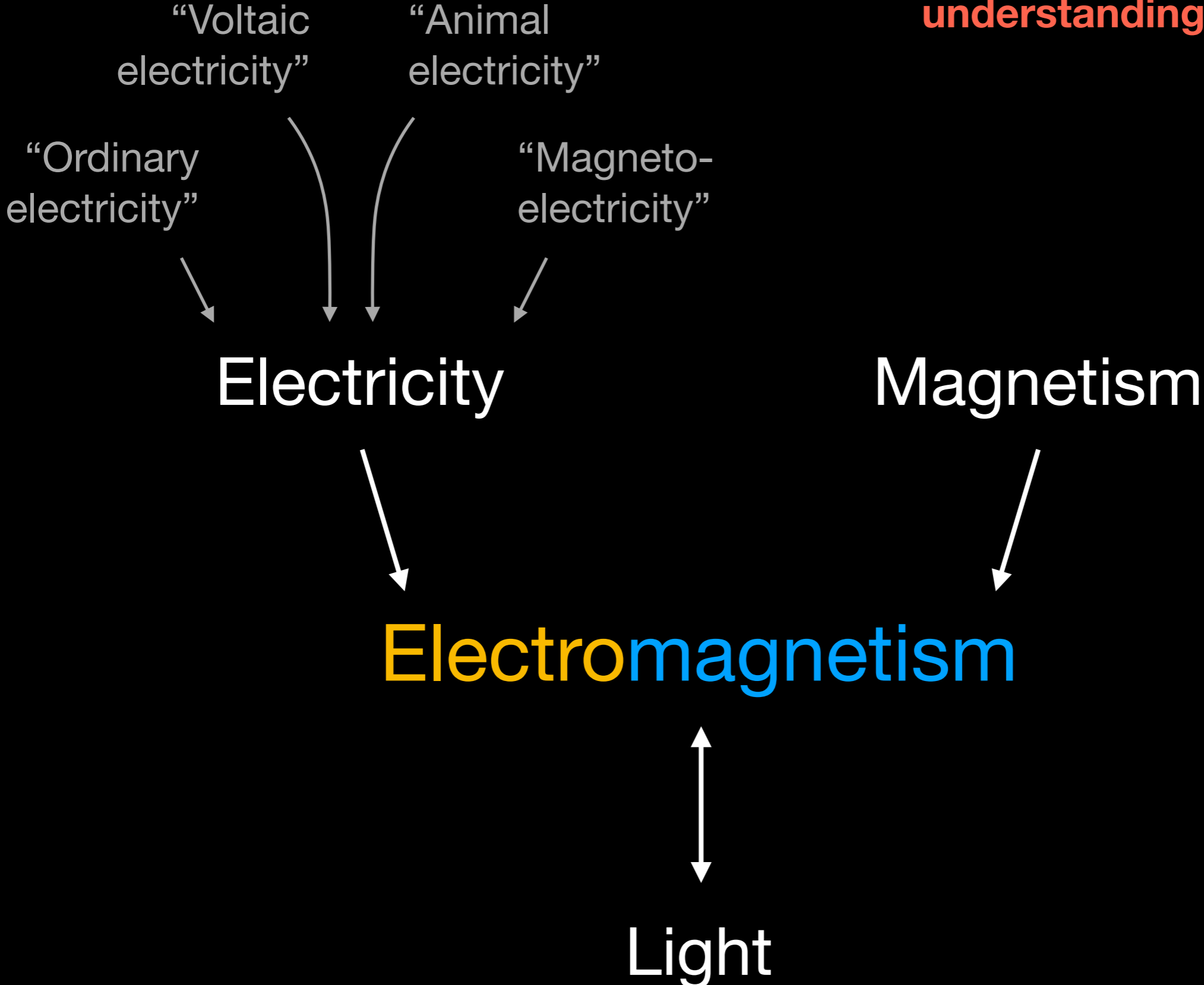
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graph TD; A["Voltaic electricity"] --> D[Electricity]; B["Animal electricity"] --> D; C["Ordinary electricity"] --> D; E["Magneto-electricity"] --> D;
```





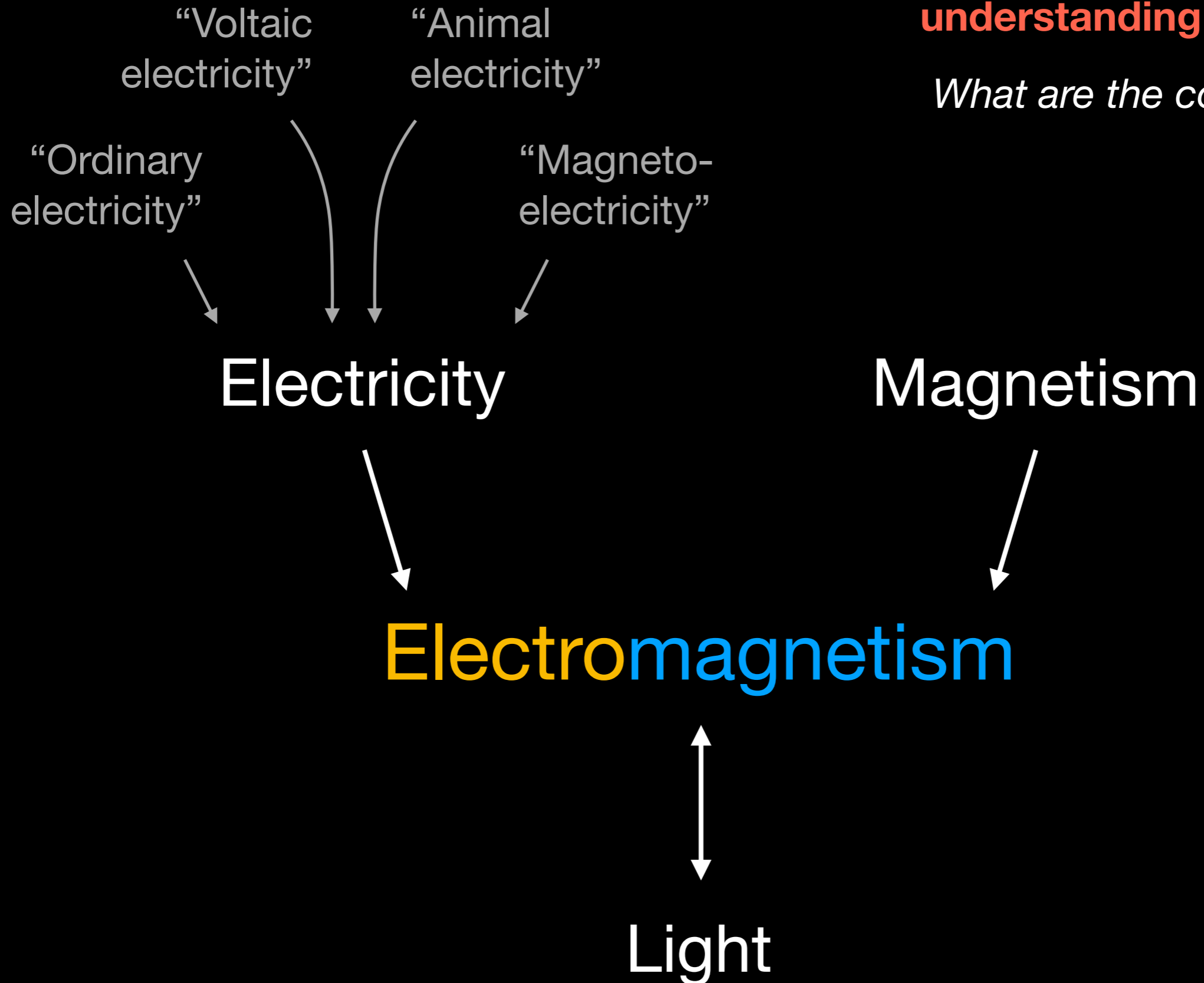


A huge improvement in our understanding of the world!



A huge improvement in our understanding of the world!

What are the consequences?



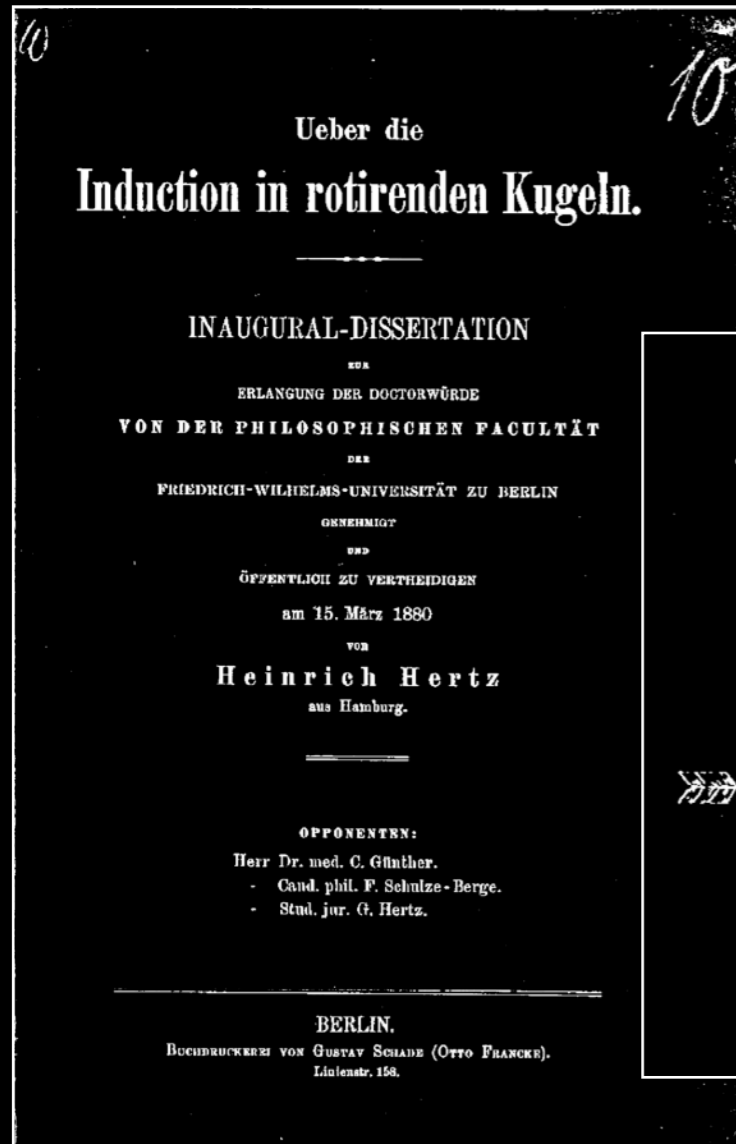
Heinrich Hertz

Physicist, experimenter



Heinrich Hertz

Physicist, experimenter

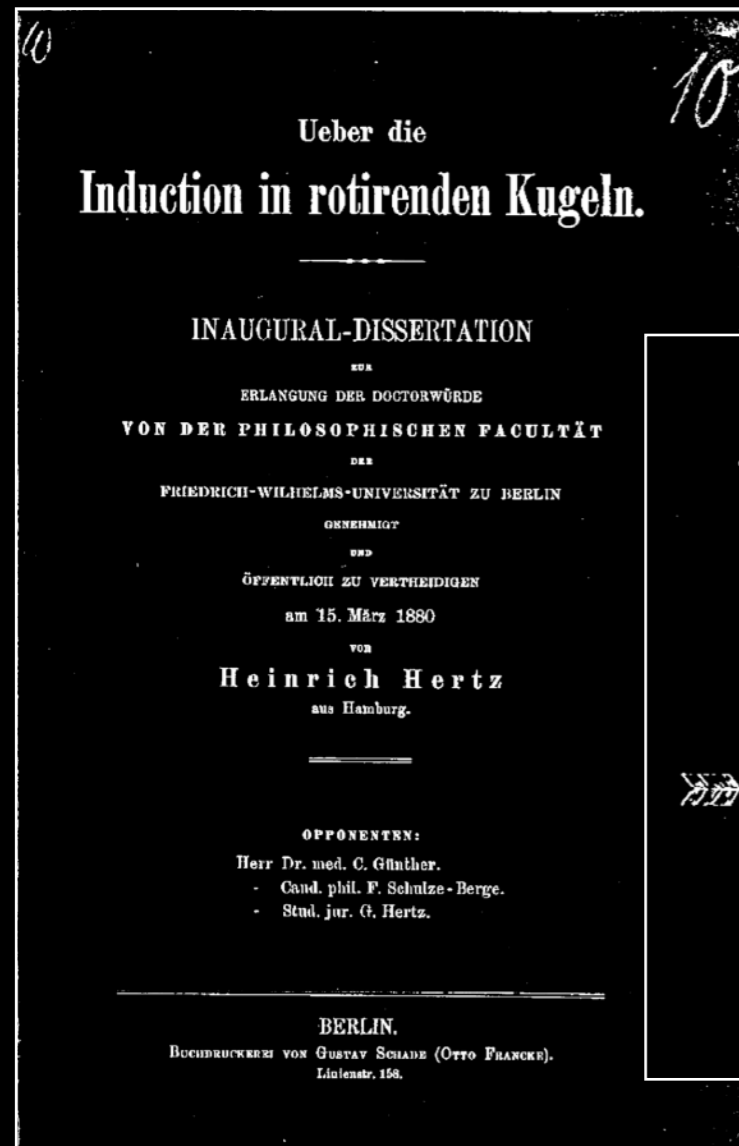


“On induction in rotating spheres”
(1880)



Heinrich Hertz

Physicist, experimenter



“On induction in rotating spheres” (1880)

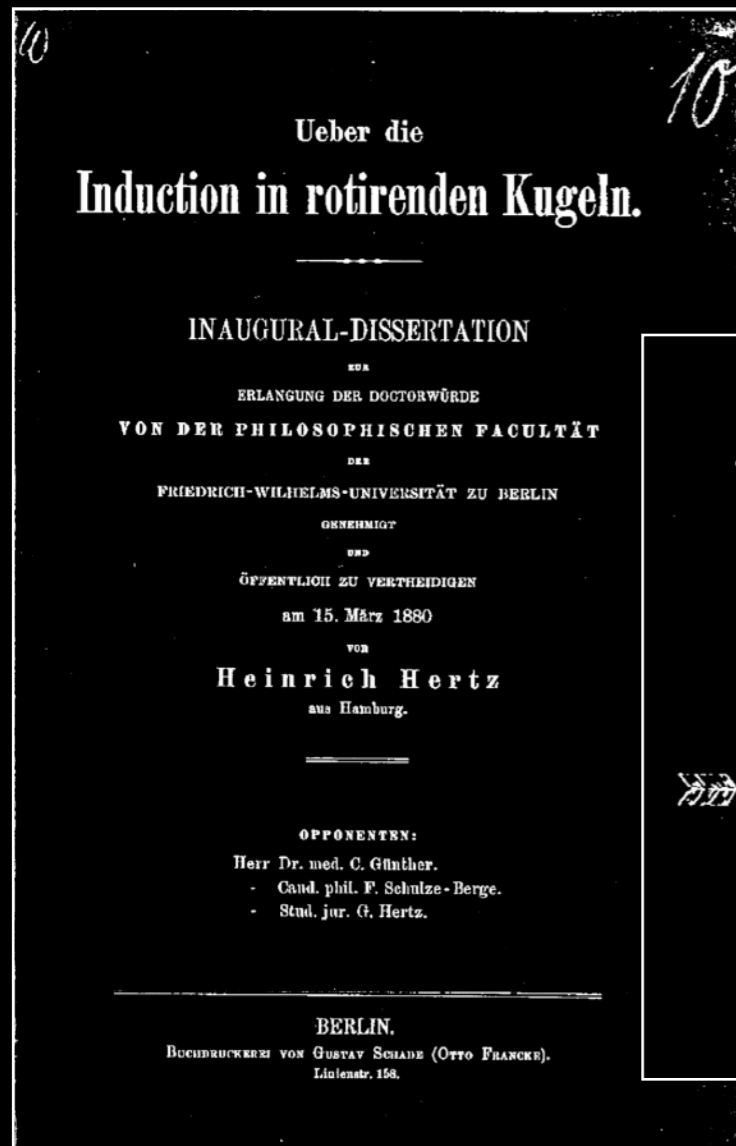


Hermann von Helmholtz (his doctoral adviser):

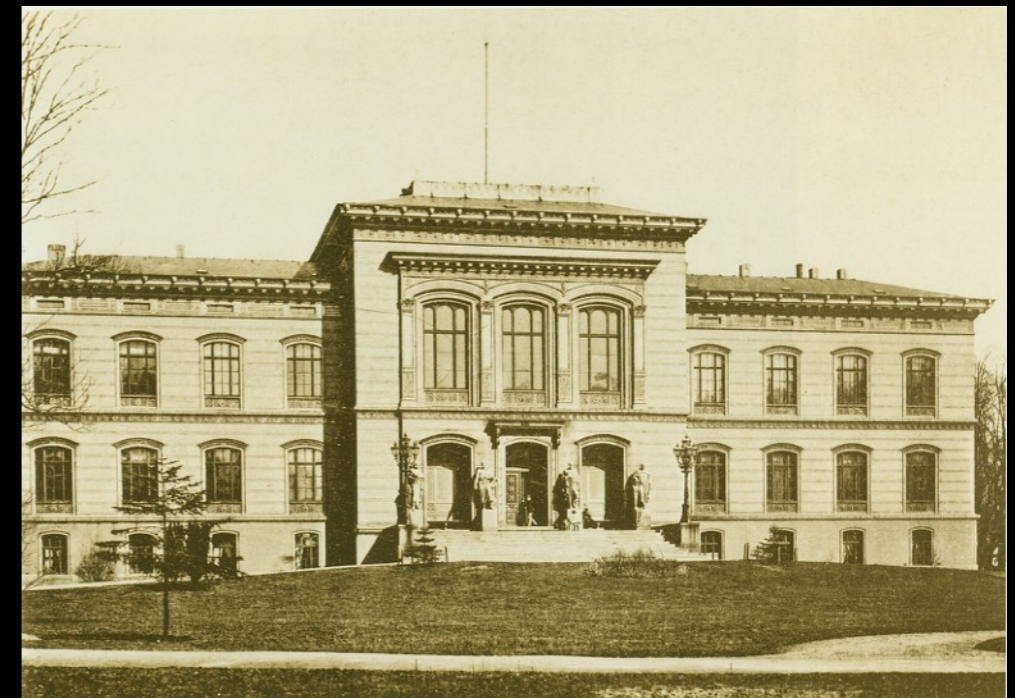
“Hertz combined theoretical insight with experimental skill.”

Heinrich Hertz

Physicist, experimenter



“On induction in rotating spheres” (1880)



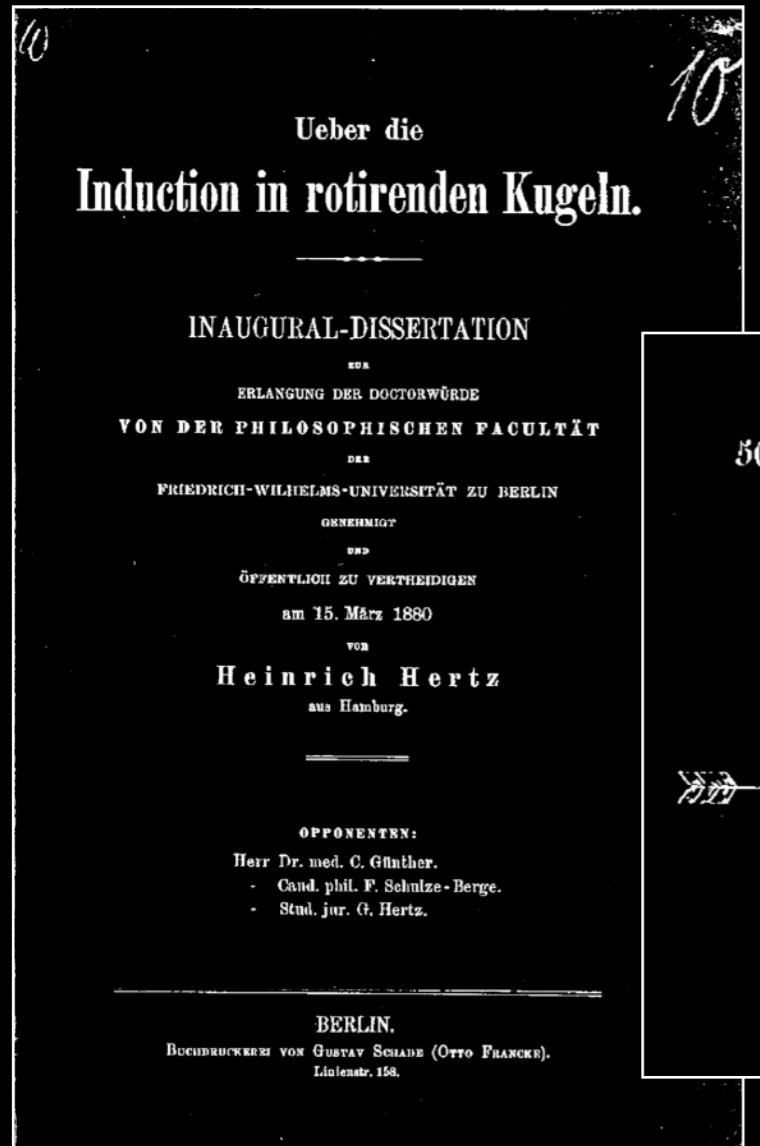
Junior faculty and lecturer in theoretical physics at Kiel

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Full professor at
Karlsruhe polytechnic university



Junior faculty and
professor in theoretical physics at Kiel

Hermann von Helmholtz (his colleague)
"Hertz combined theoretical and experimental physics"

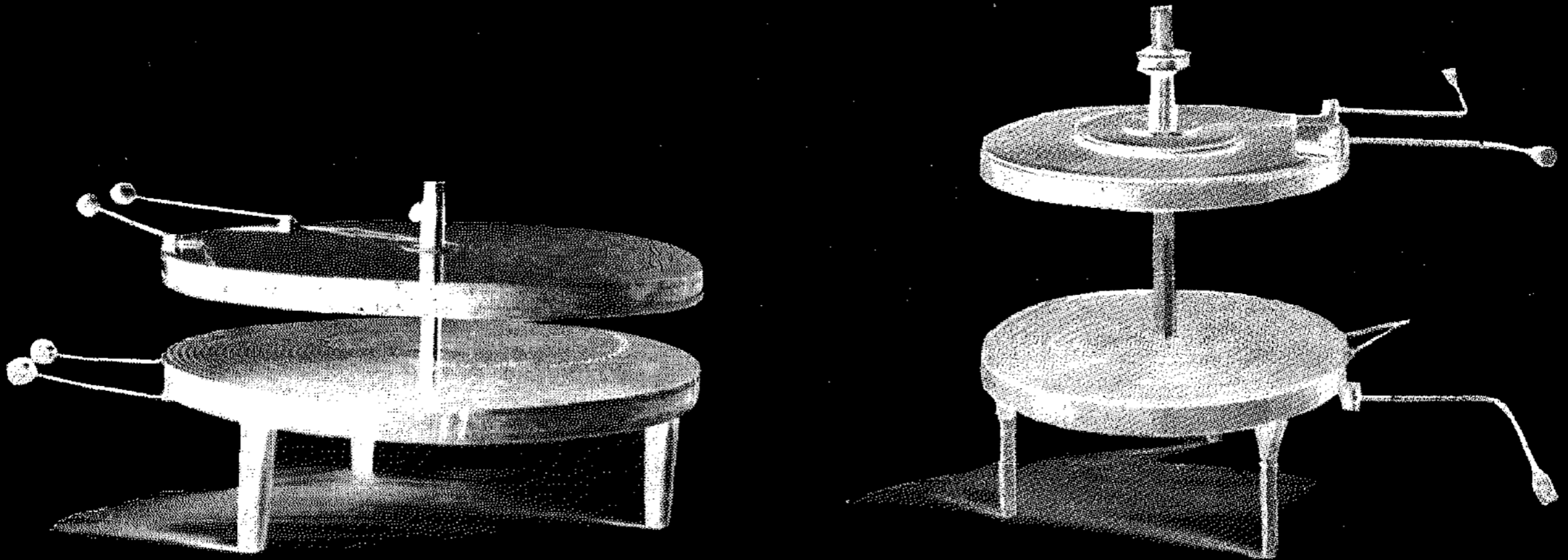
Rummaging in Karlsruhe's laboratory

Rummaging in Karlsruhe's laboratory

Riess induction coils:

Rummaging in Karlsruhe's laboratory

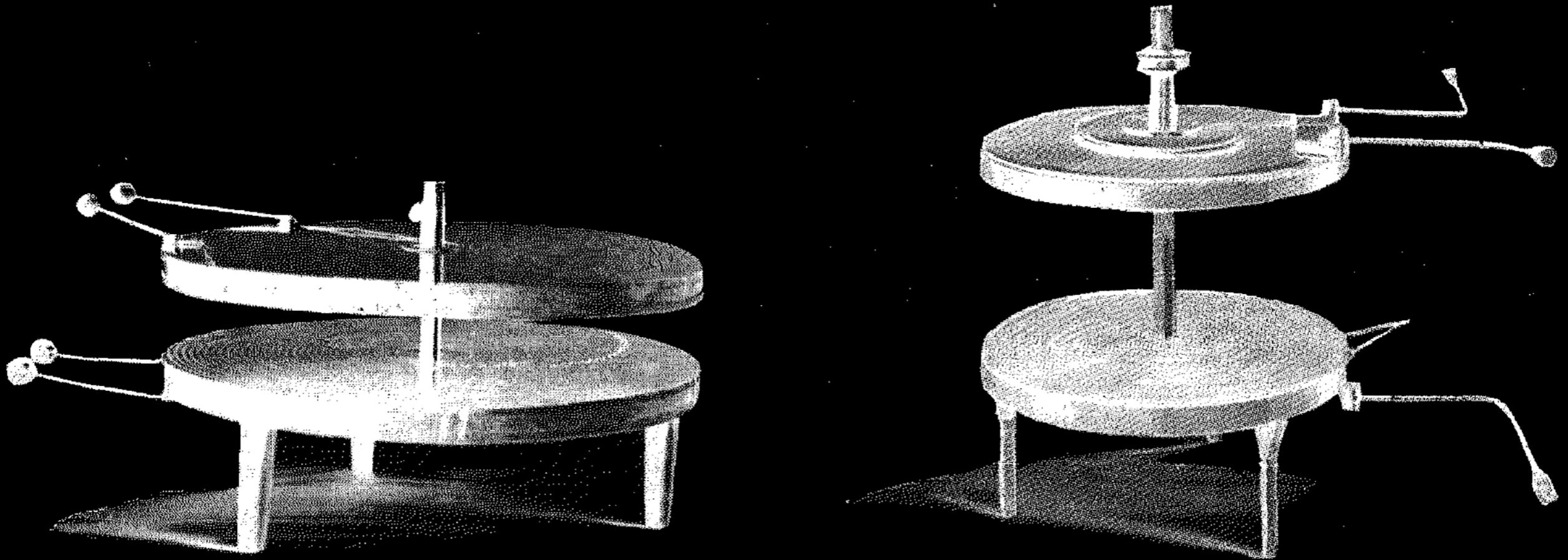
Riess induction coils:



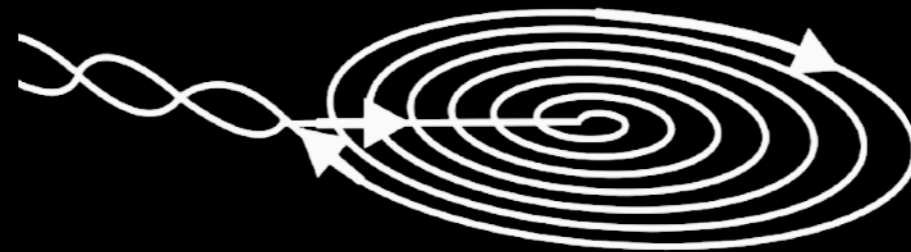
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Rummaging in Karlsruhe's laboratory

Riess induction coils:

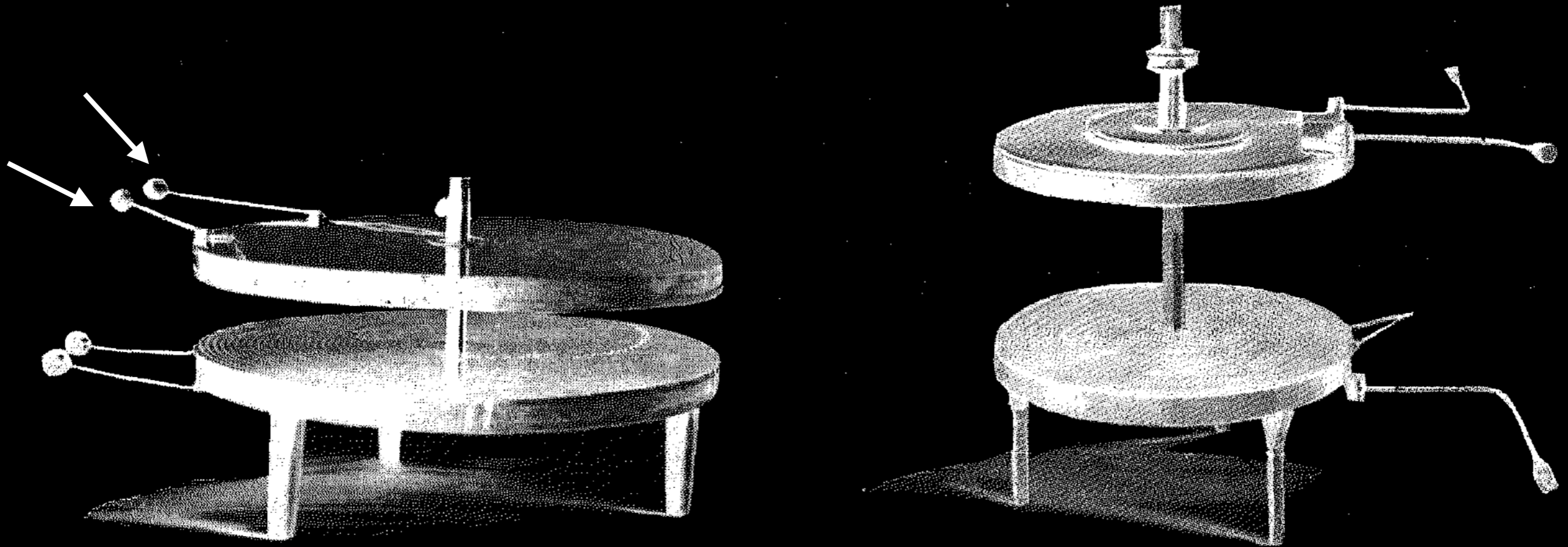


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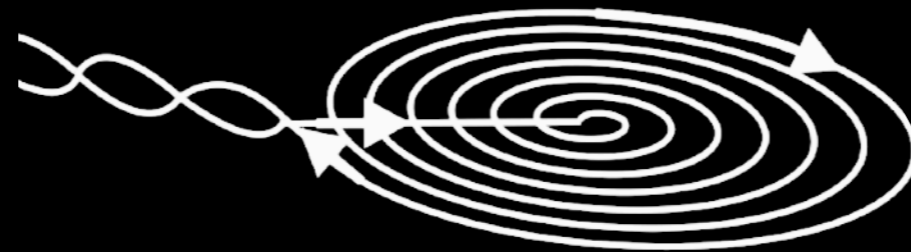


Rummaging in Karlsruhe's laboratory

Riess induction coils:

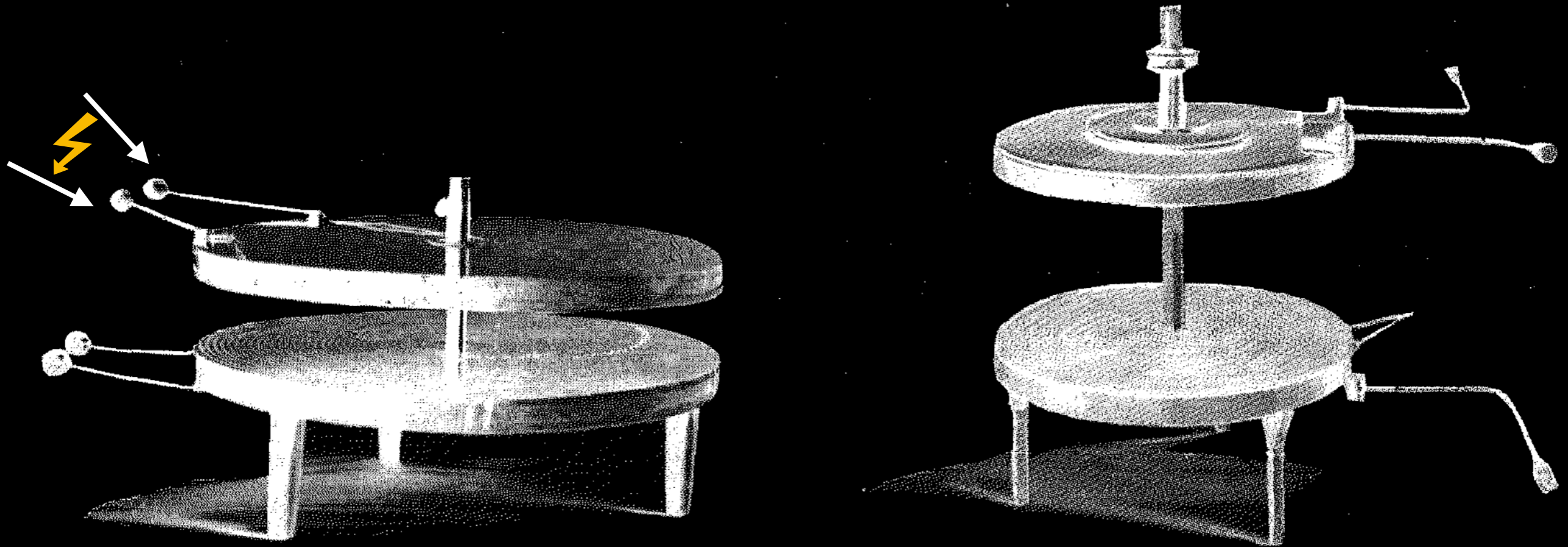


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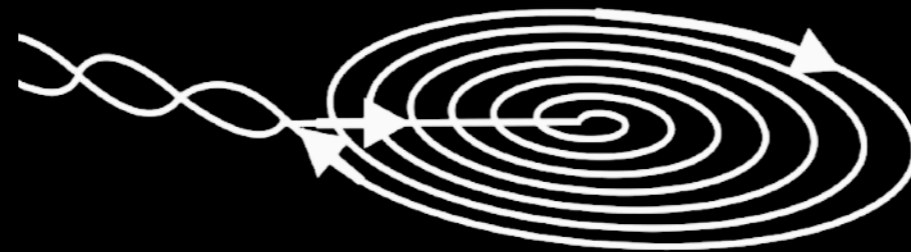


Rummaging in Karlsruhe's laboratory

Riess induction coils:

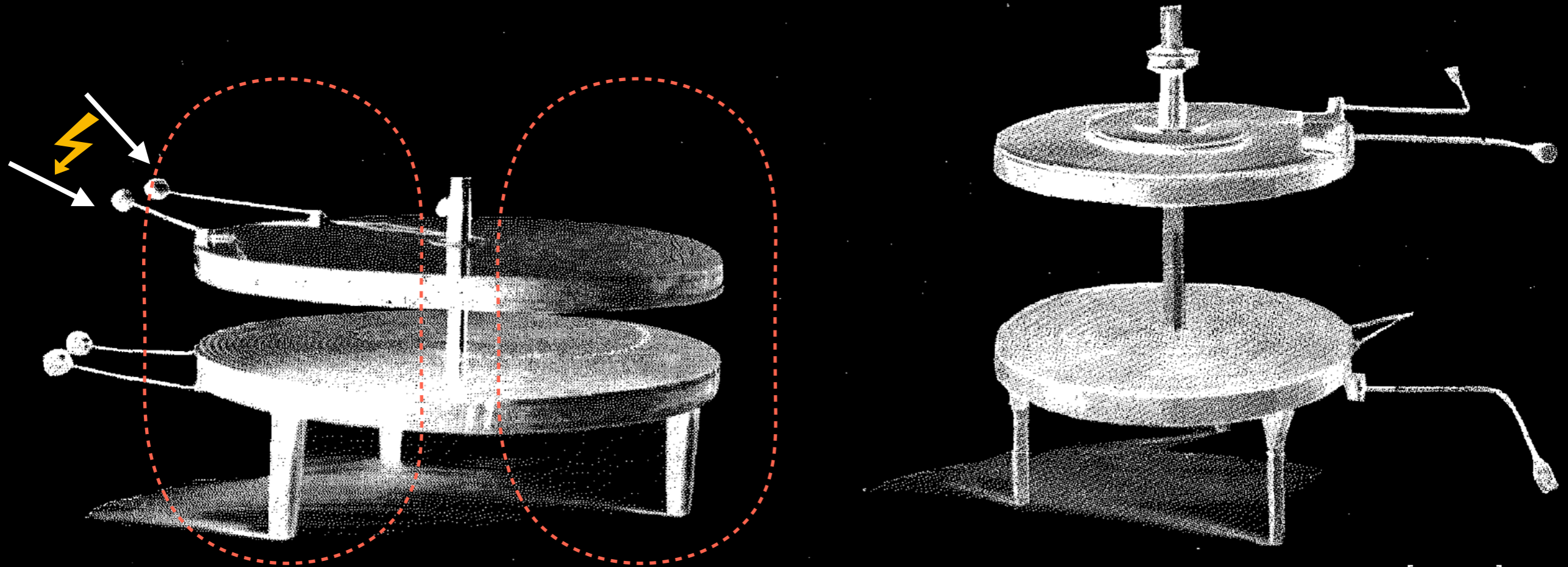


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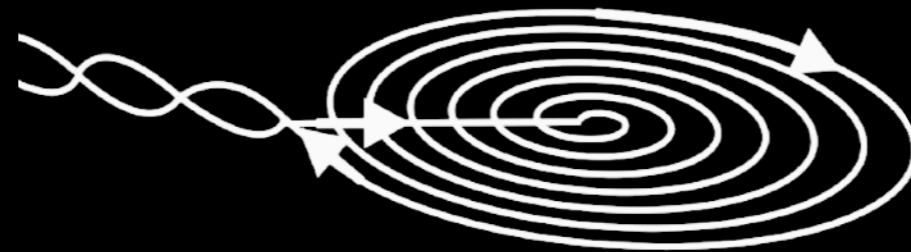


Rummaging in Karlsruhe's laboratory

Riess induction coils:

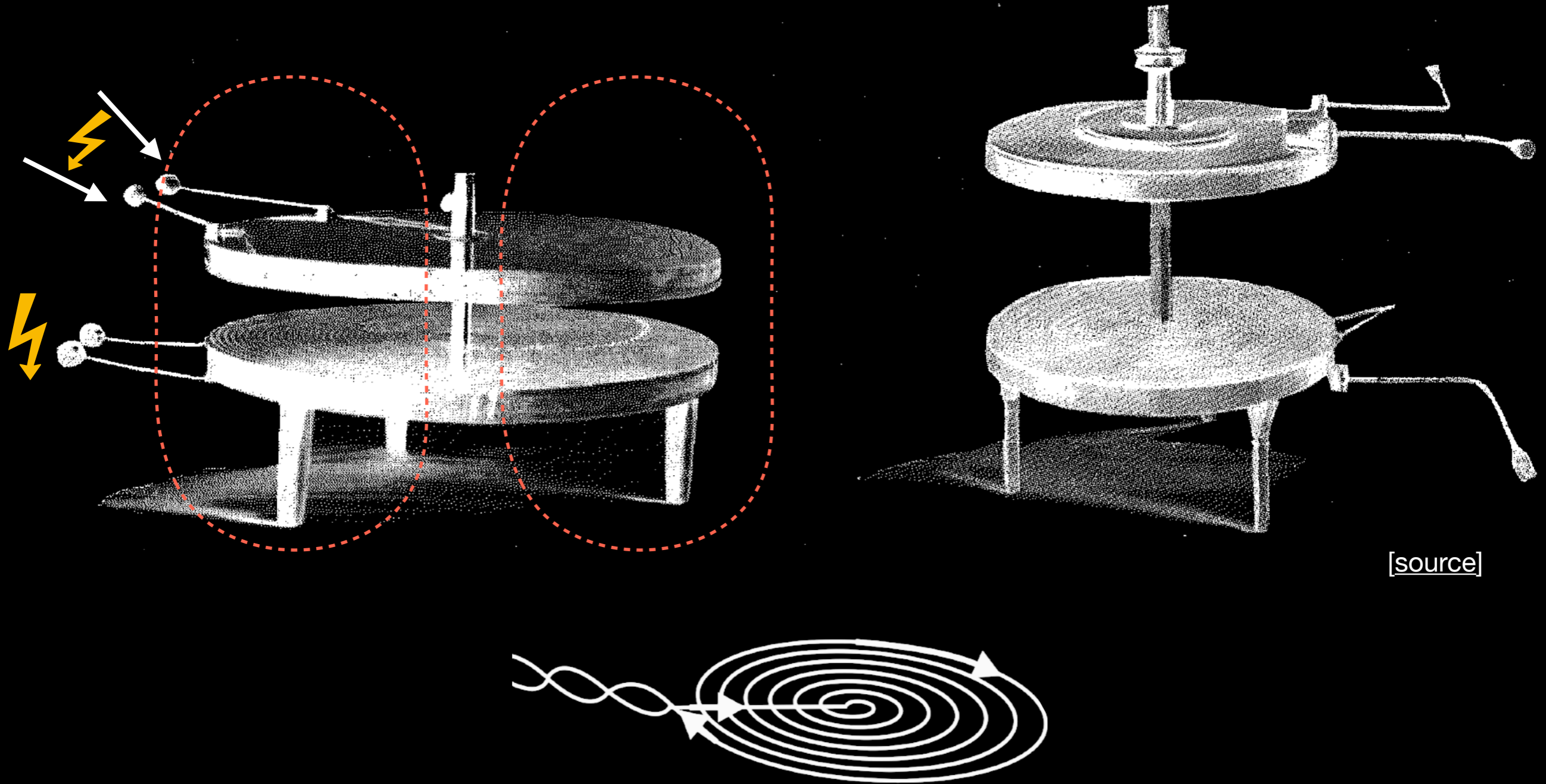


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Rummaging in Karlsruhe's laboratory

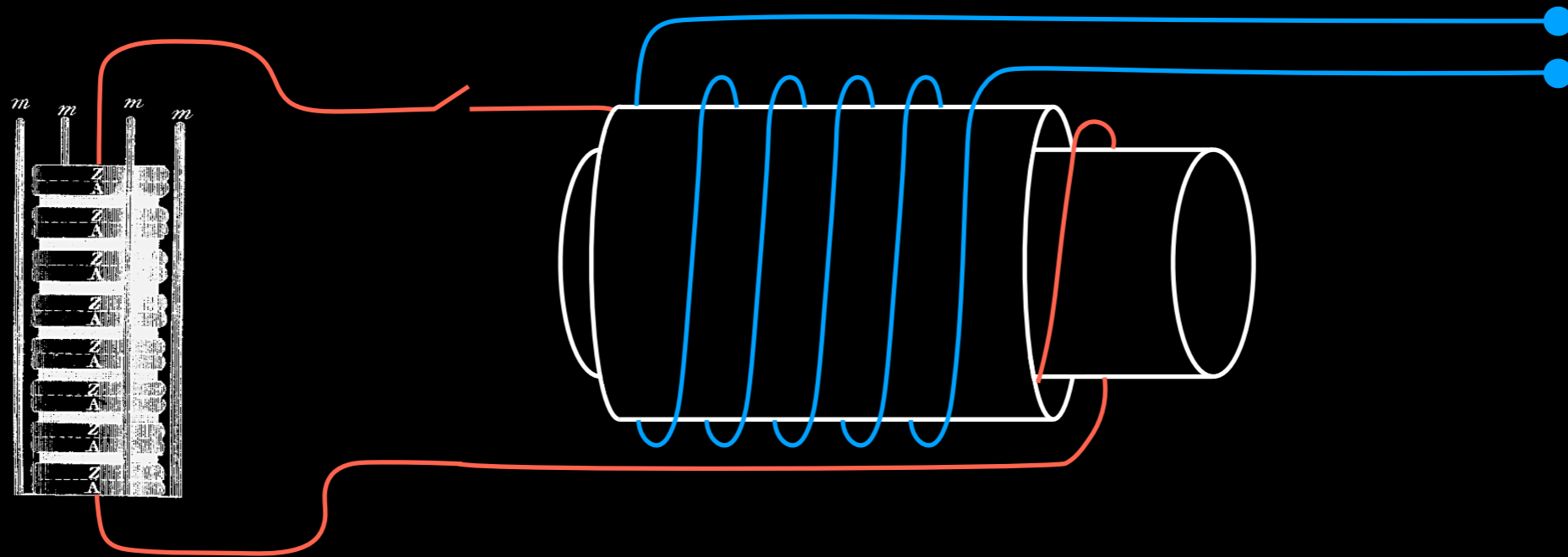
Riess induction coils:



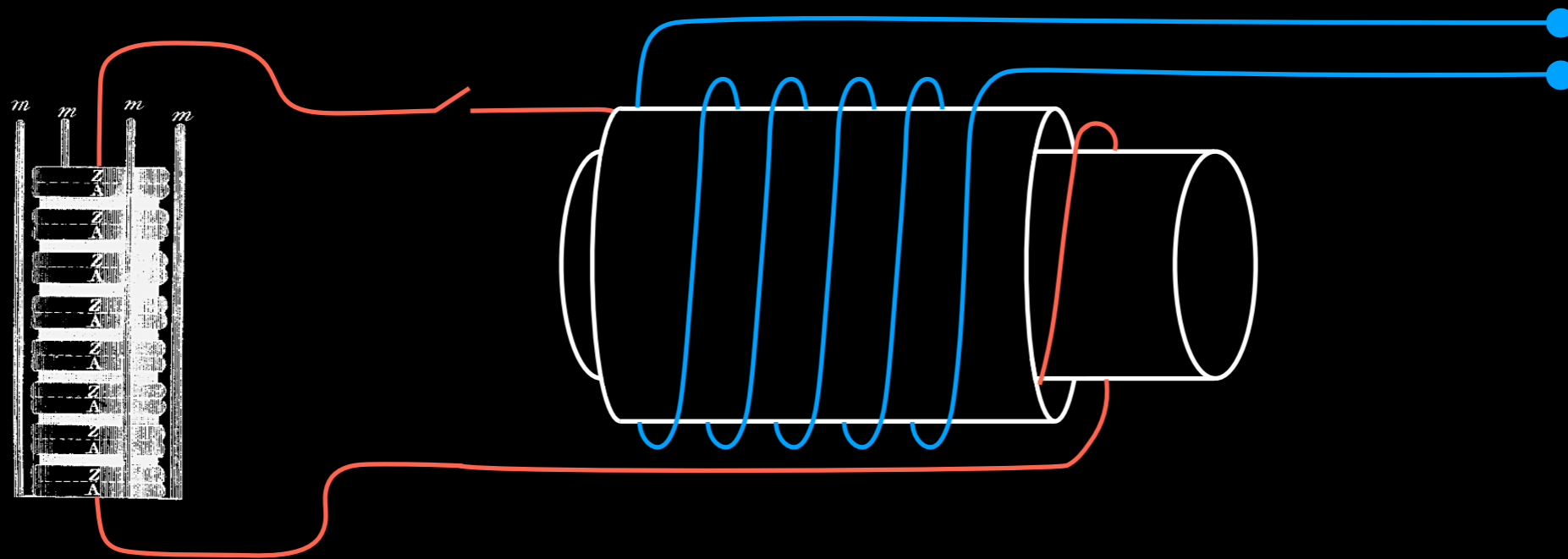
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Generating short spikes

Generating short spikes



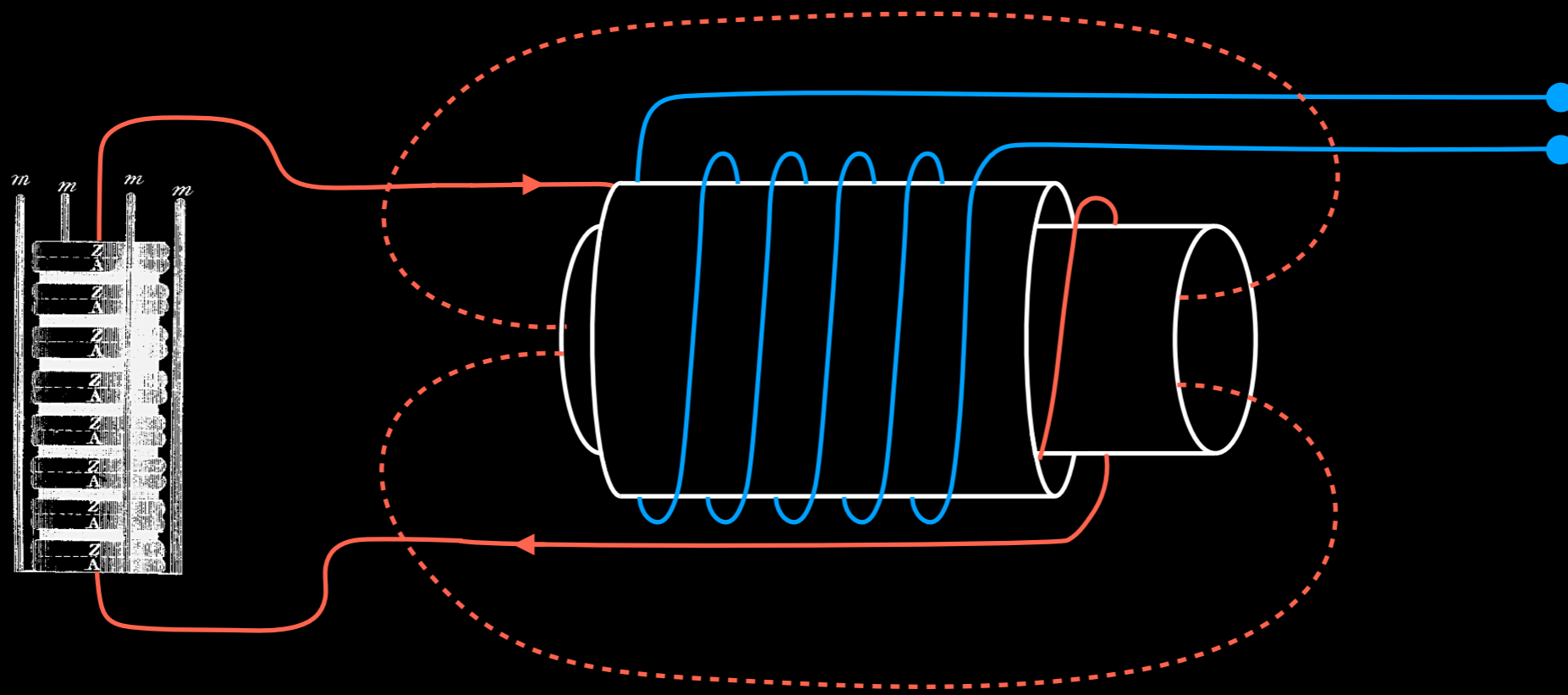
Generating short spikes



Faraday's table:

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

Generating short spikes



Faraday's table:

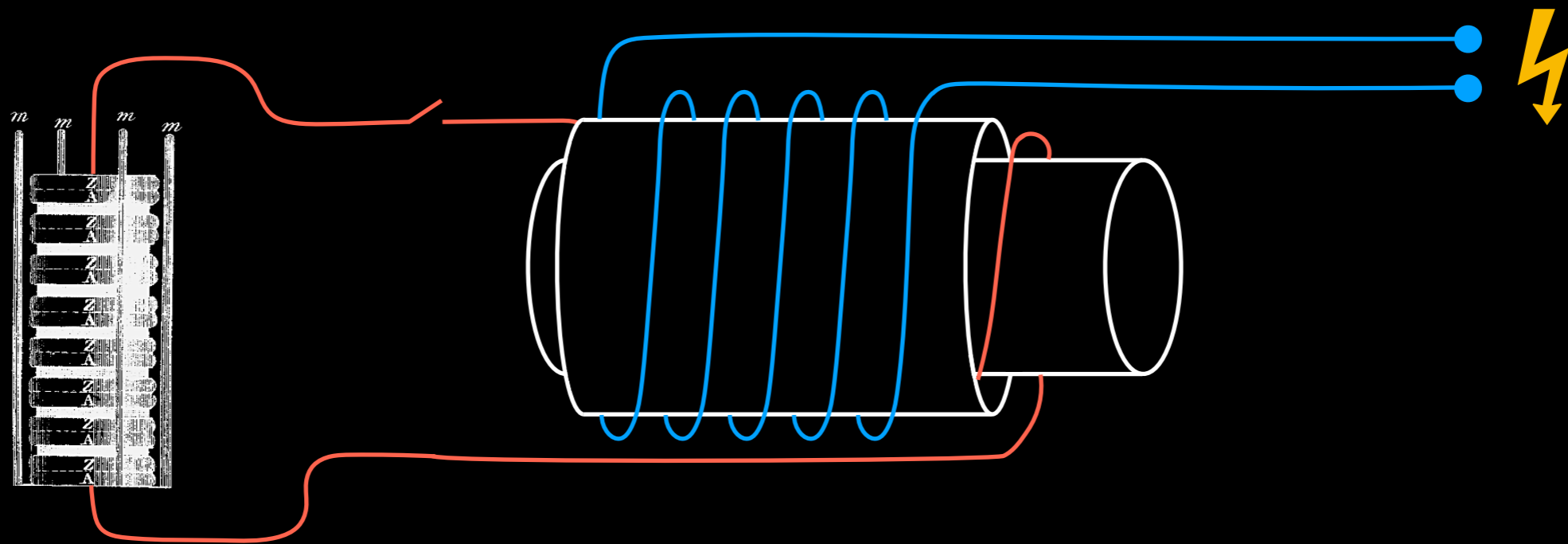
	Physiological Effects.	Magnetic Deflection.	Magnets made.	Spark.	Heating Power.	Attraction and Repulsion.	Discharge by Hot Air.
Voltaic electricity . . .	×	×	×	×	×	×	×
Common electricity...	×	×	×	×	×	×	×
Magneto-Electricity..	×	×	×	×	×	×	
Animal Electricity...	×	×	×	+	+		

1) Connect battery to “primary” coil

2) Electric current starts flowing, induces electricity in “secondary” coil

(Not enough to create a spark)

Generating short spikes

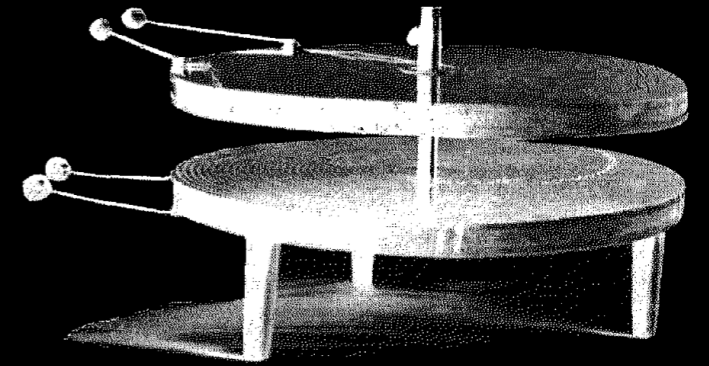


Faraday's table:

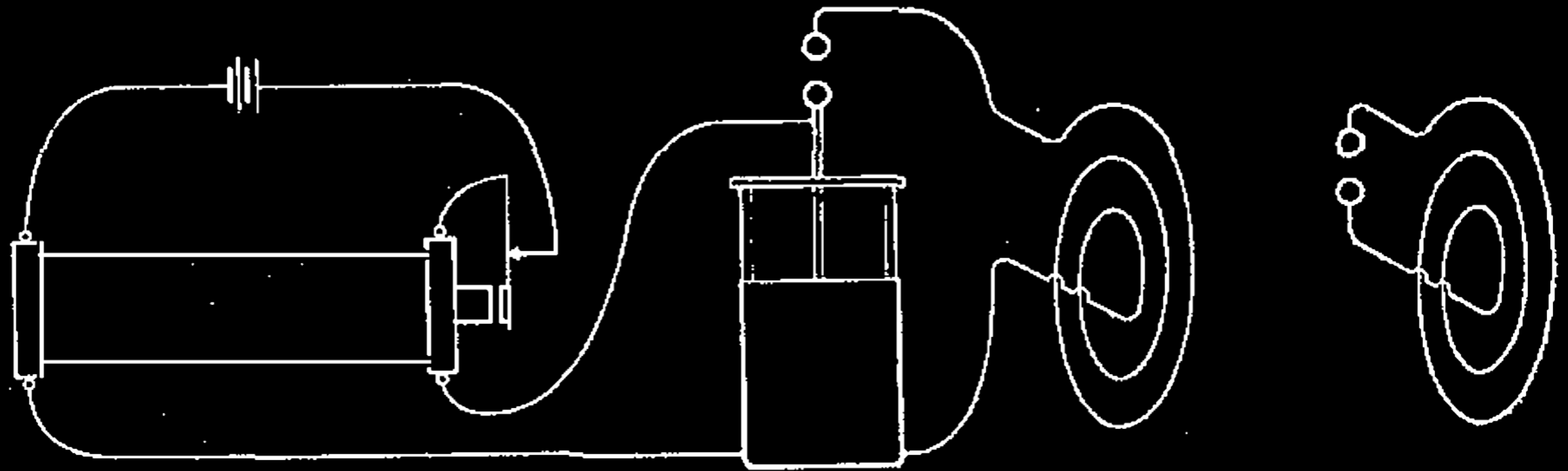
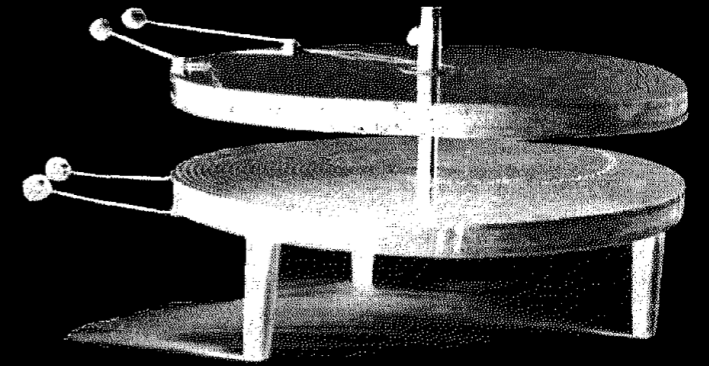
	Physiological Effects.	Magnetic Deflection.	Magnets made.	Spark.	Heating Power.	Attraction and Repulsion.	Discharge by Hot Air.
Voltaic electricity . . .	x	x	x	x	x	x	x
Common electricity...	x	x	x	x	x	x	x
Magneto-Electricity..	x	x	x	x	x	x	
Animal Electricity...	x	x	x	+	+		

- 1) Connect battery to “primary” coil
- 2) Electric current starts flowing, induces electricity in “secondary” coil
(Not enough to create a spark)
- 3) Interrupt current quickly
Very strong induction generates spark

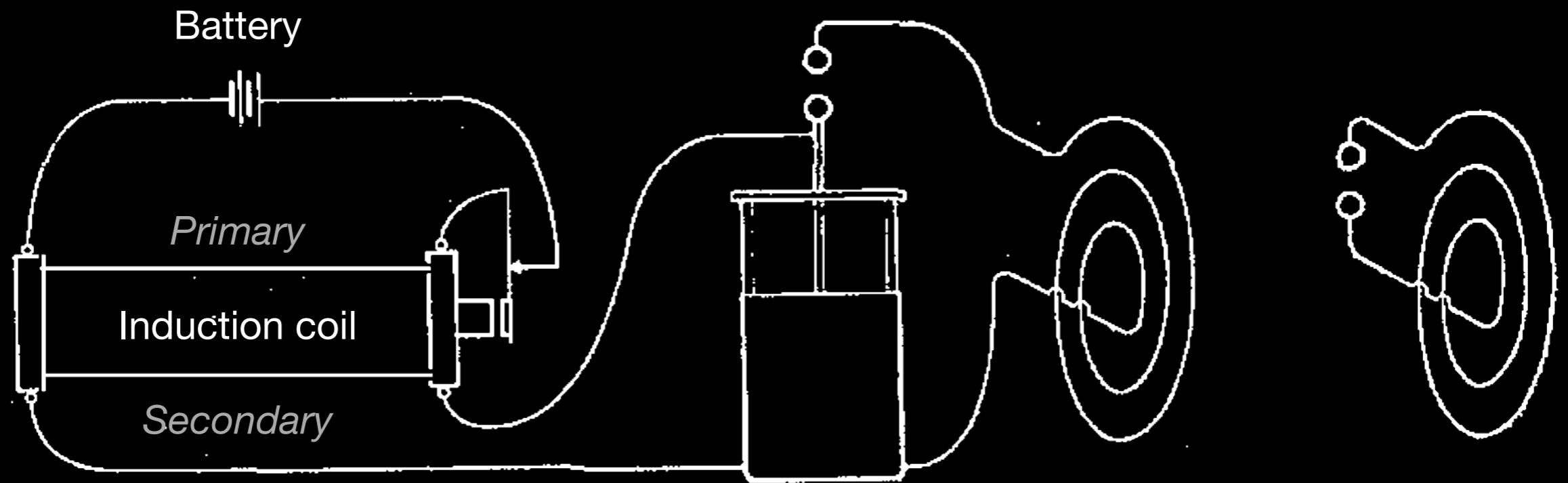
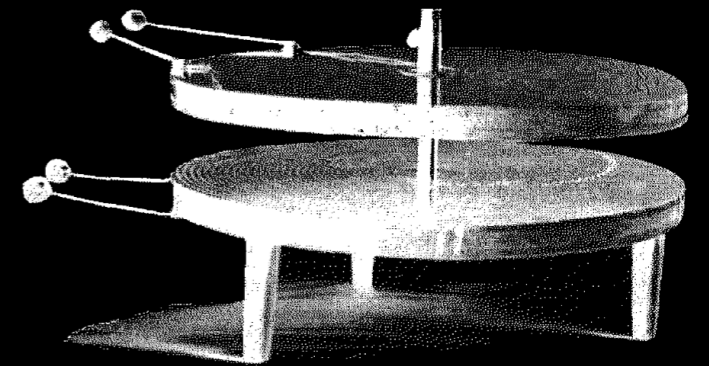
“Transmitting” sparks



“Transmitting” sparks



“Transmitting” sparks

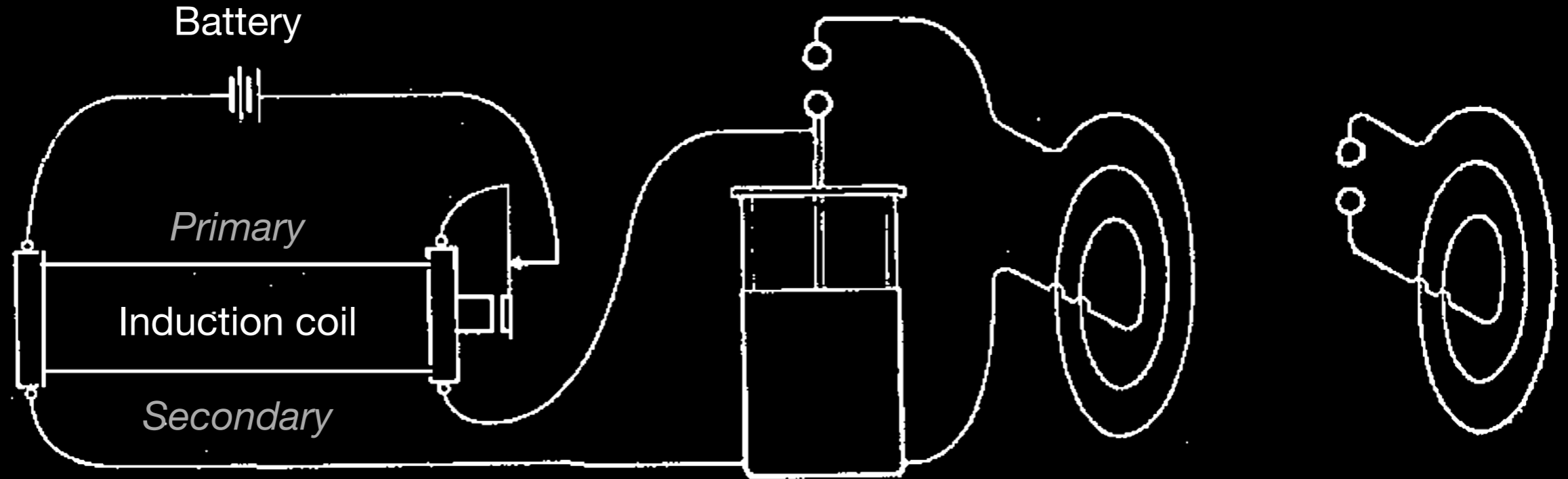
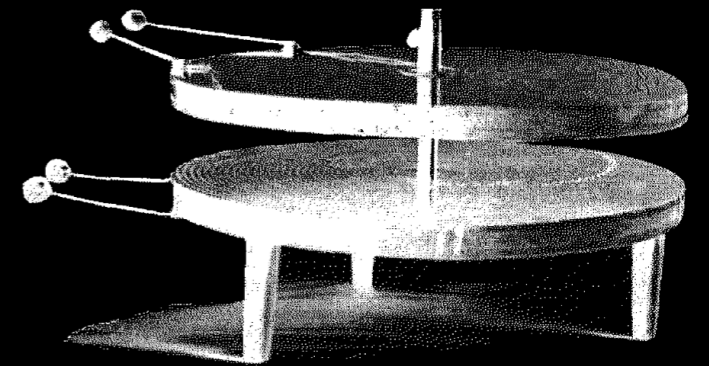


Leyden jar

Riess coils

“Transmitting” sparks

Short spikes of electricity charge Leyden jar and drive one Riess coil

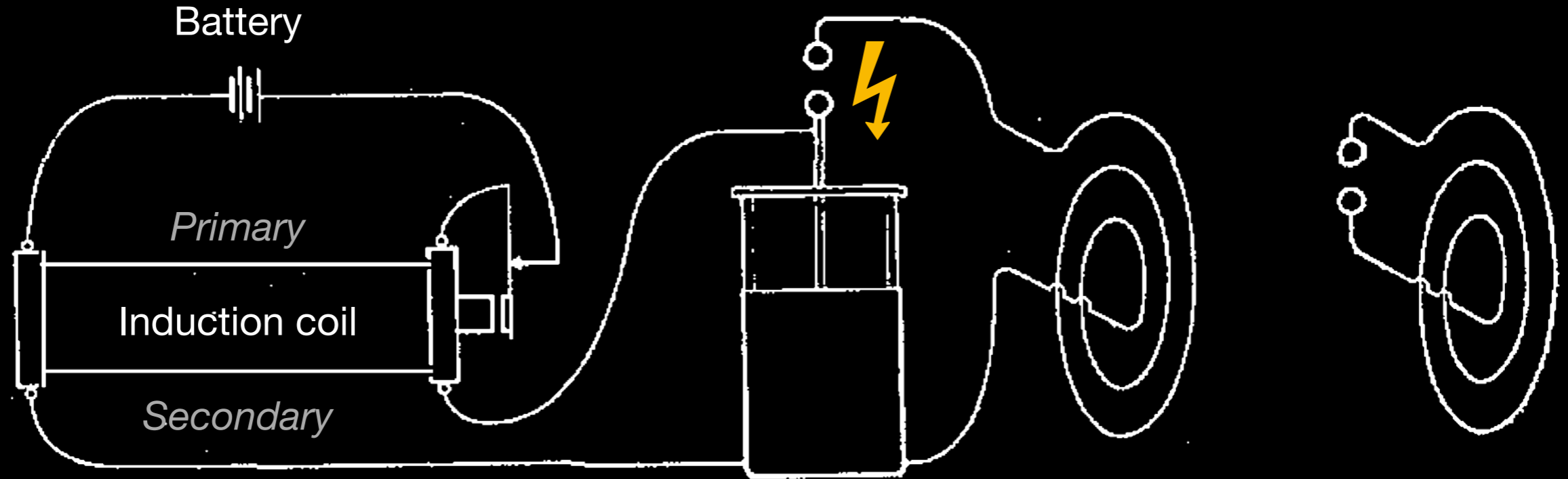
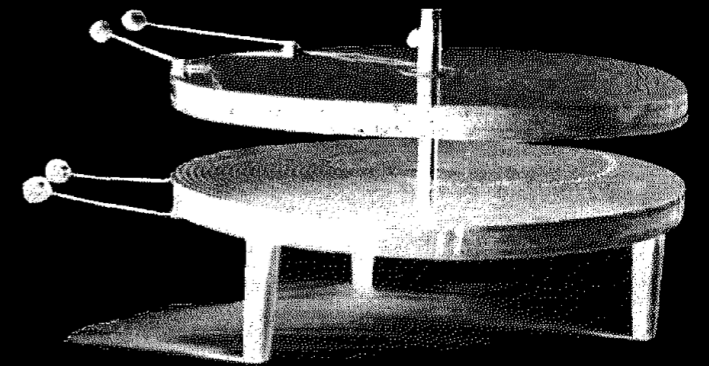


Leyden jar

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Short spikes of electricity charge Leyden jar and drive one Riess coil

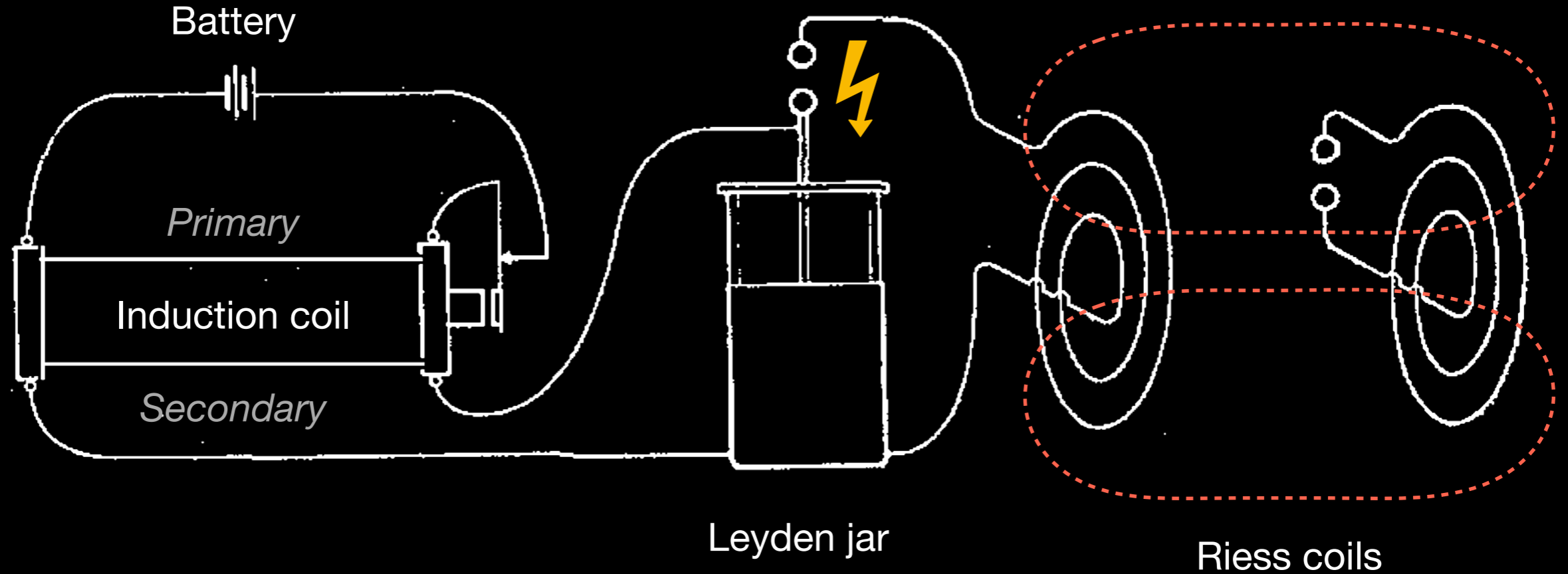
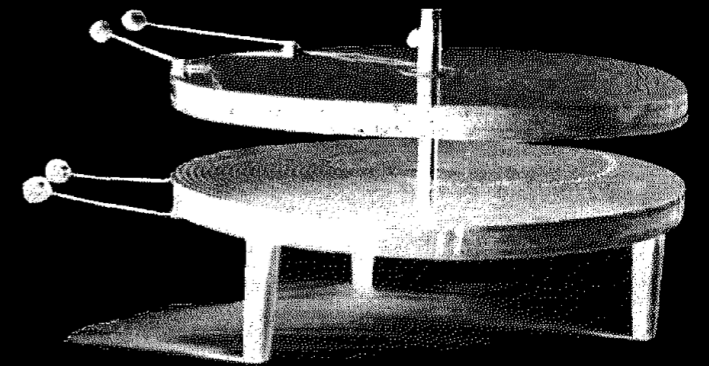


Leyden jar

Riess coils

“Transmitting” sparks

Short spikes of electricity charge Leyden jar and drive one Riess coil

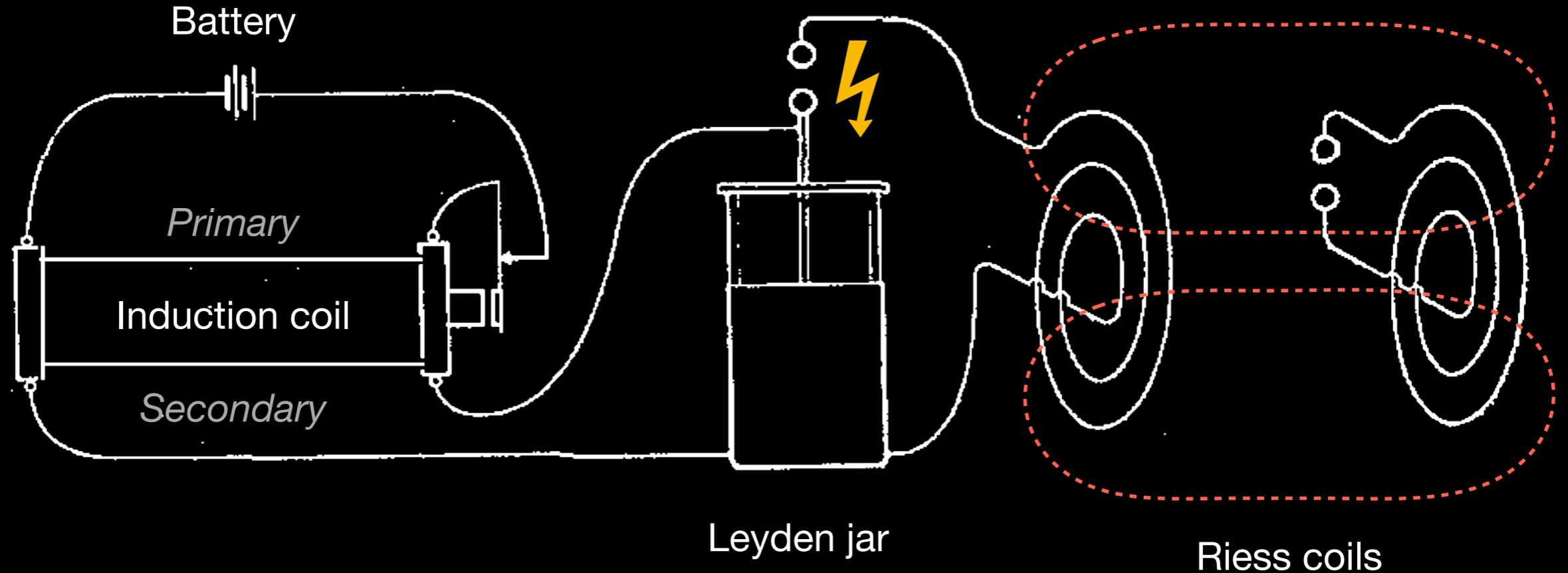
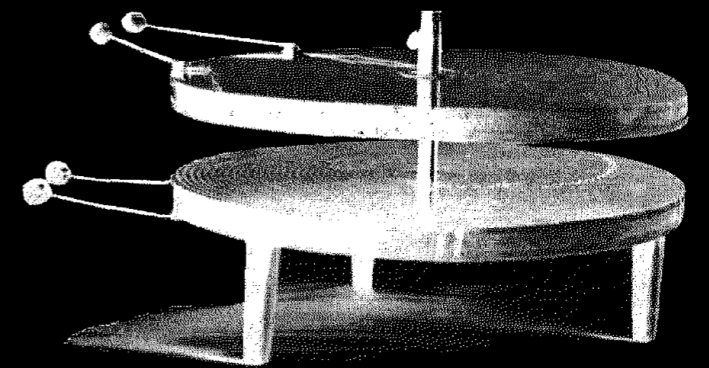


“Transmitting” sparks

Short spikes of electricity charge Leyden jar and drive one Riess coil



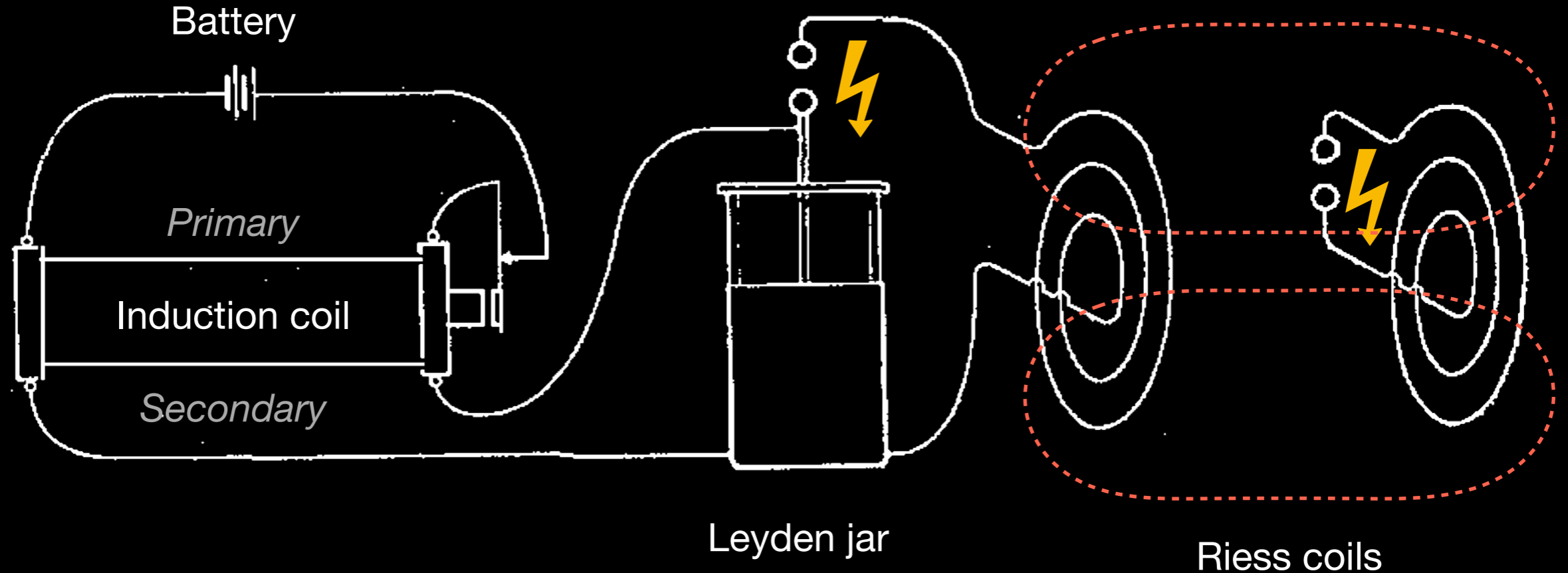
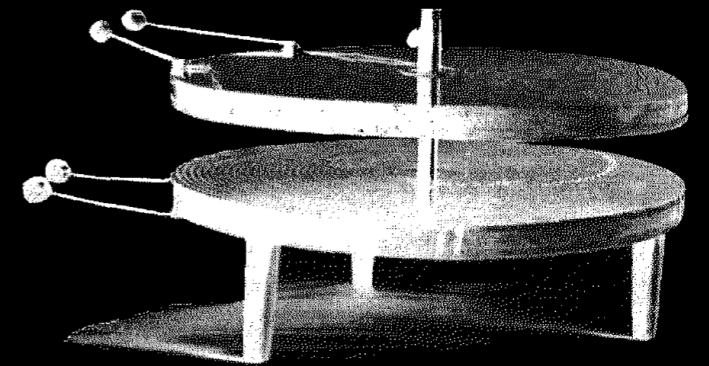
Induction leads to sparks in the other Riess coil, a short distance away



“Transmitting” sparks

Short spikes of electricity charge Leyden jar and drive one Riess coil

Induction leads to sparks in the other Riess coil, a short distance away



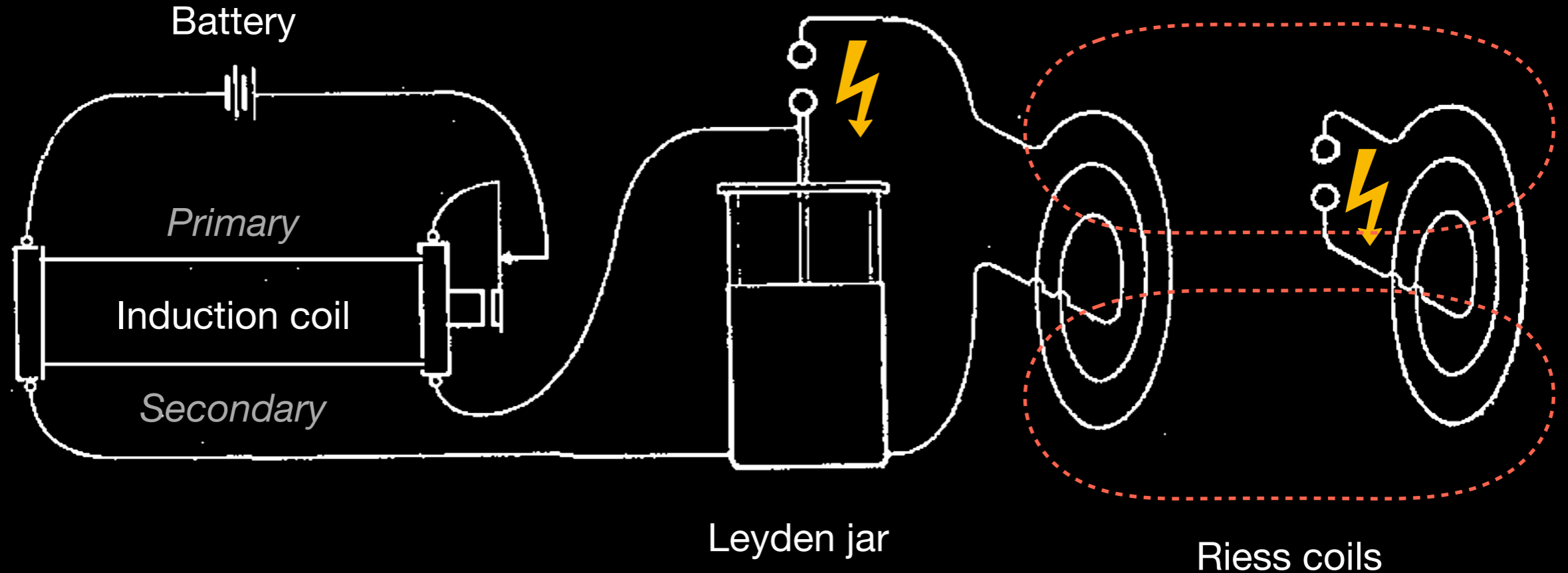
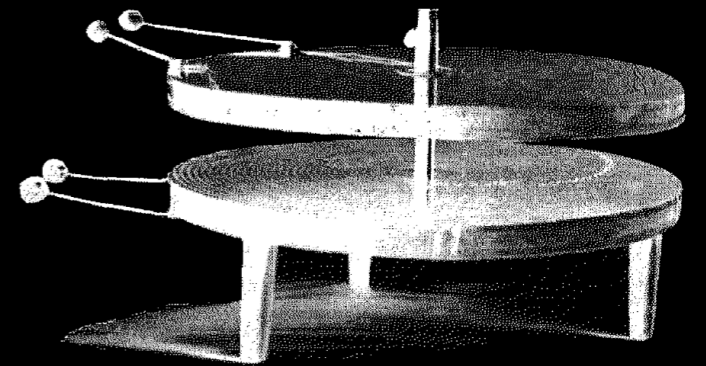
“Transmitting” sparks

Very strong sparking!

Short spikes of electricity charge Leyden jar and drive one Riess coil



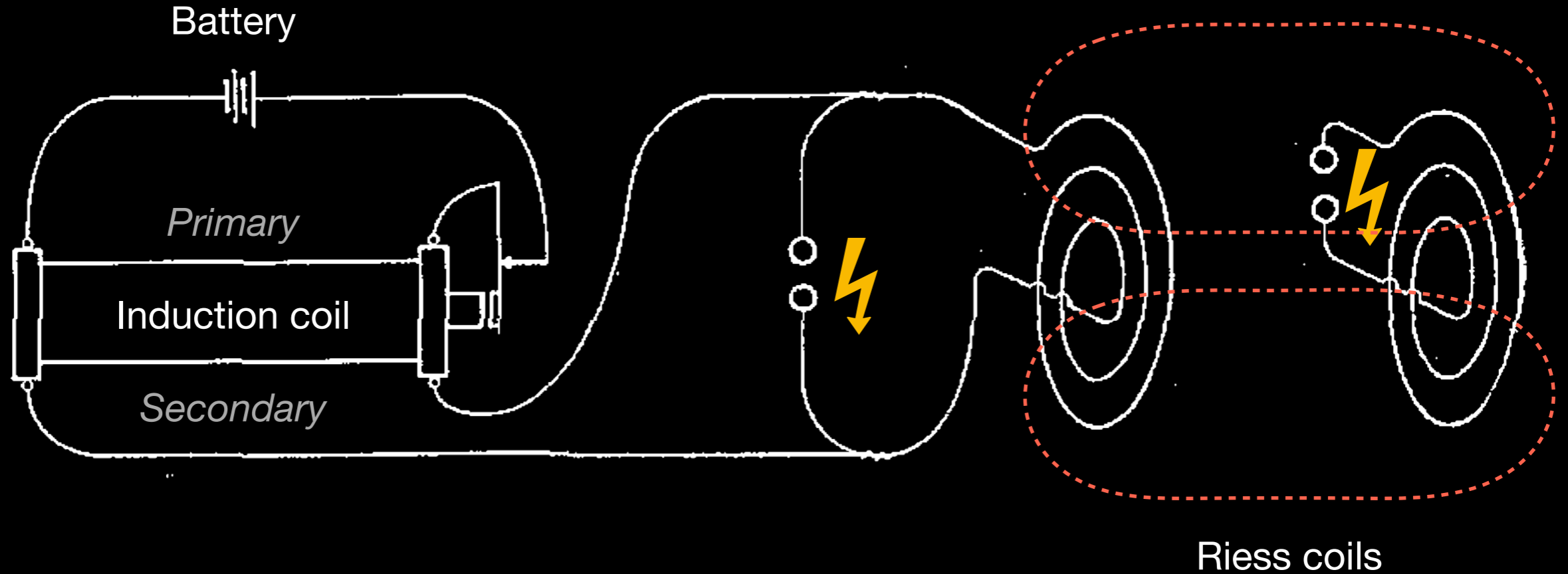
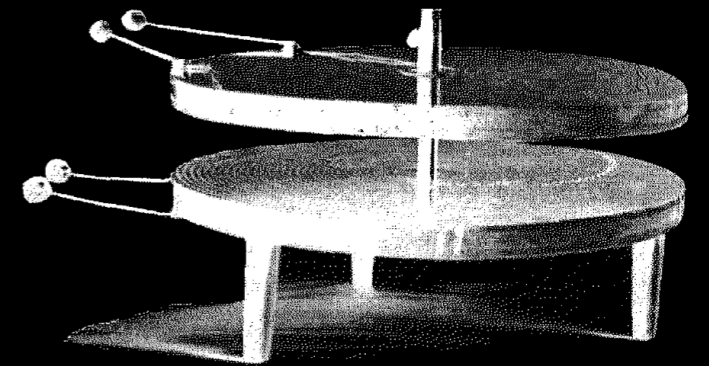
Induction leads to sparks in the other Riess coil, a short distance away



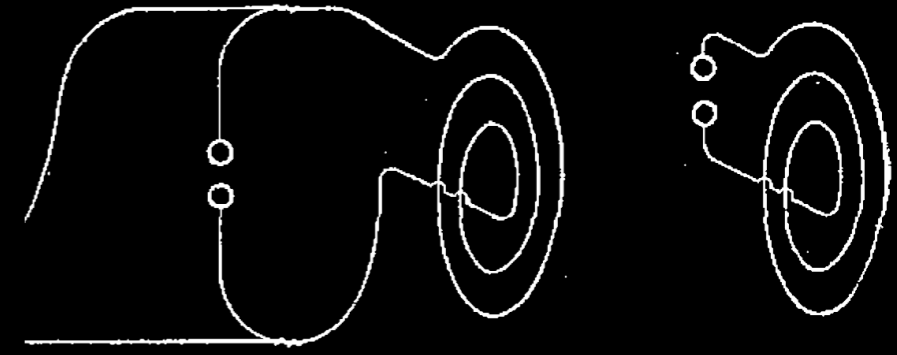
Simplifying the experiment

Very strong sparking even without Leyden jar

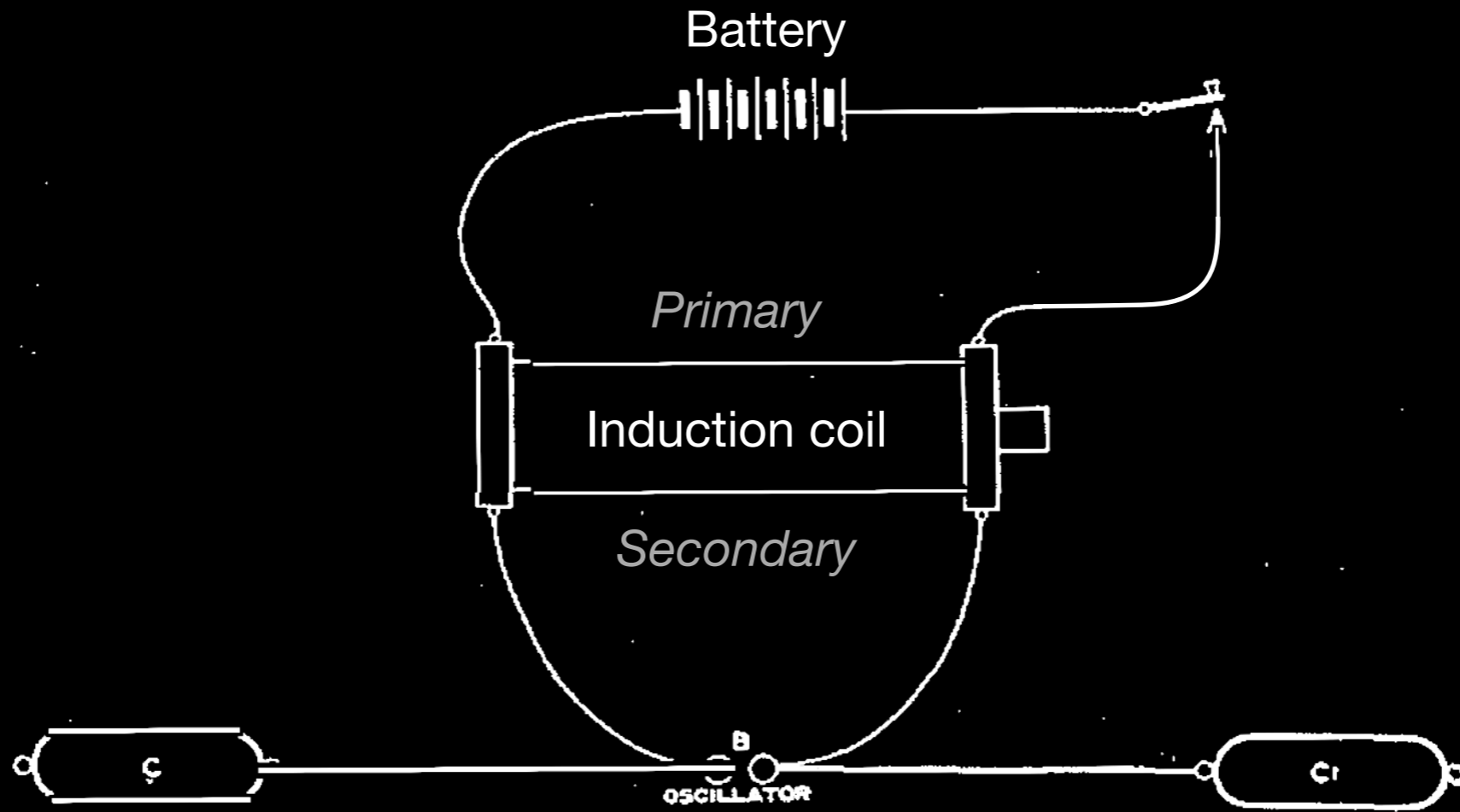
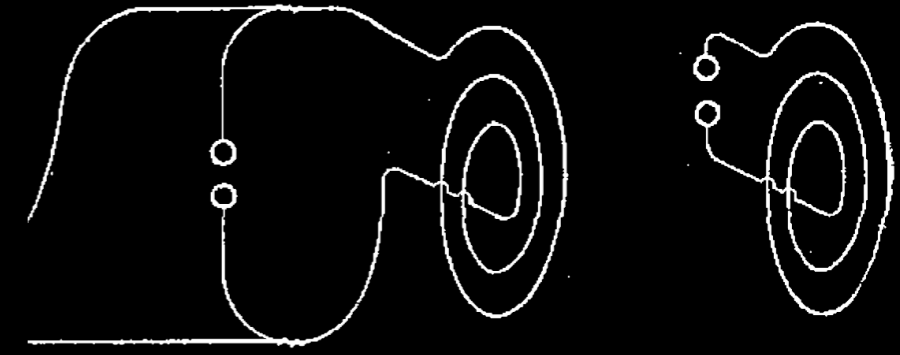
Very strong sparking!



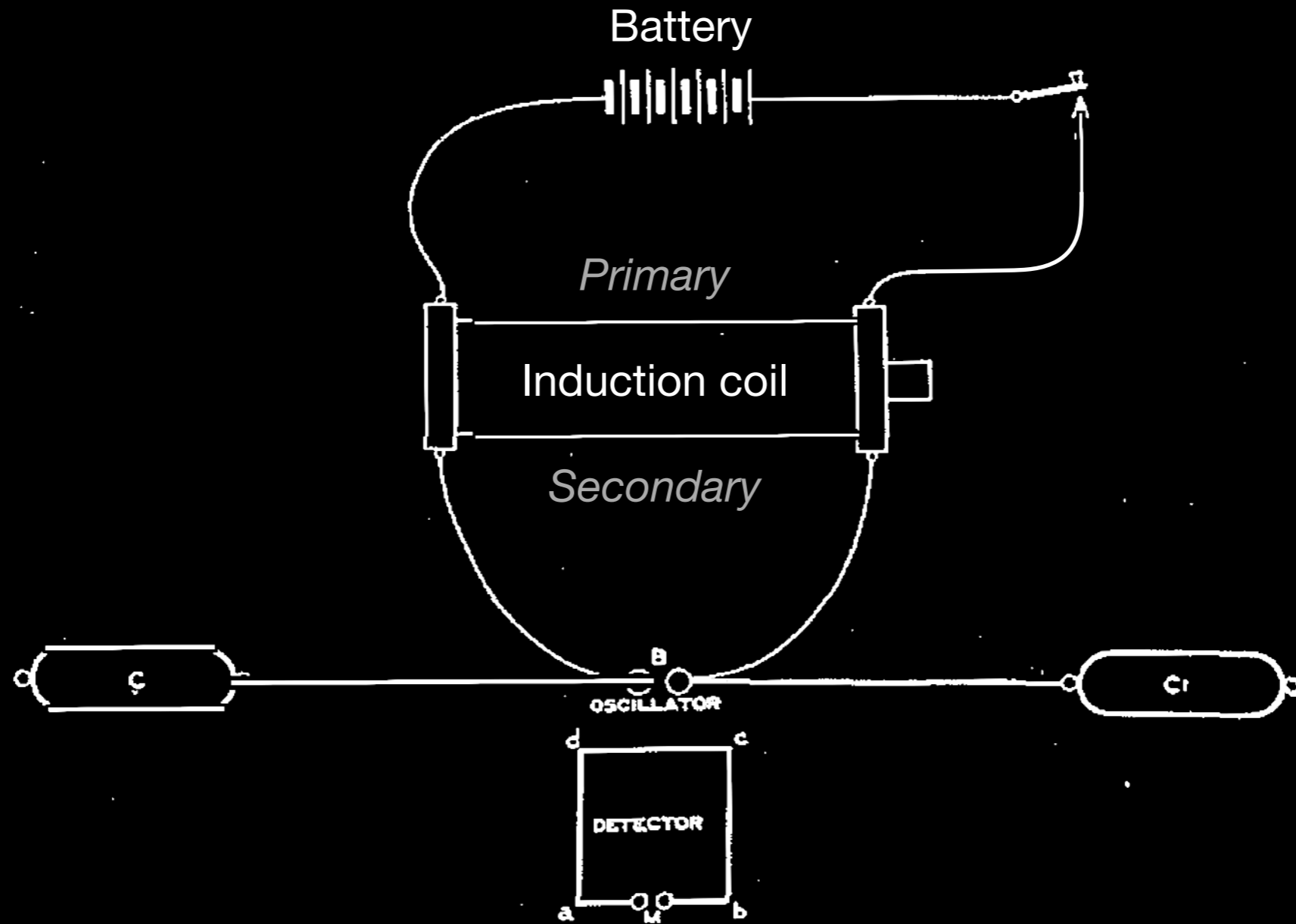
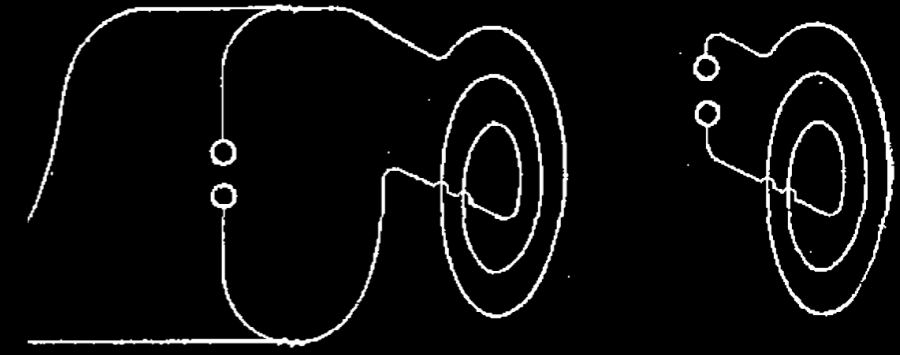
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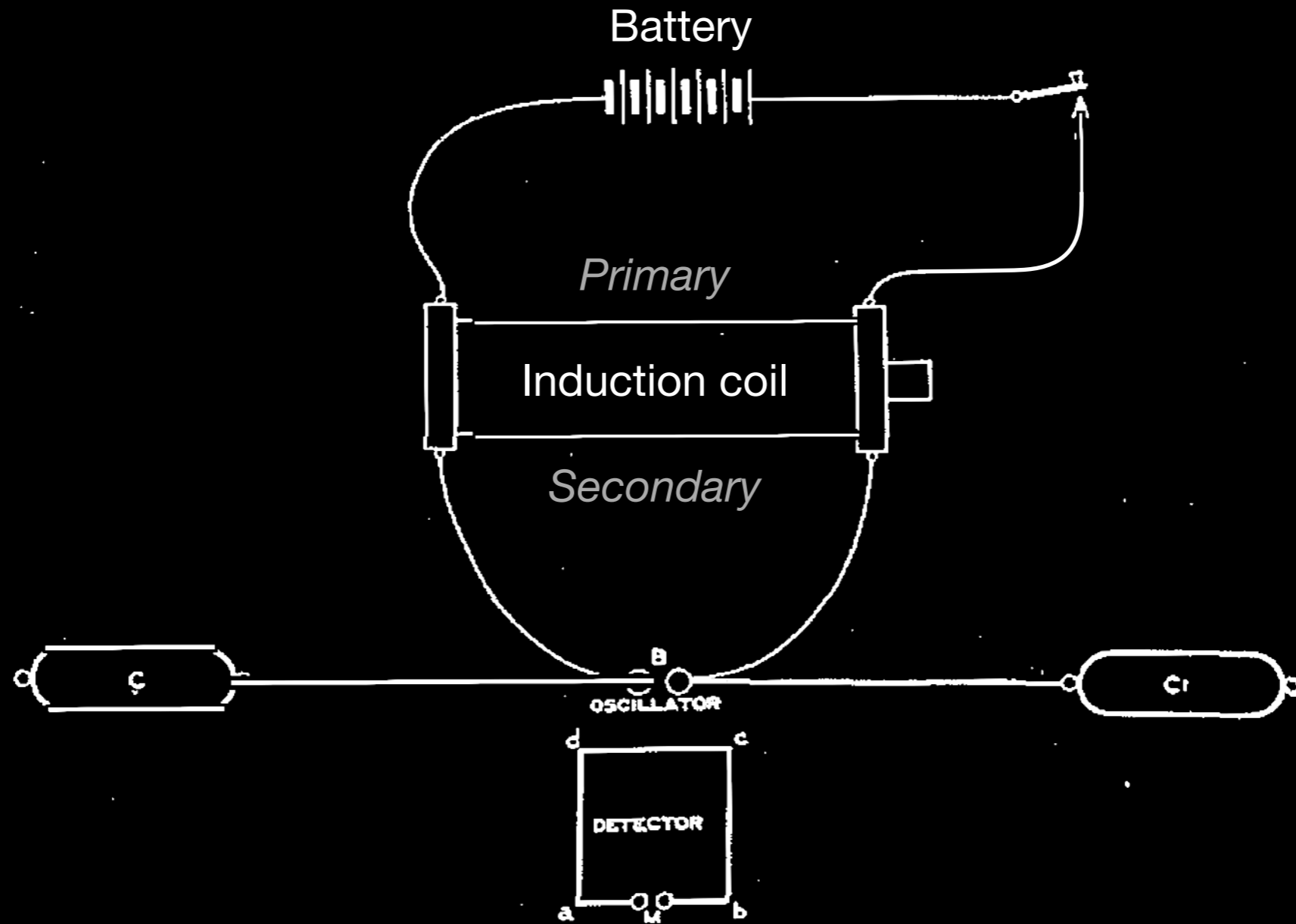
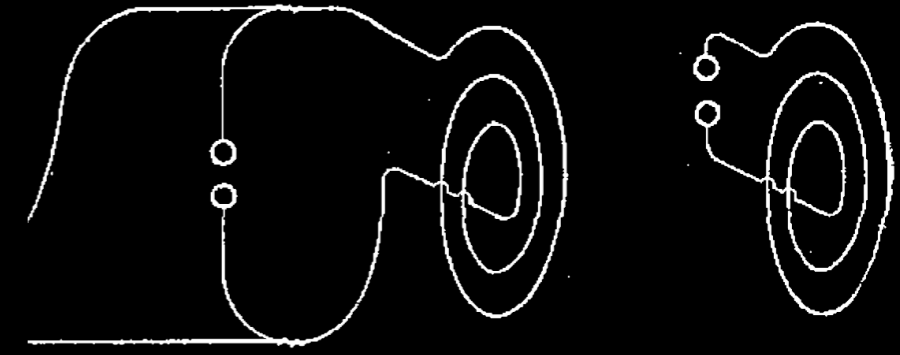


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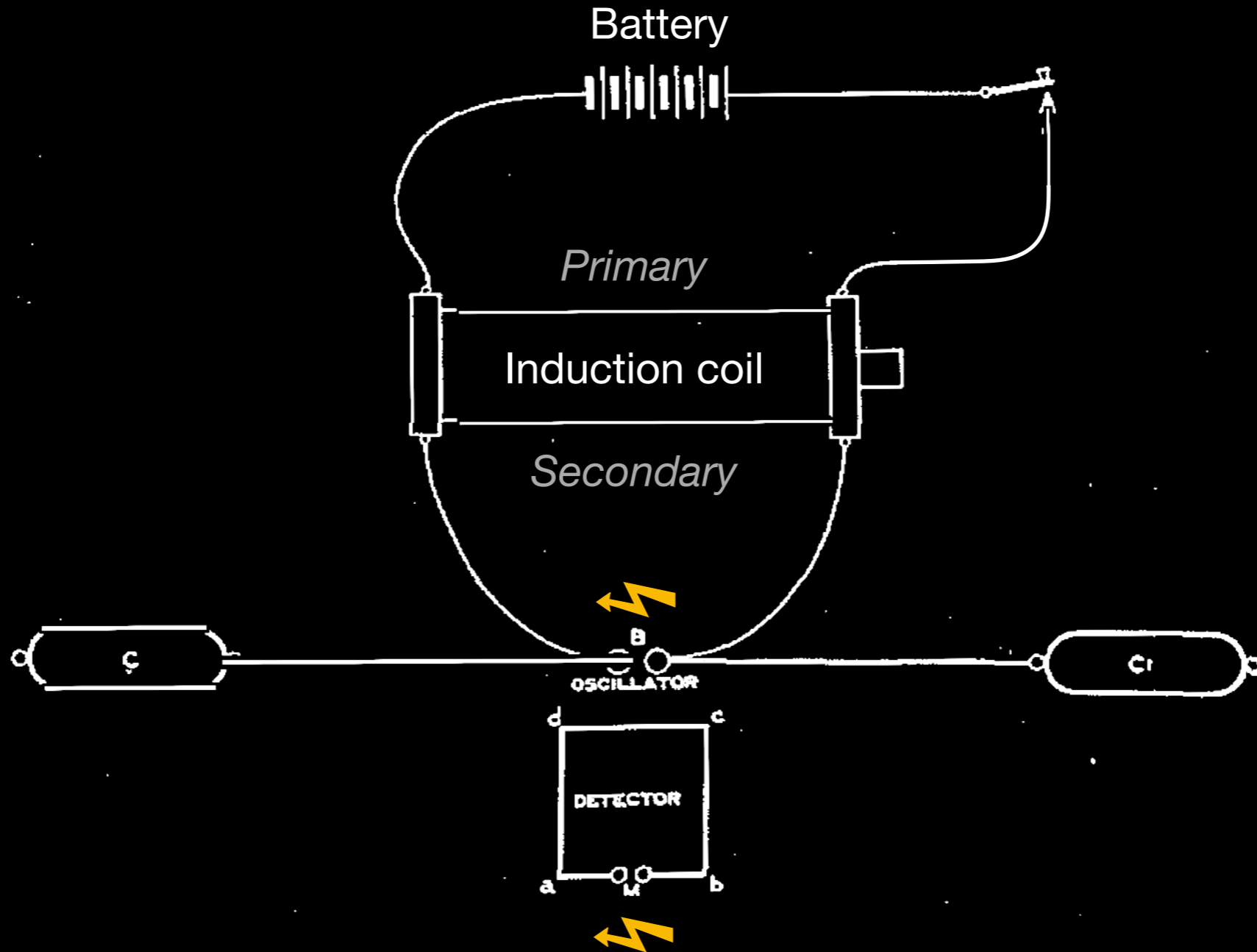
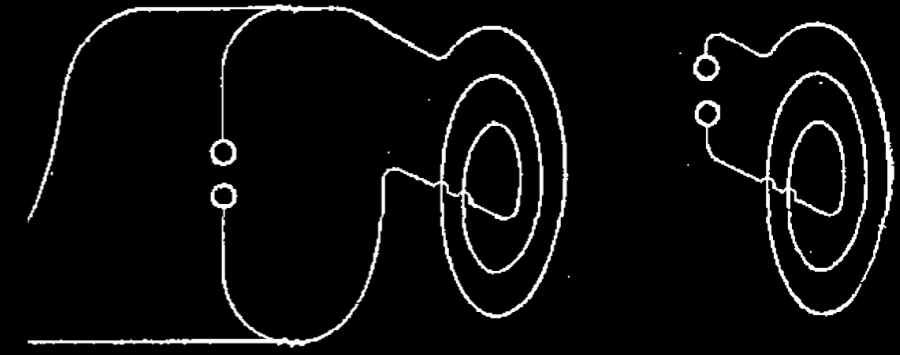
Simplifying the experiment

Strong sparking even without a coil



Simplifying the experiment

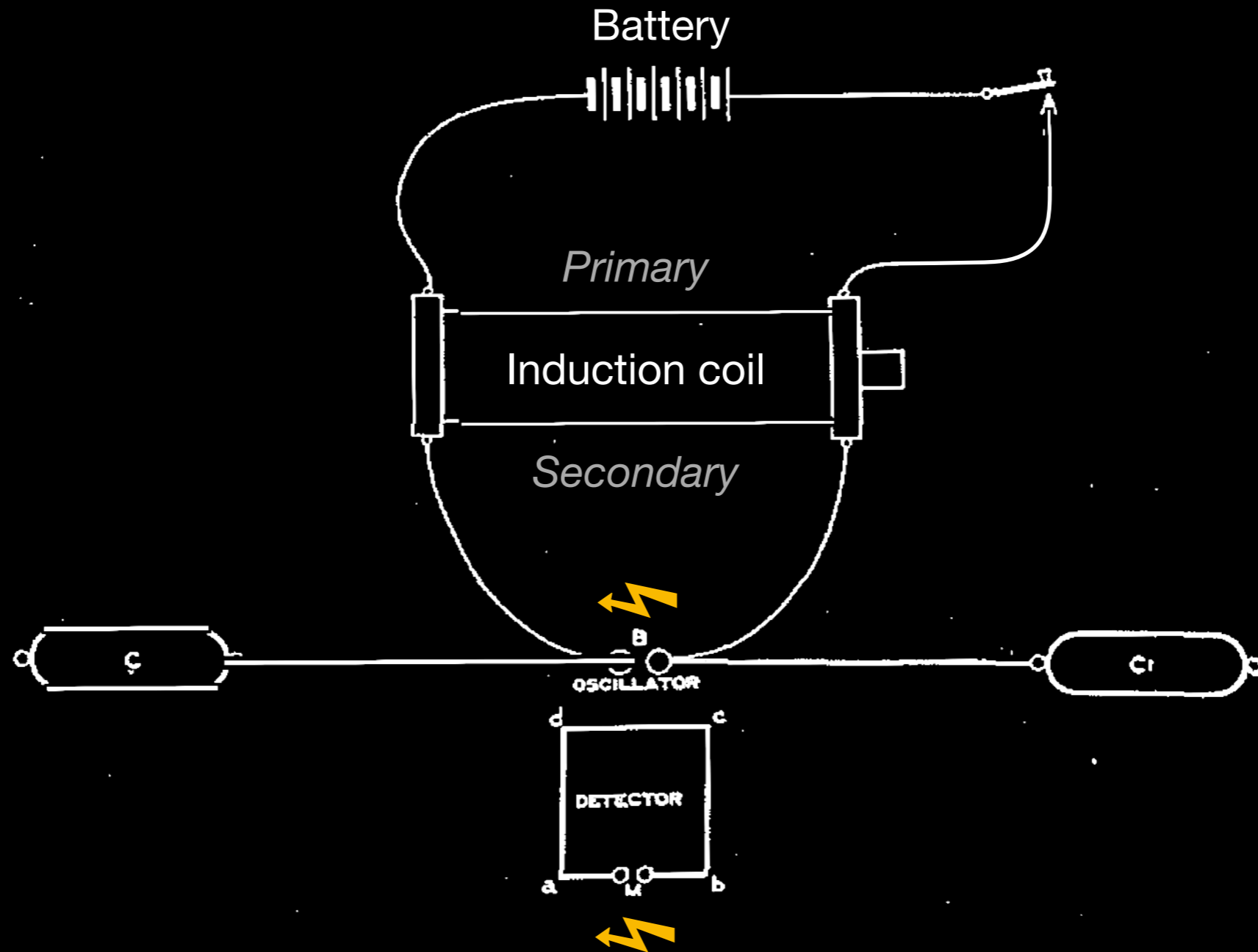
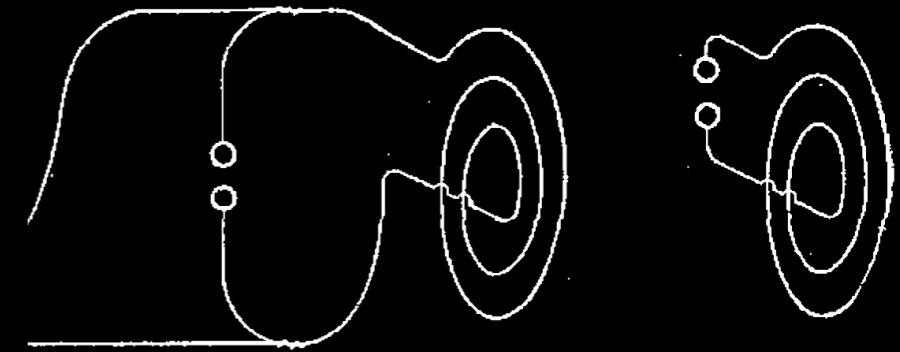
Strong sparking even without a coil



Simplifying the experiment

Strong sparking even without a coil

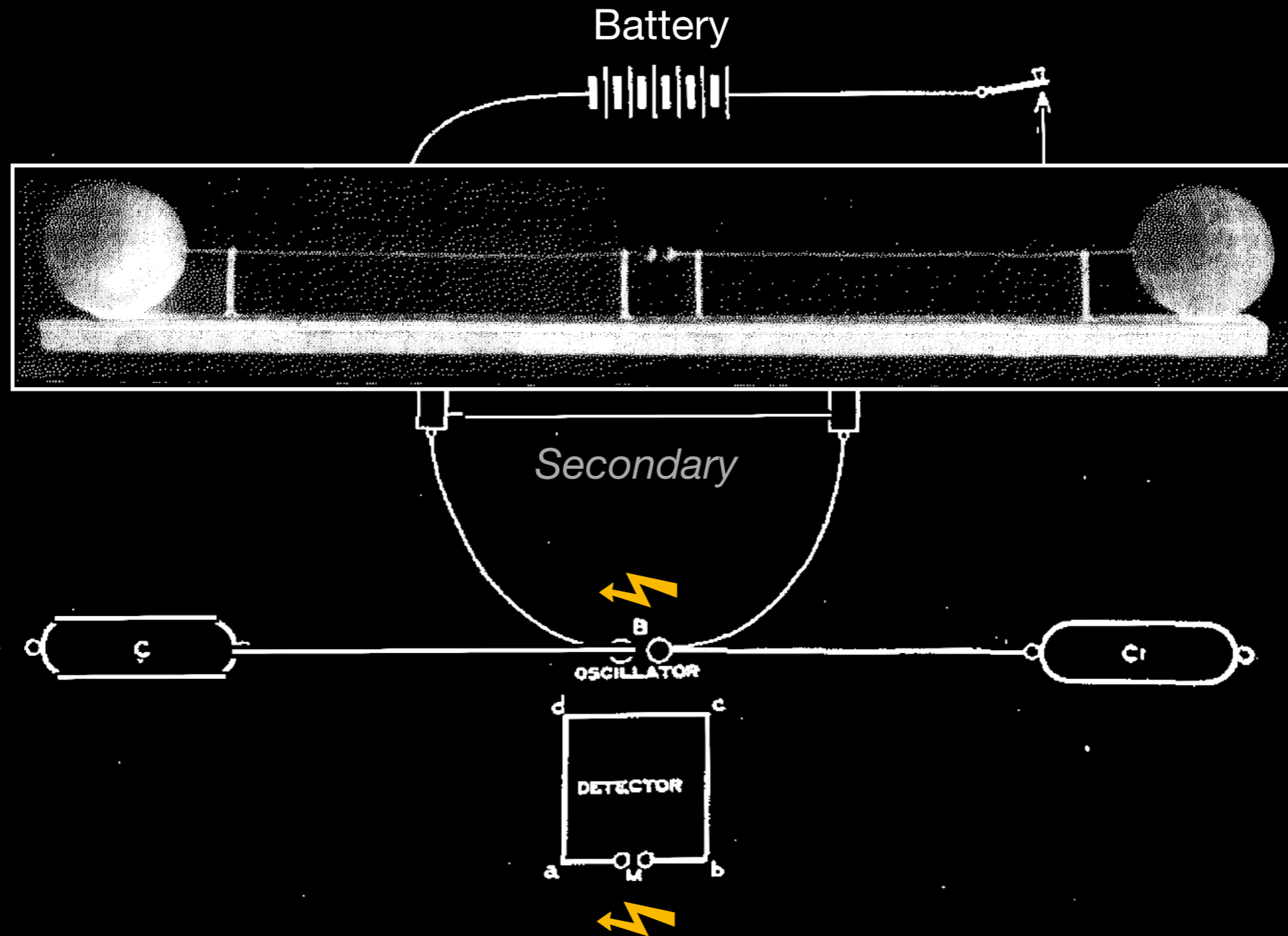
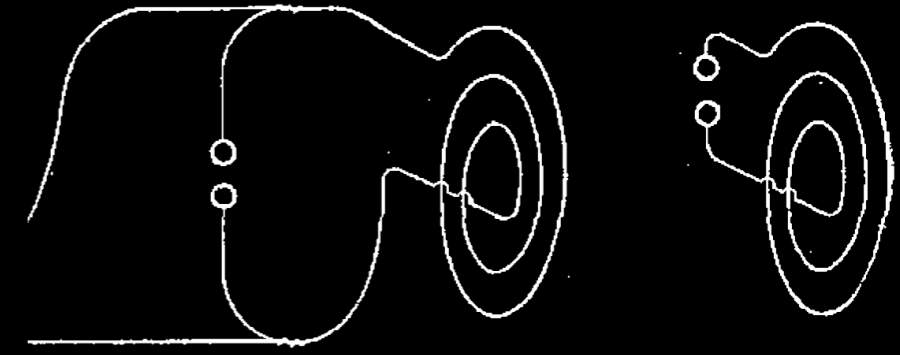
Is induction really behind this?



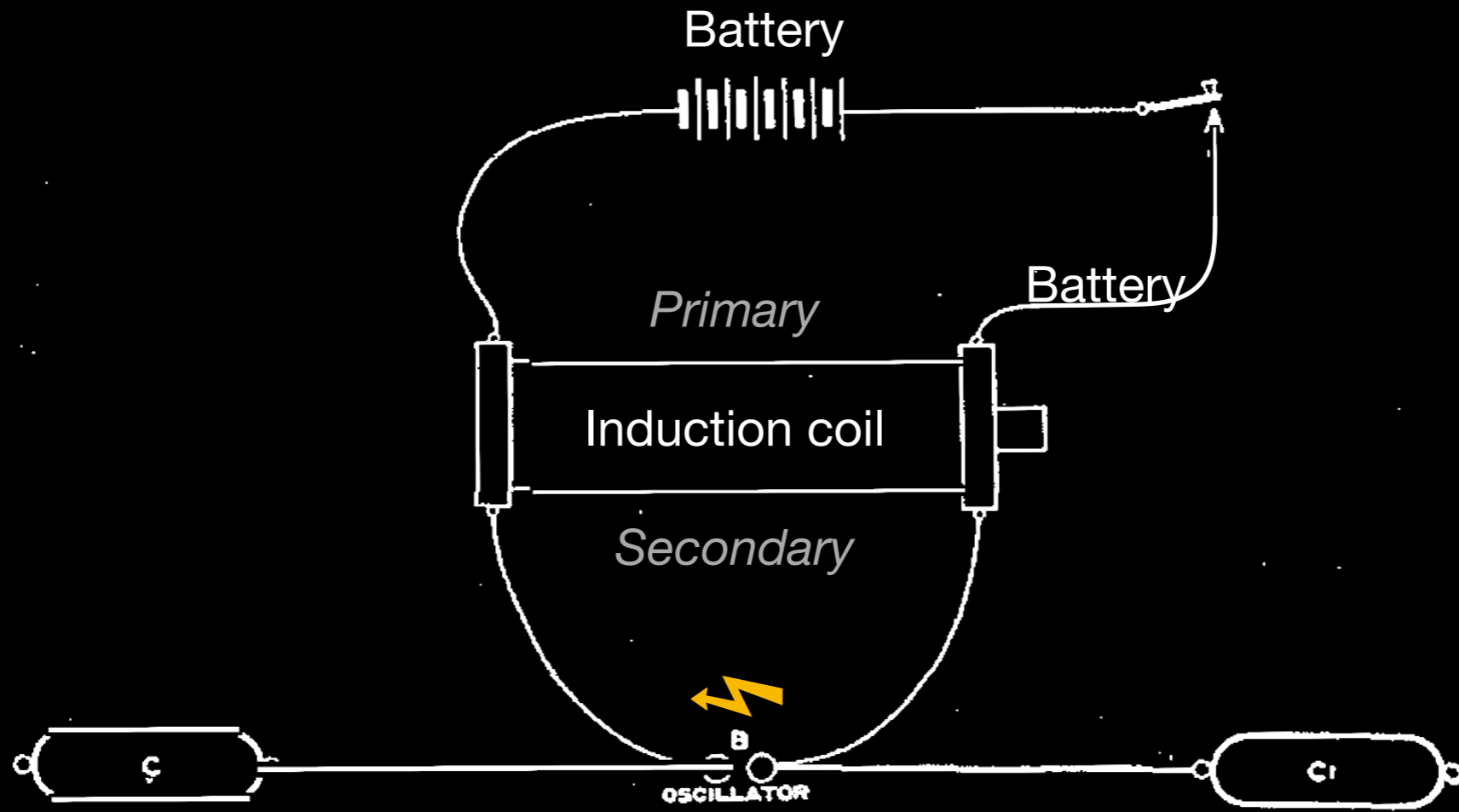
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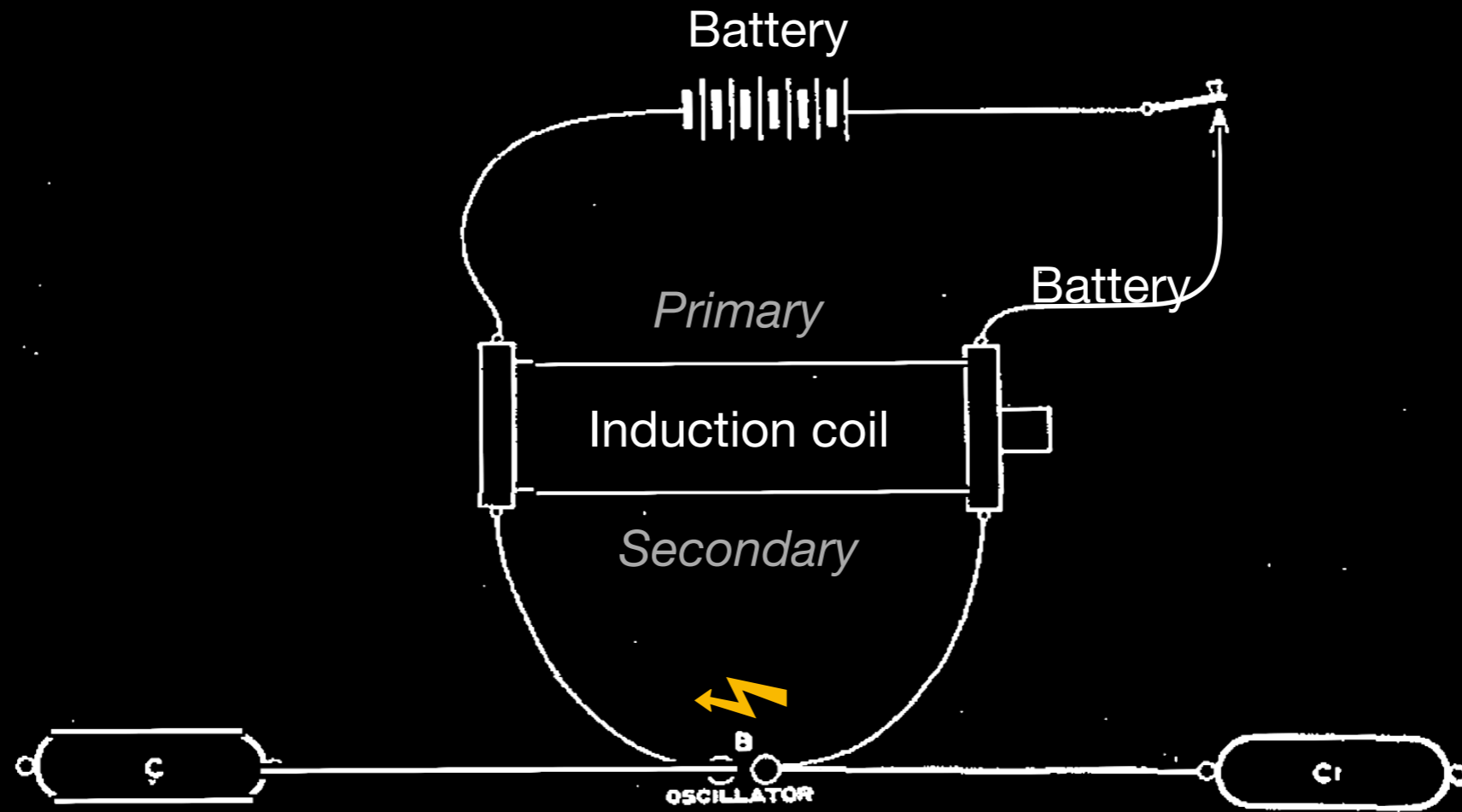
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Oscillations?

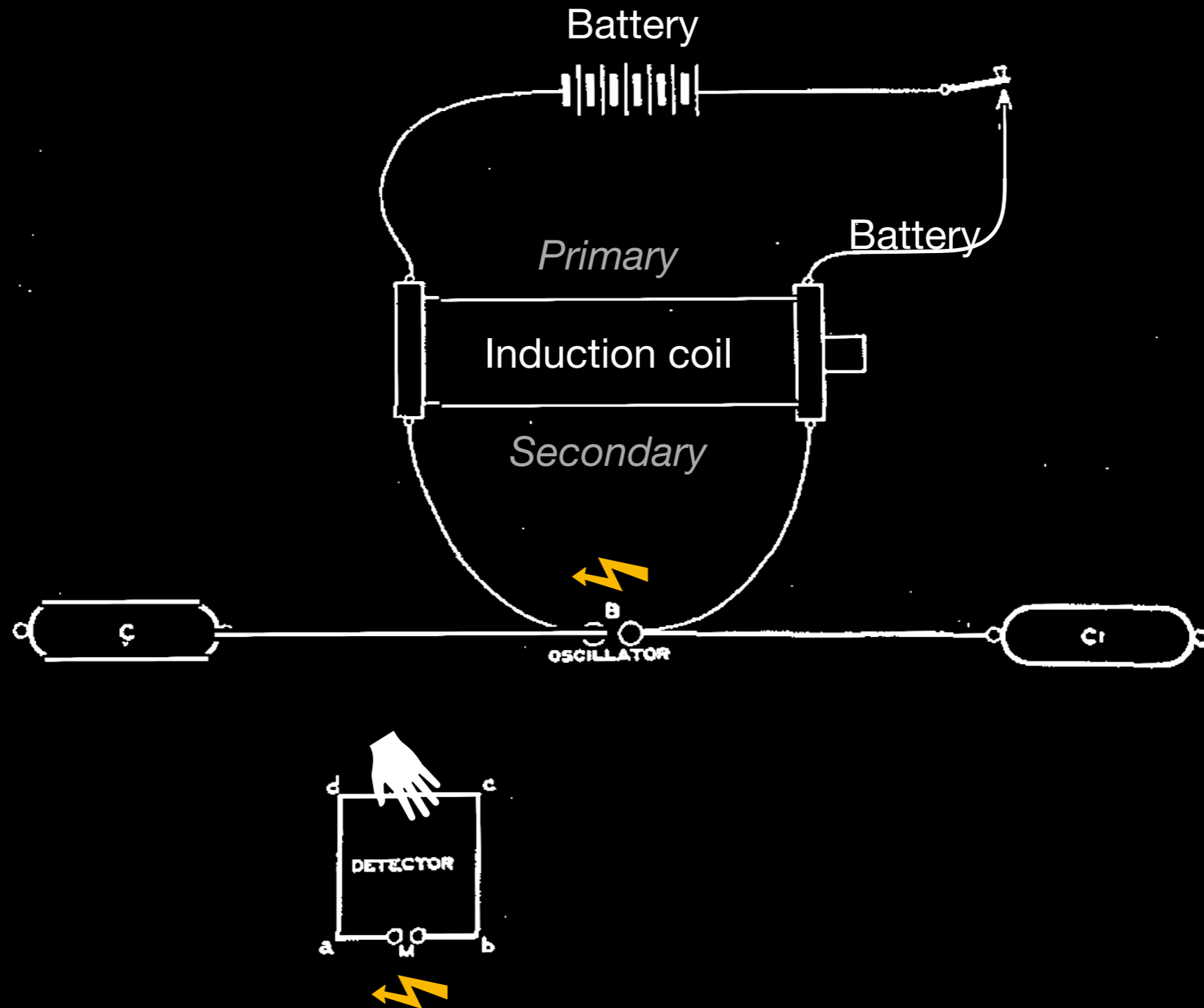


Oscillations?



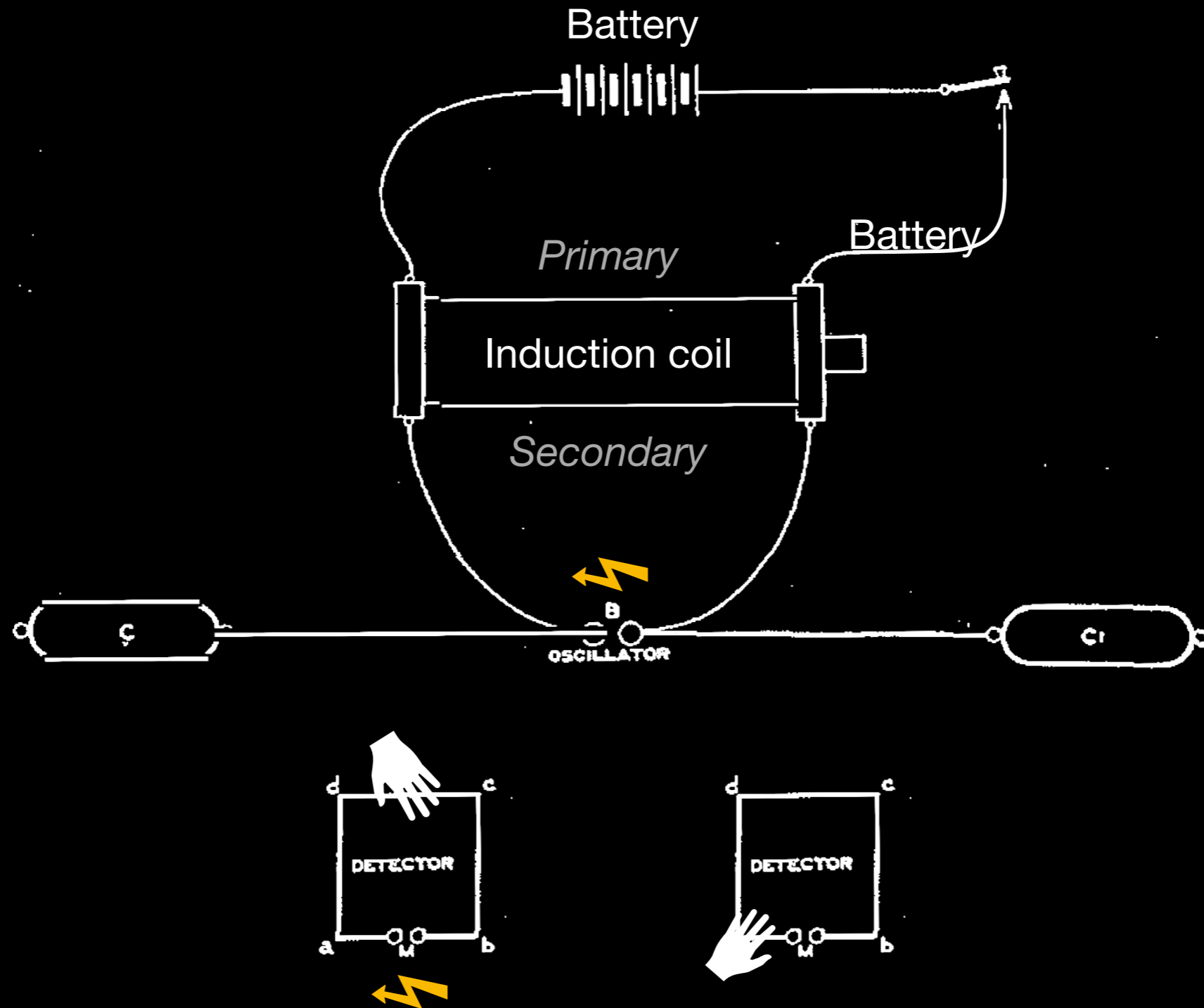
“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

Oscillations?



“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

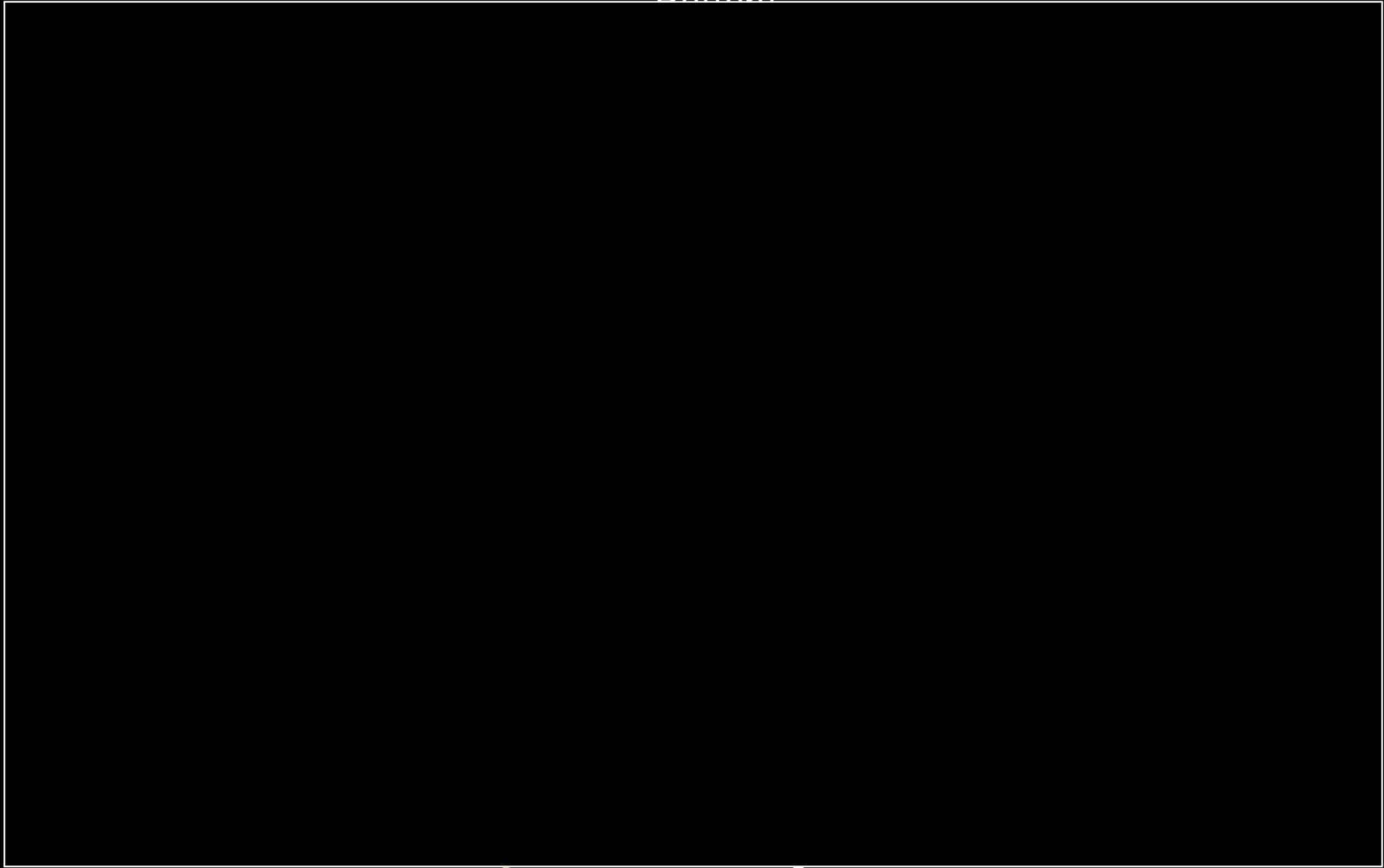
Oscillations?



“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

Oscillations?

Battery



“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

Oscillations?

Battery

“While the potential at the ends oscillates backwards and forwards continually between two limits, it always retains the same mean value in the middle of the circuit.”



“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

Oscillations?

Pottery

“While the potential at the ends oscillates backwards and forwards continually between two limits, it always retains the same mean value in the middle of the circuit.

This middle point is therefore a node of the electric oscillation, and the oscillation has only this one node.”



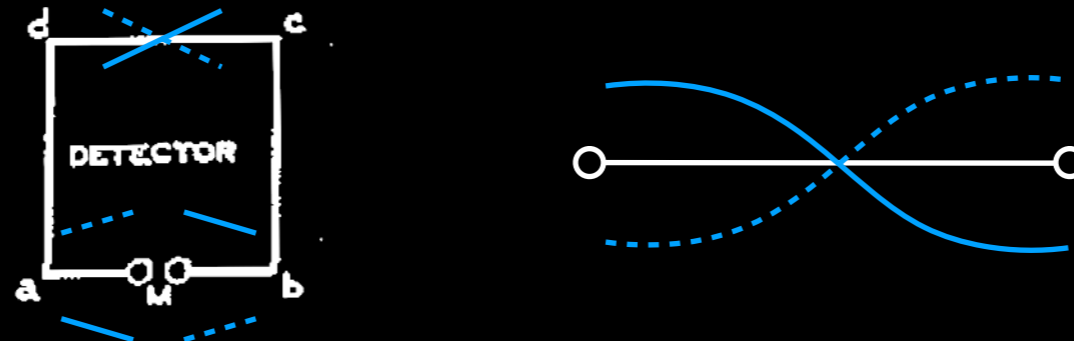
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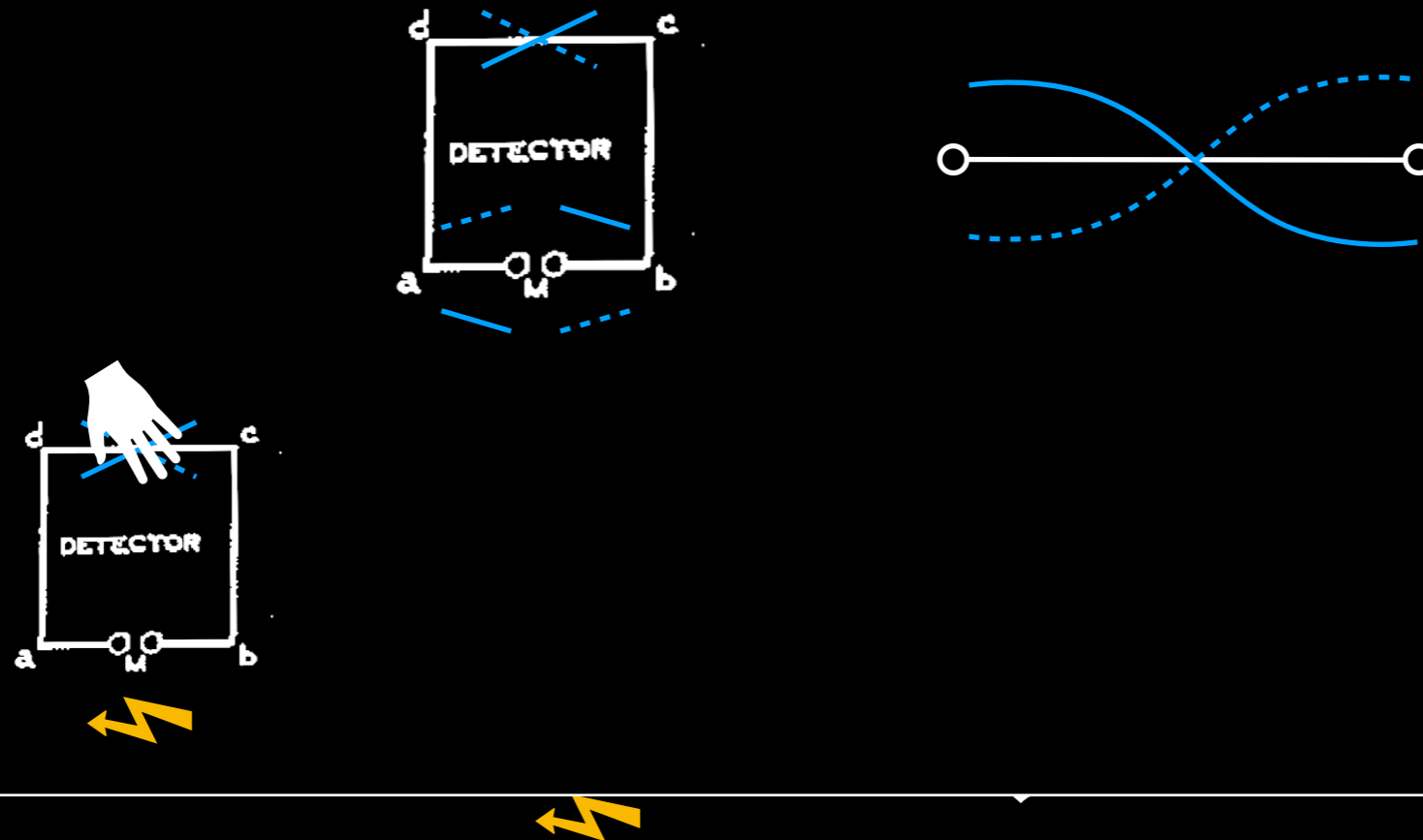
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Pottery

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This middle point is therefore a node of the electric oscillation, and the oscillation has only this one node.”



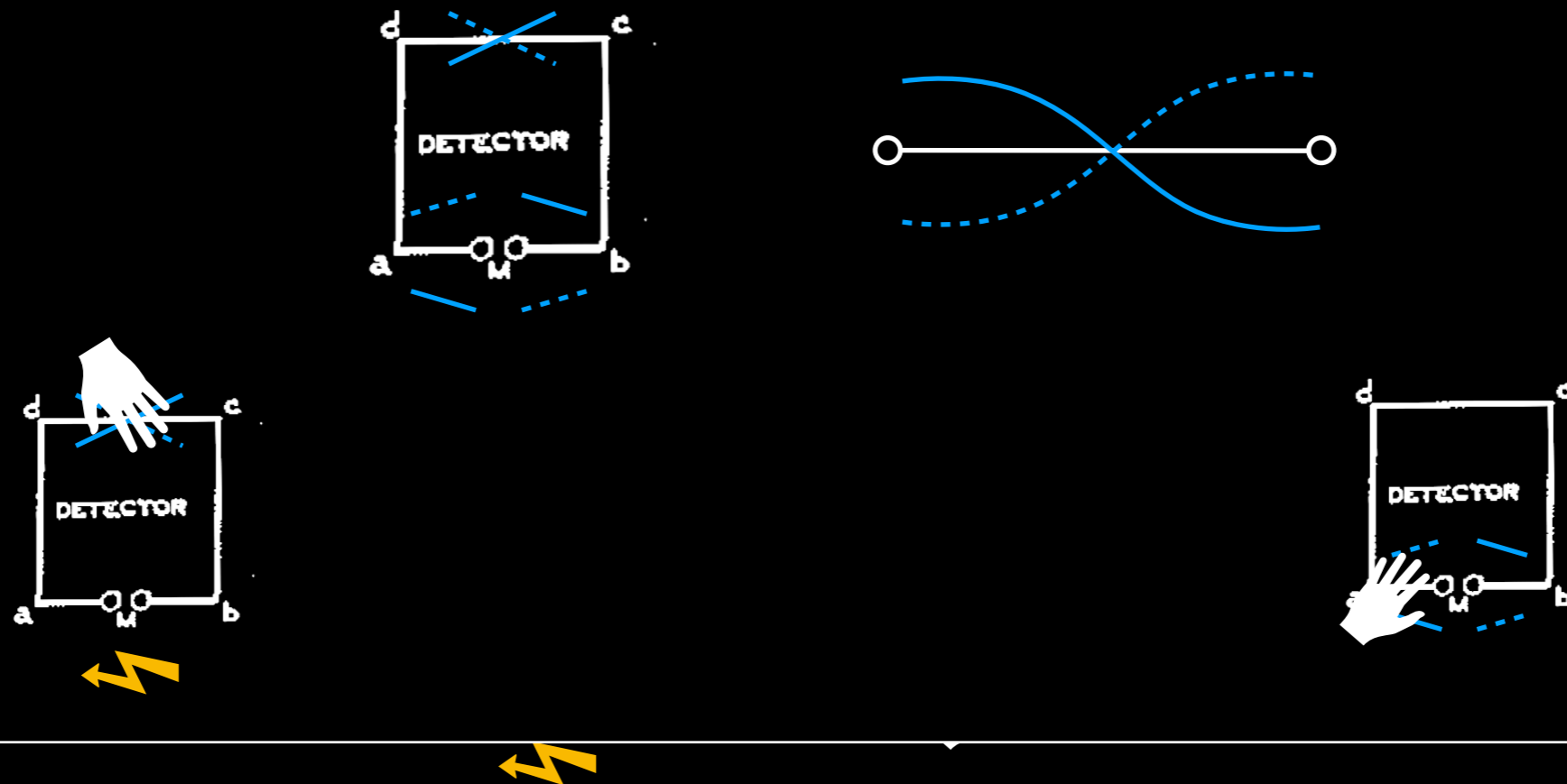
“The middle of the wire can be touched with the hand without affecting the sparks; similar interference at the ends causes the sparks to disappear.”

Oscillations?

Pottery

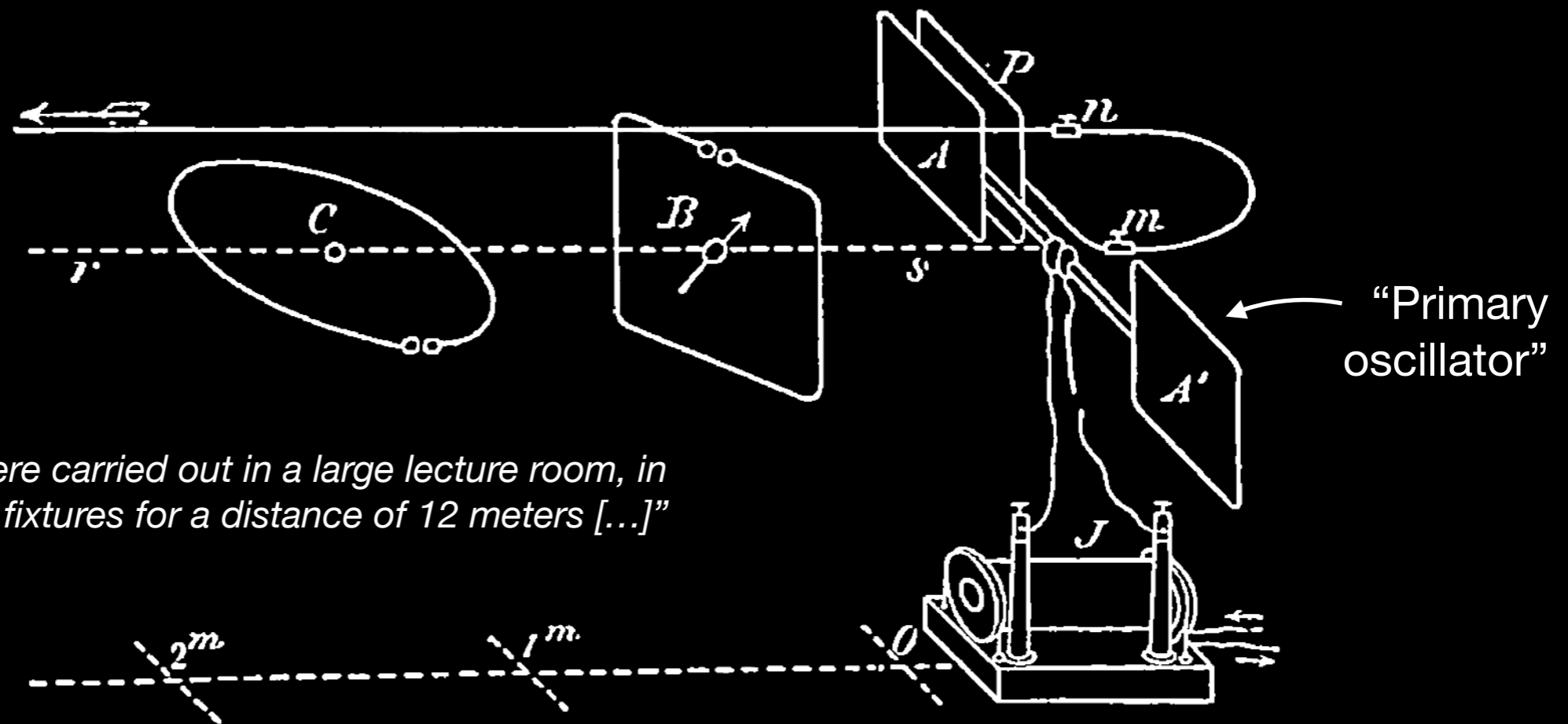
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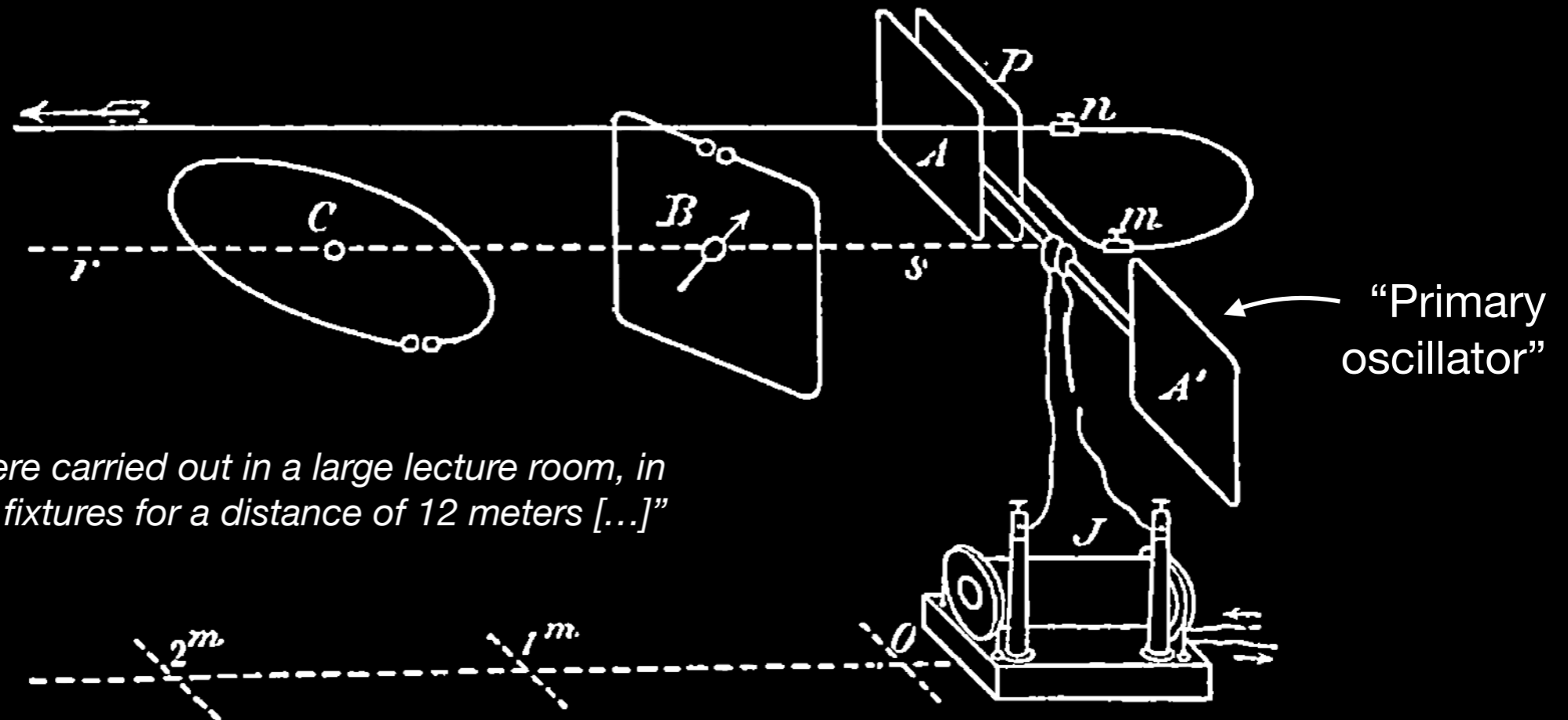
Testing different separations



“The experiments were carried out in a large lecture room, in which there were no fixtures for a distance of 12 meters [...]”

Testing different separations

“As the distance from the primary oscillator increases, the length of the sparks diminishes, at first rapidly but afterwards very slowly.”

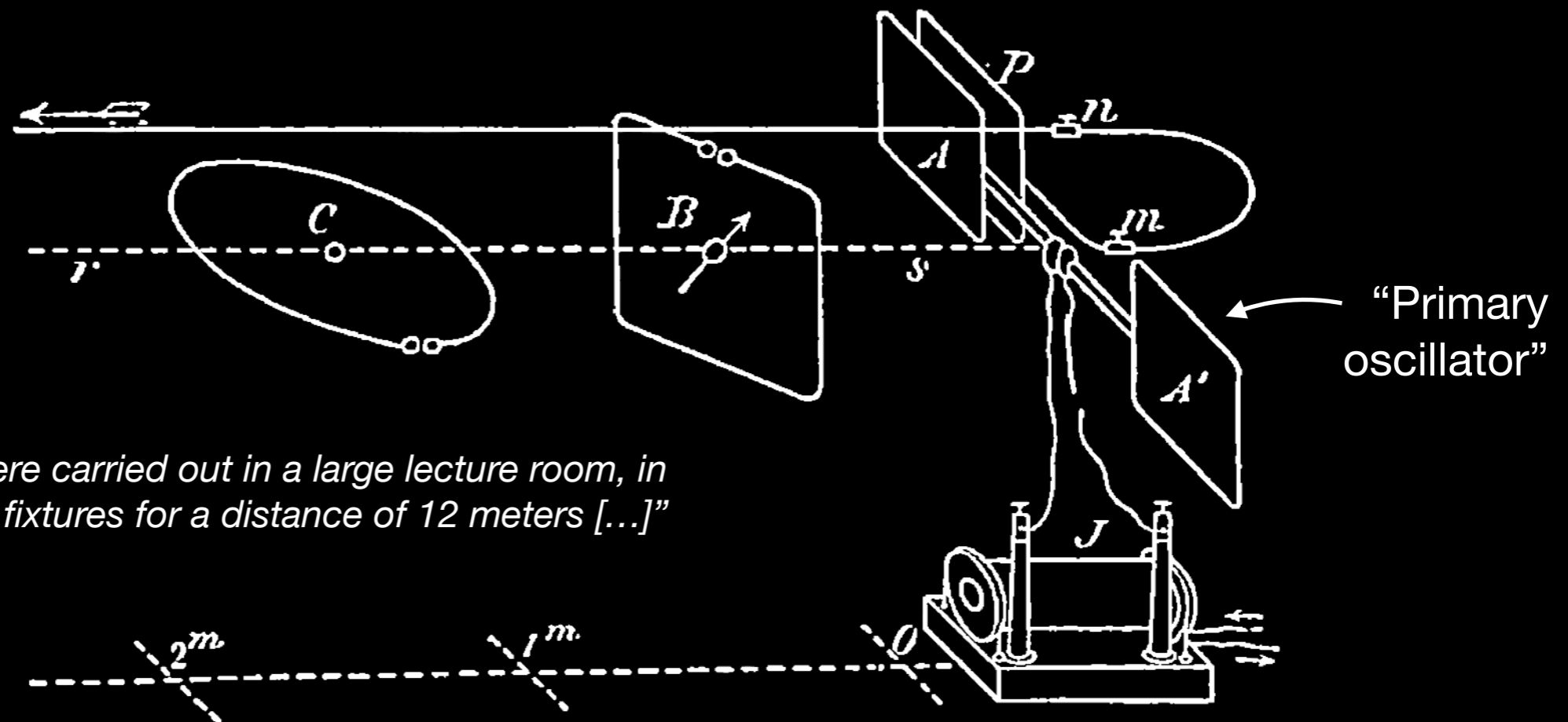


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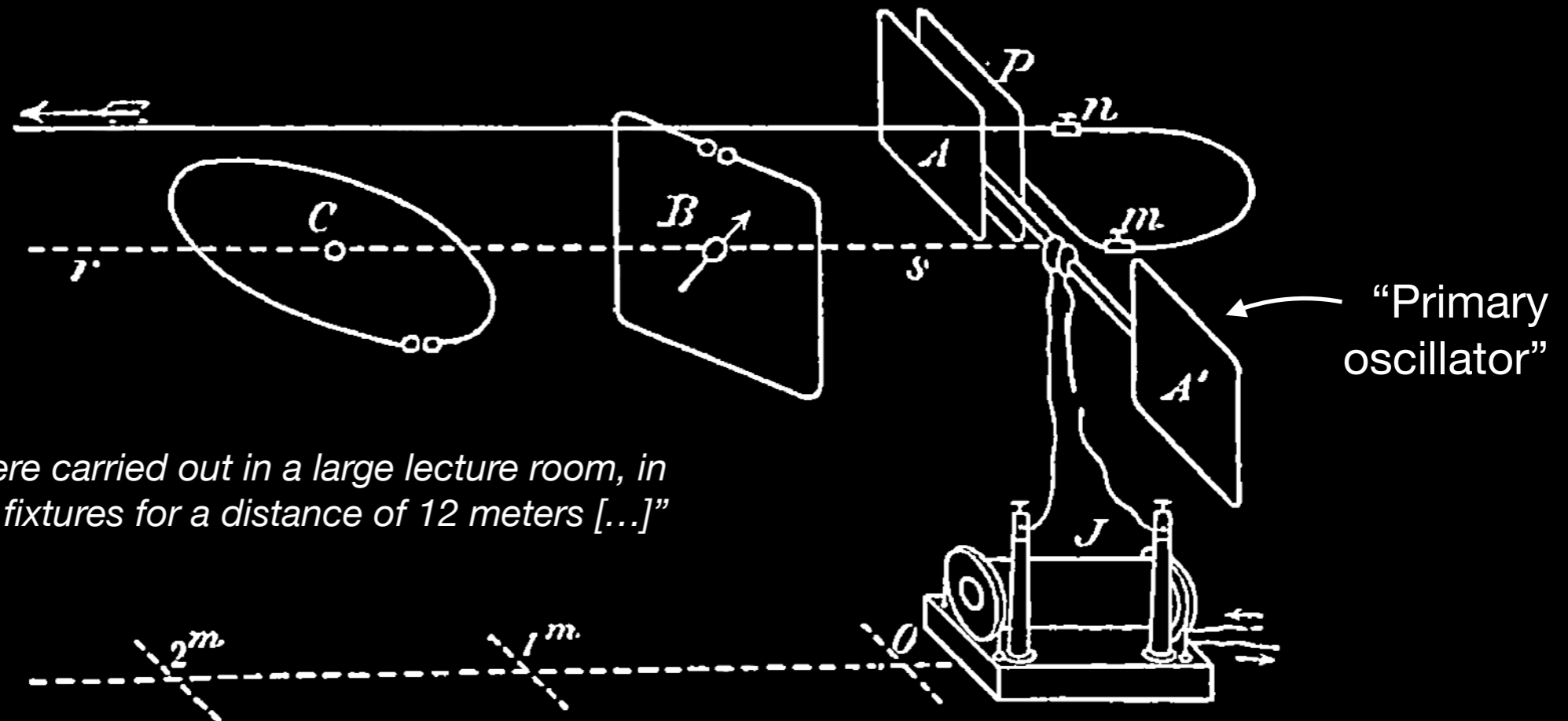
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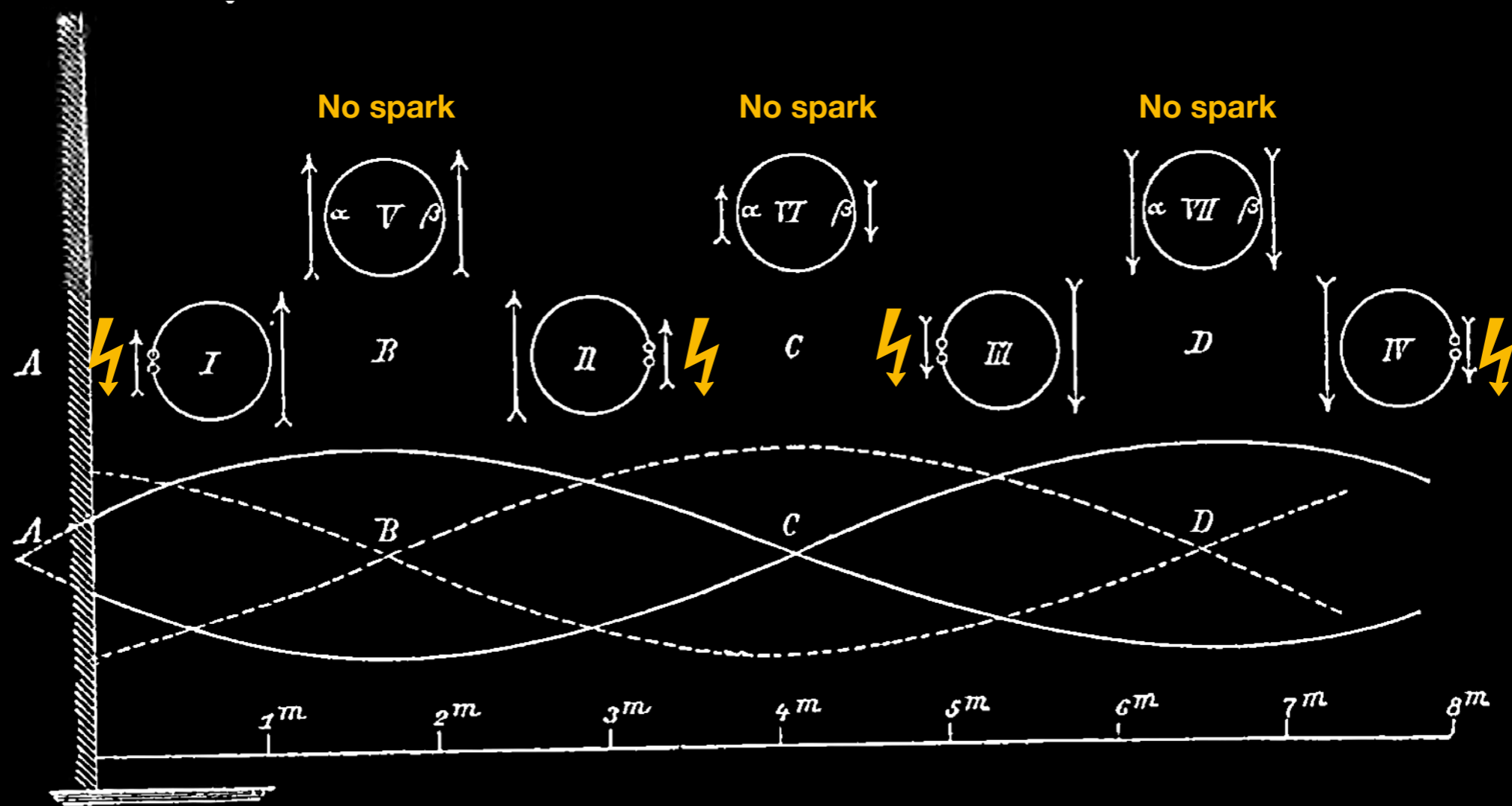
“The total force may be split up into the electrostatic part and the electromagnetic part.”

“There is no doubt that at short distances the former, at greater distances the latter, preponderates and settles the direction of the total force.”



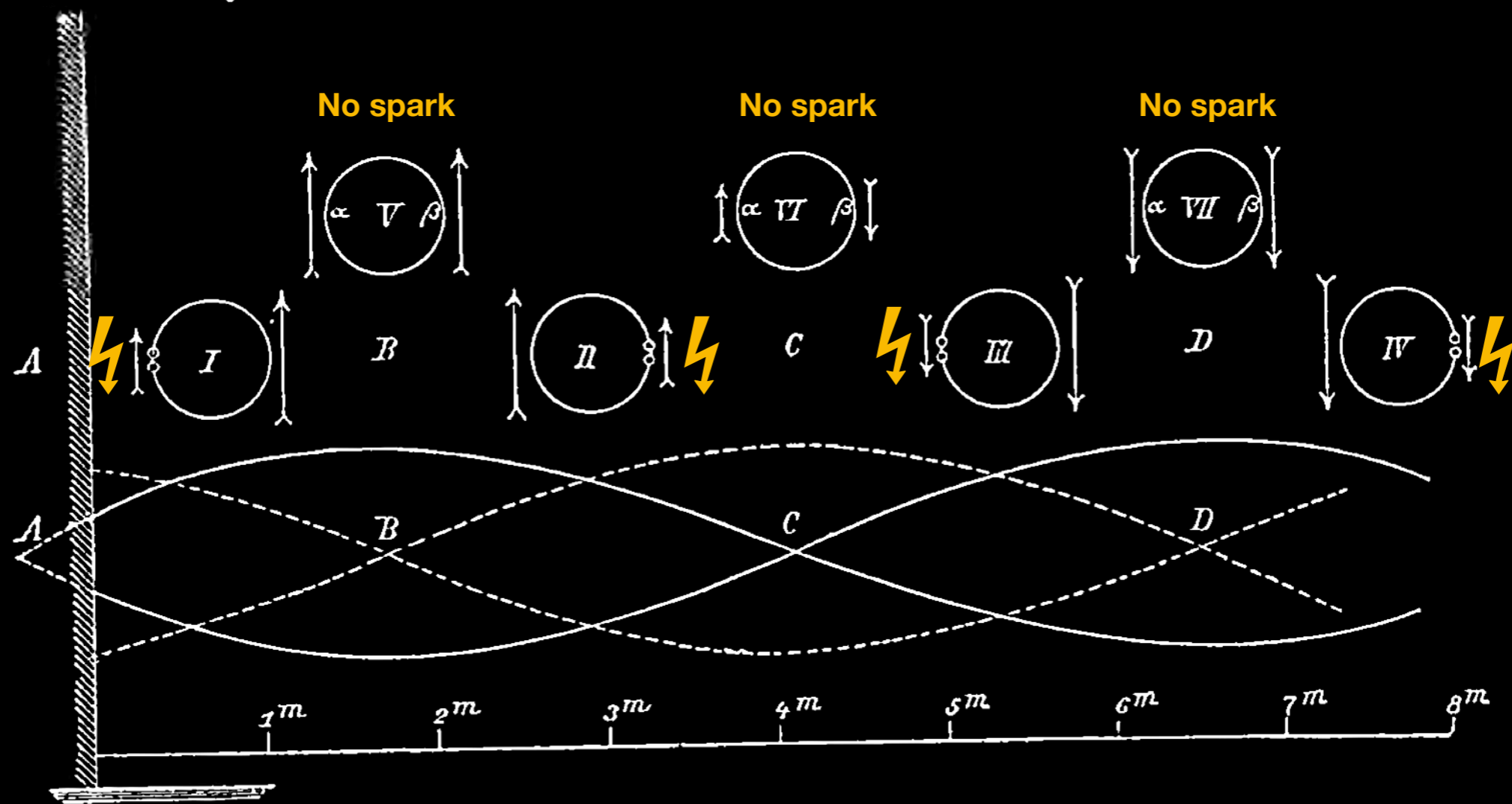
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Making the waves visible



Making the waves visible

“For let us suppose that a vertical wave of electric force proceeds towards the wall, it is reflected with slightly diminished intensity, and so gives rise to stationary waves.”

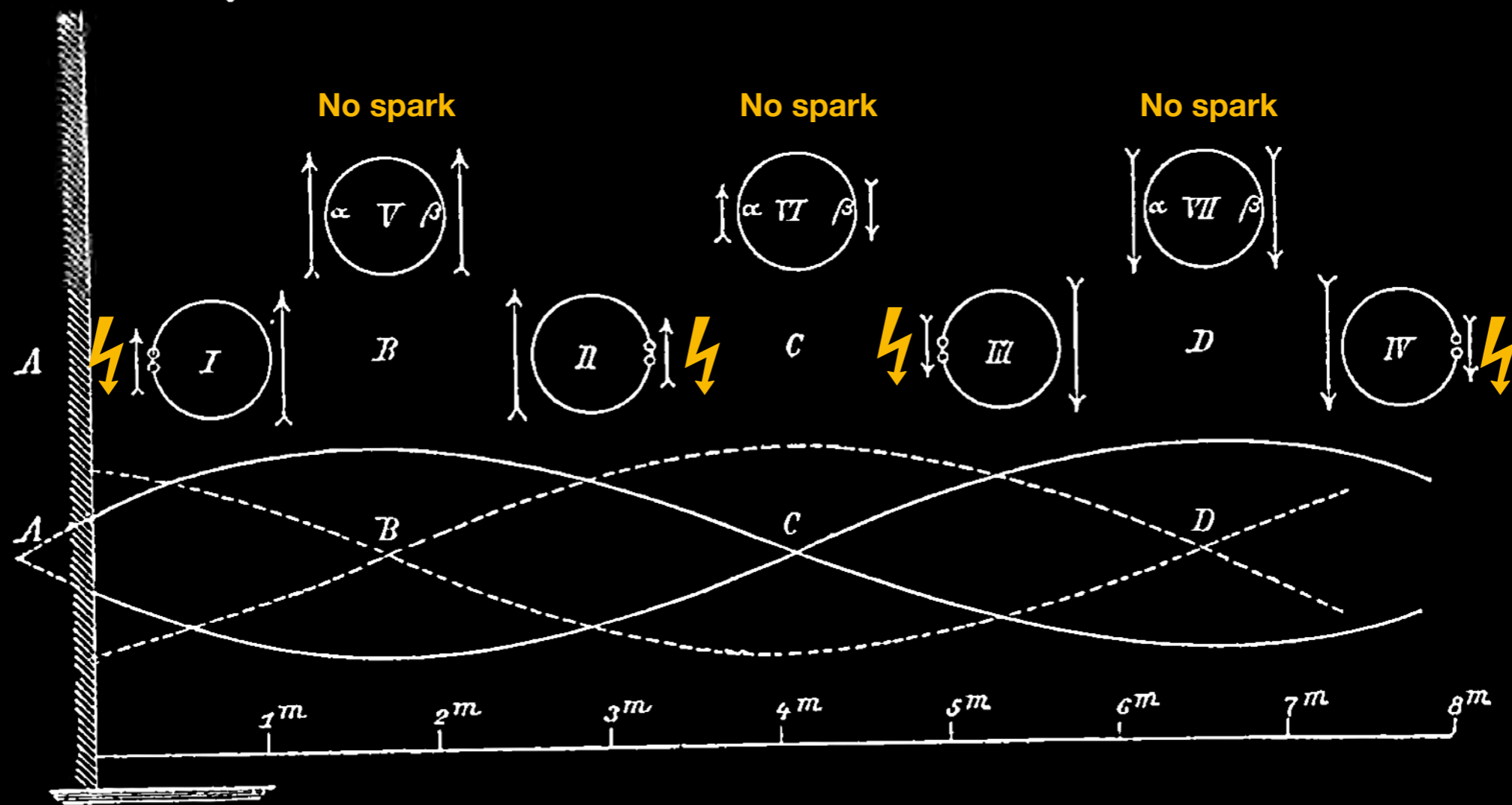


Making the waves visible

“For let us suppose that a vertical wave of electric force proceeds towards the wall, it is reflected with slightly diminished intensity, and so gives rise to stationary waves.”



[source]



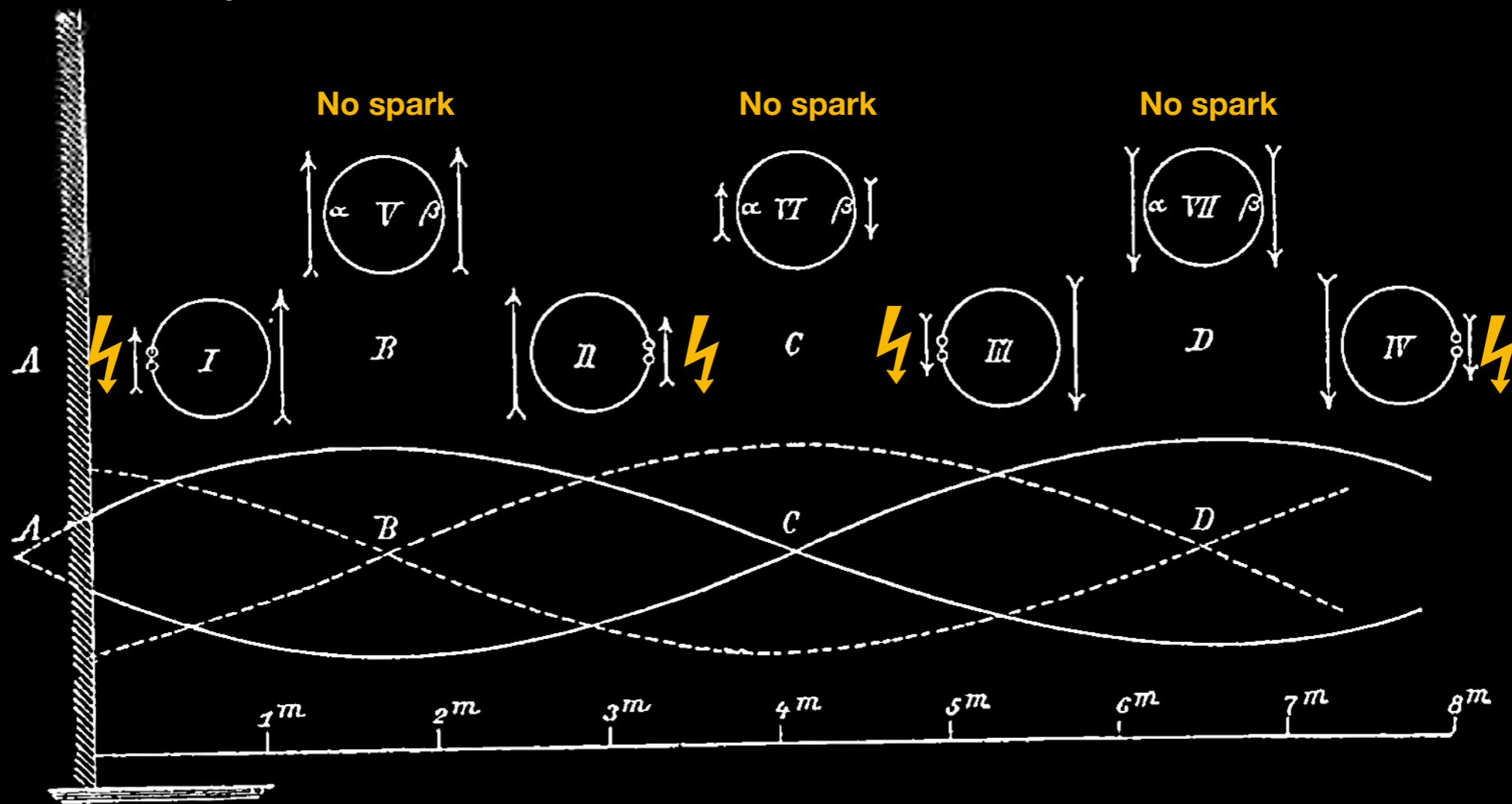
Making the waves visible

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[source]

Locations where sparking occurs make the “electric wave” visible!



Making the waves visible

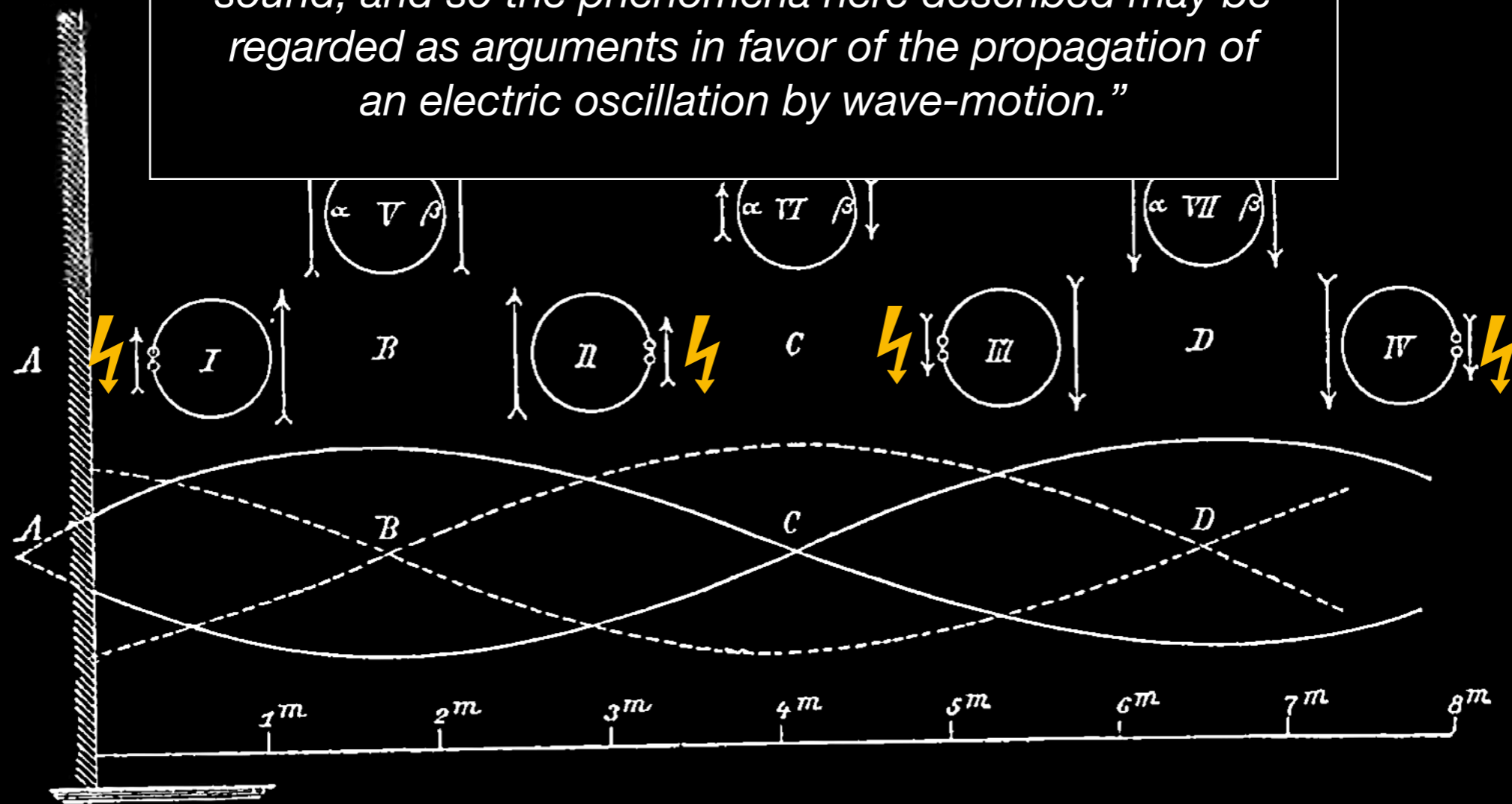
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[source]

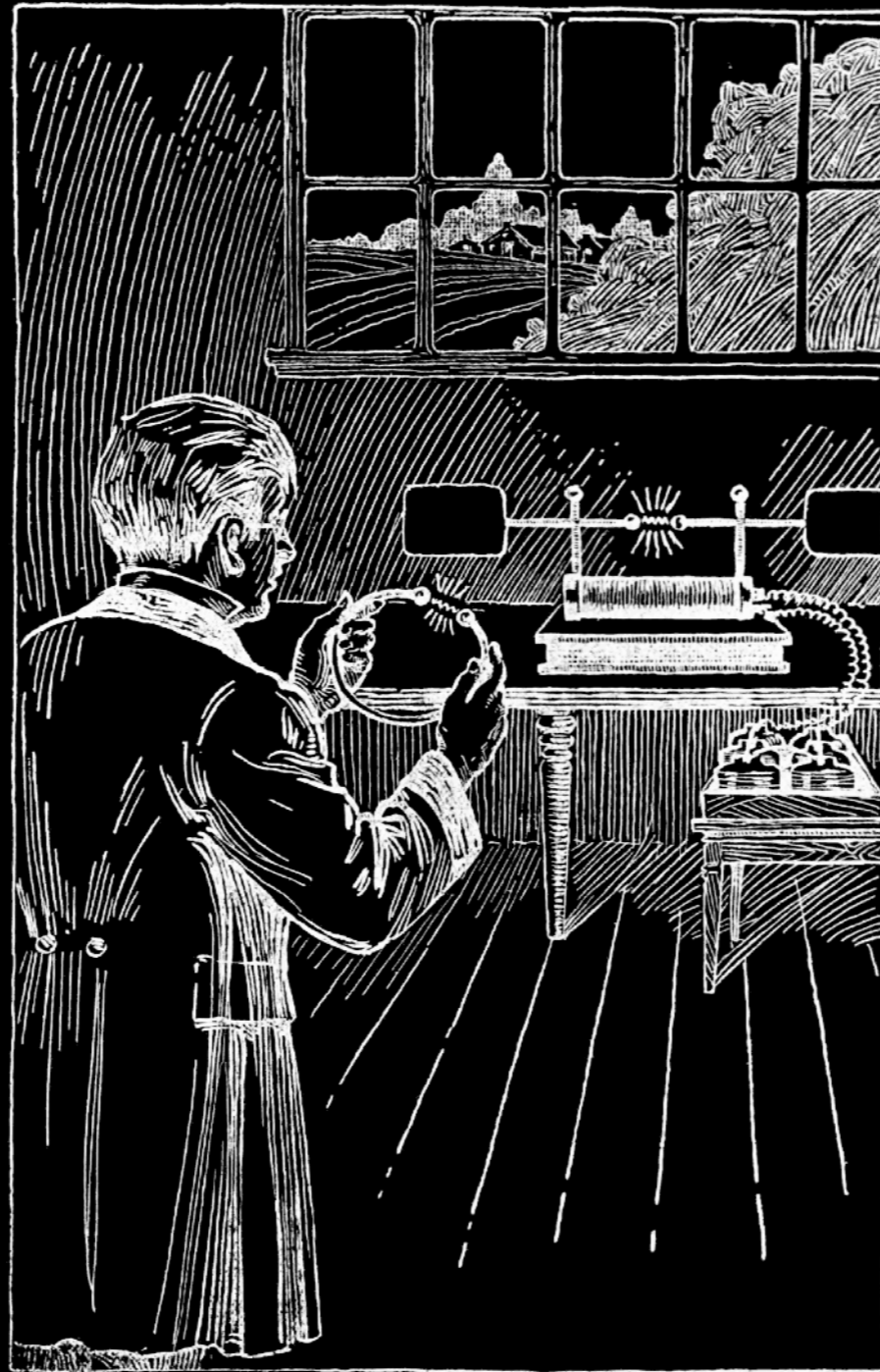
1887:

“In optics and acoustics these experiments count as arguments in favor of the wave-nature of light and sound; and so the phenomena here described may be regarded as arguments in favor of the propagation of an electric oscillation by wave-motion.”



visible!

Electromagnetic waves exist!



“It's of no use whatsoever ... this is just an experiment that proves Maestro Maxwell was right—we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.”

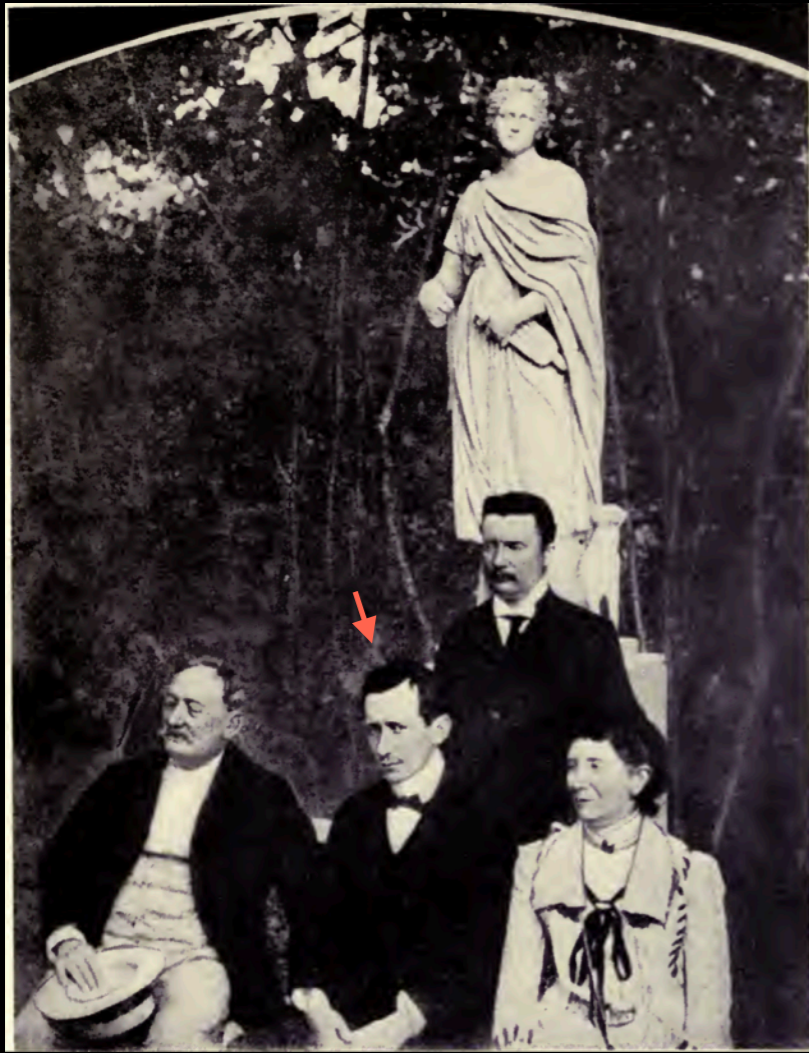
Guglielmo Marconi

Self-taught inventor and engineer



Guglielmo Marconi

Self-taught inventor and engineer



At their family residence
at Villa Grifone

Guglielmo Marconi

Self-taught inventor and engineer



His middle school teacher:
*“It is necessary to improve your
pronunciation of Italian,
my dear boy [...]”*



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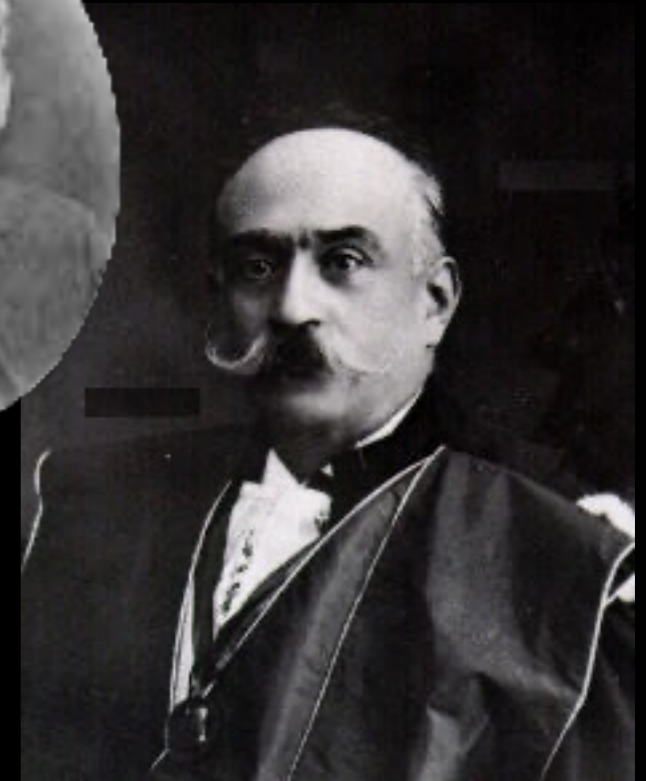


At their family residence
at Villa Grifone

Vincenzo Rosa
(At Livorno)



Augusto Righi
(At Bologna)



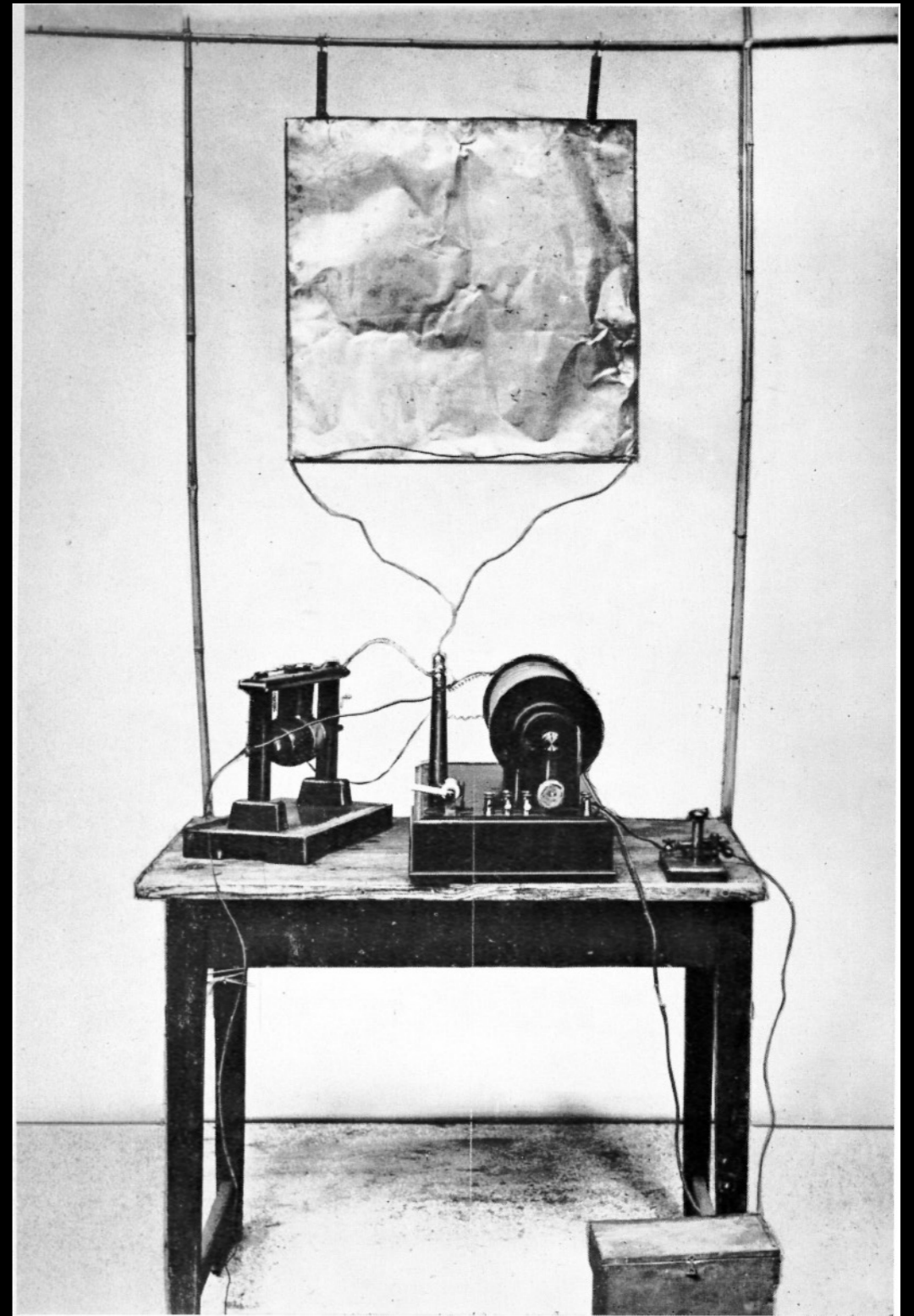
Seeing opportunity where others did not

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“At my home near Bologna, in Italy, I commenced early in 1895 to carry out tests and experiments with the object of determining whether it would be possible by means of Hertzian waves to transmit to a distance telegraphic signs and symbols without the aid of connecting wires.”

Seeing opportunity where others did not

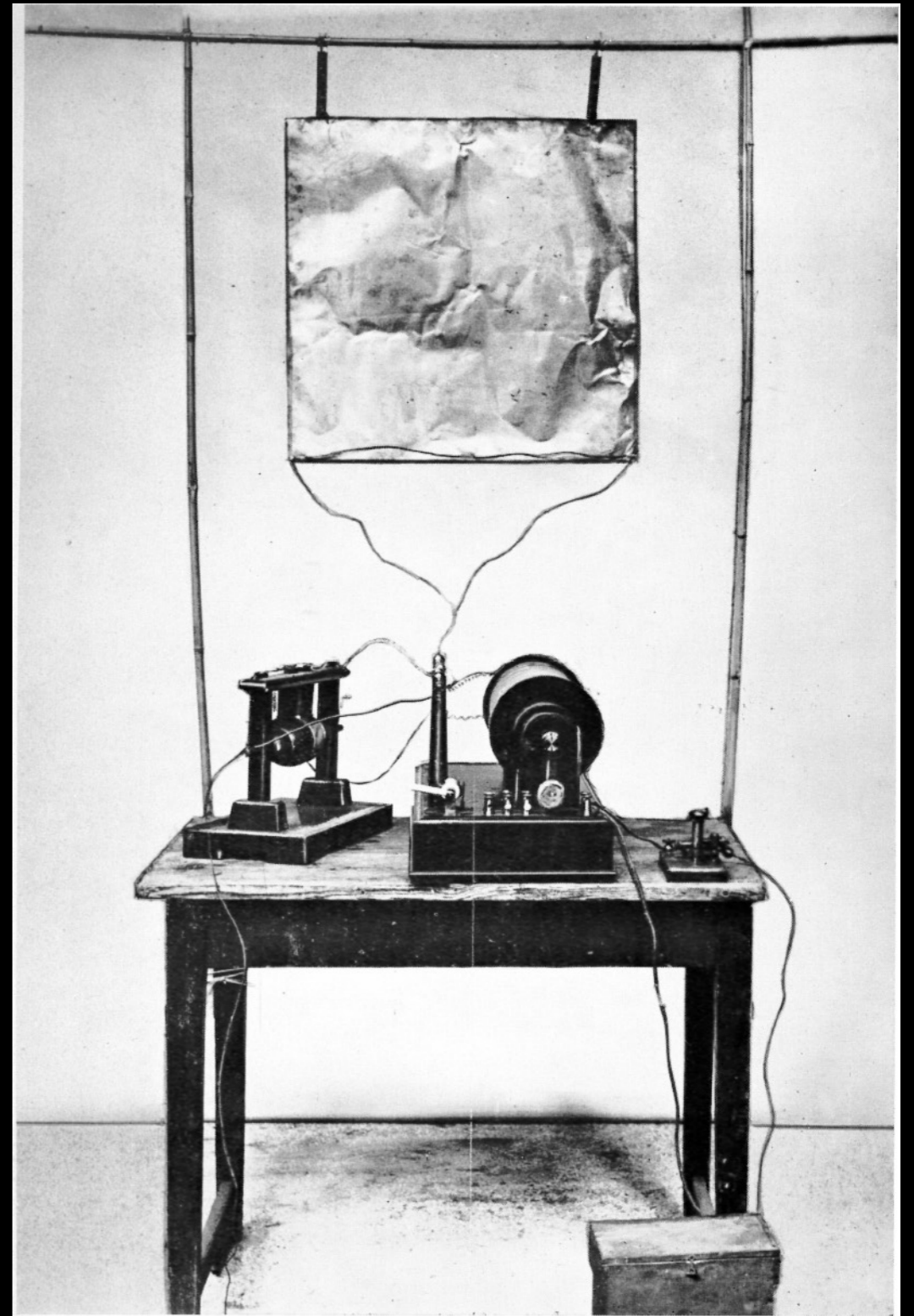
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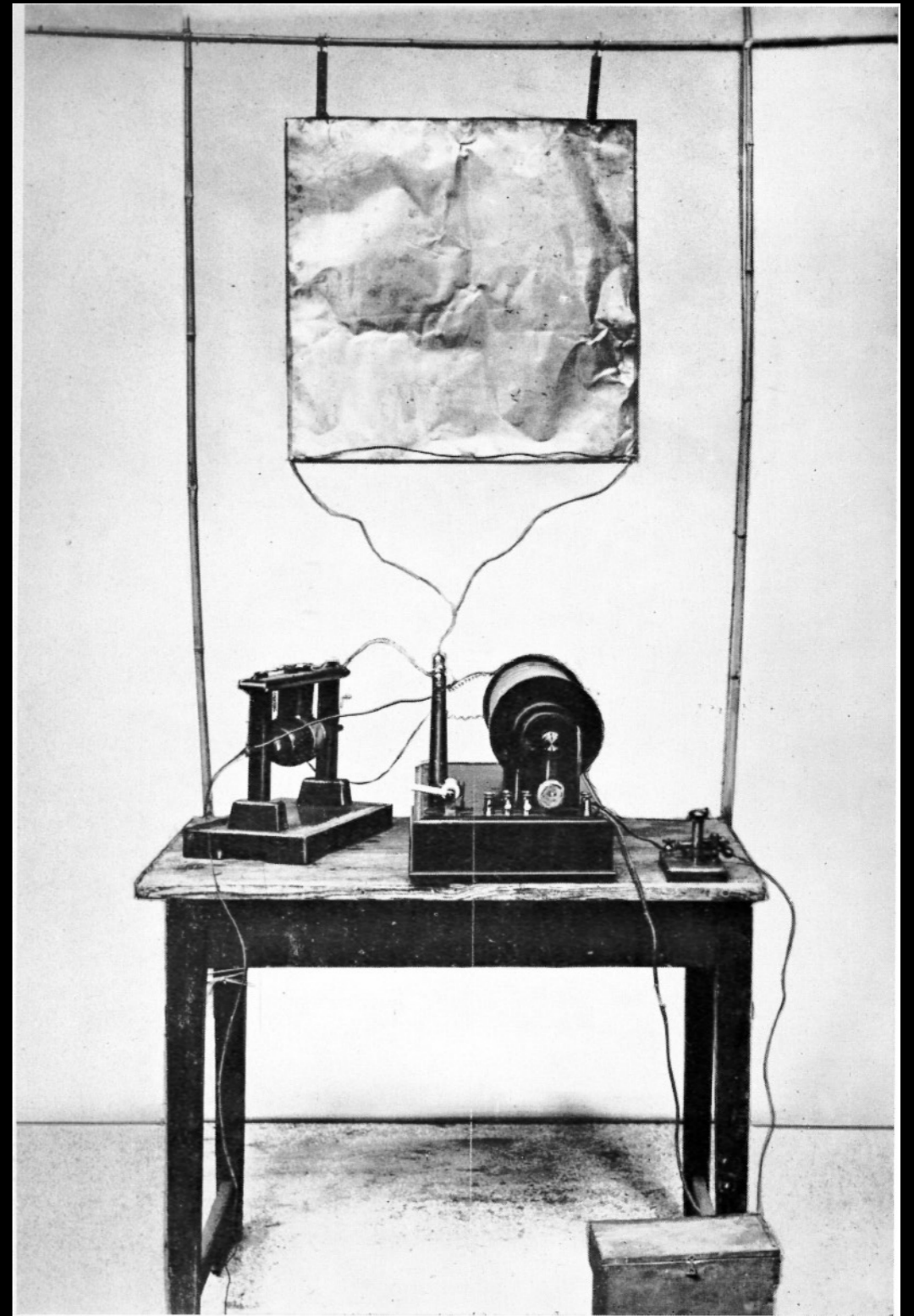


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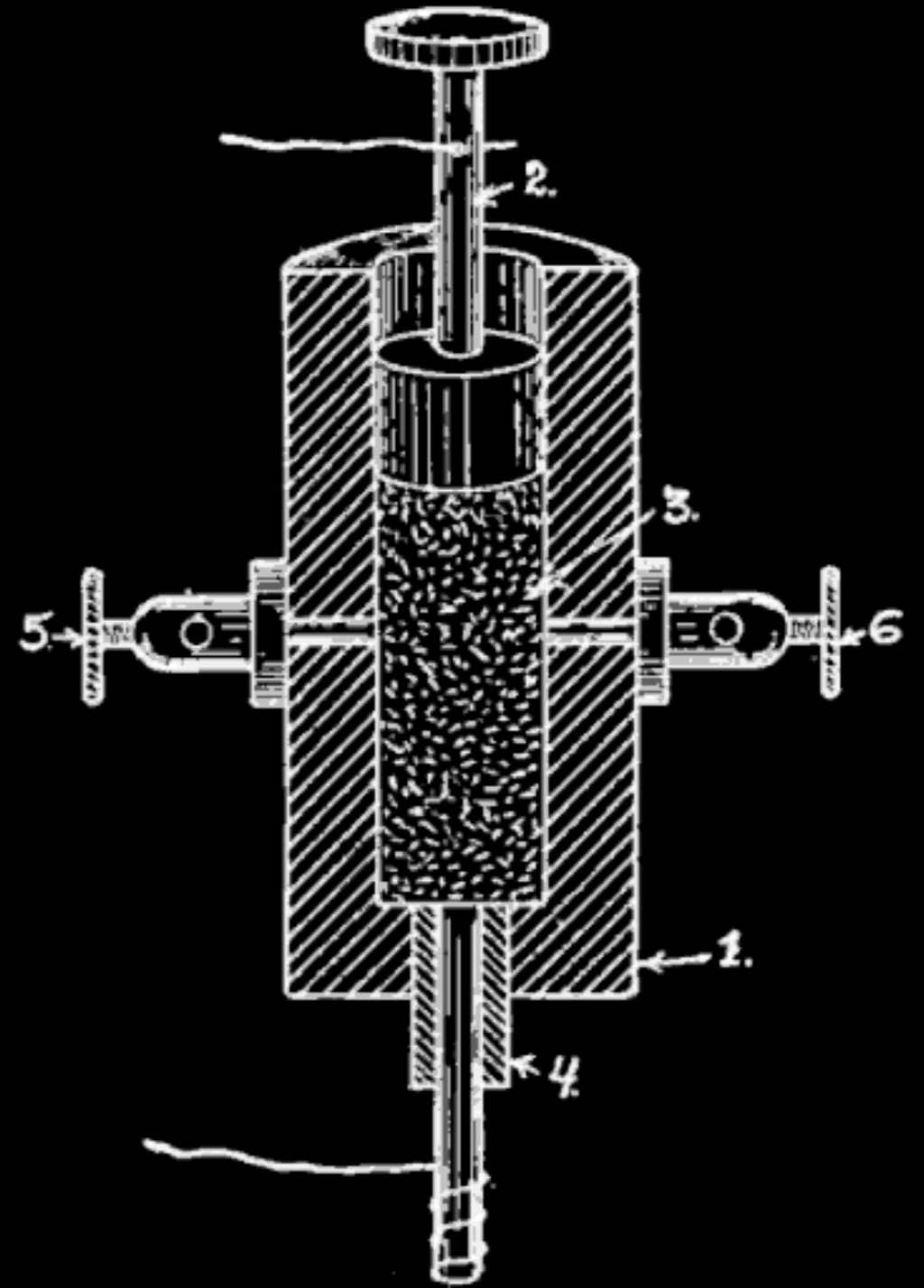
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“With such apparatus I was able to telegraph up to a distance of about half a mile.”



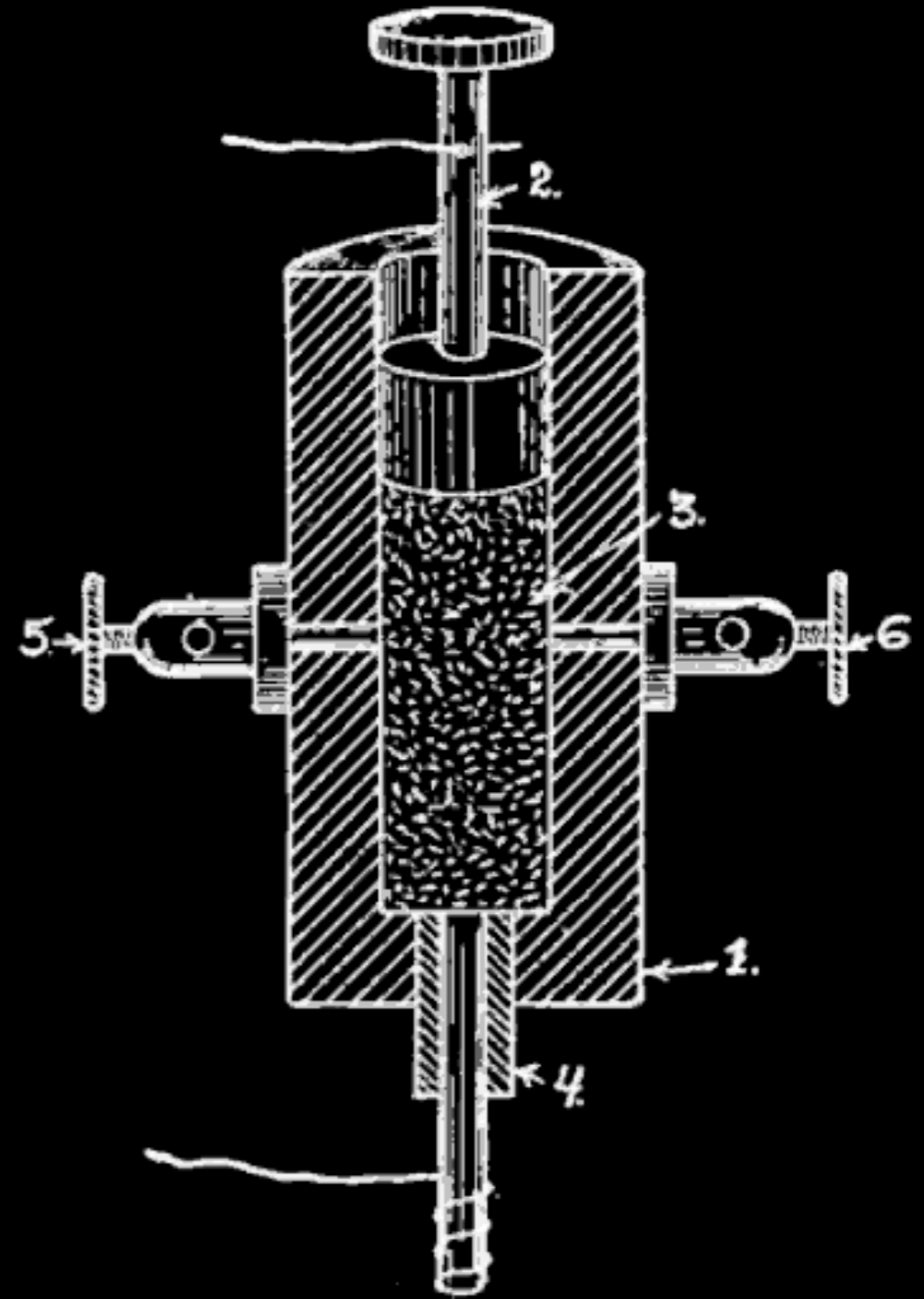
Marconi's "coherer" receiver



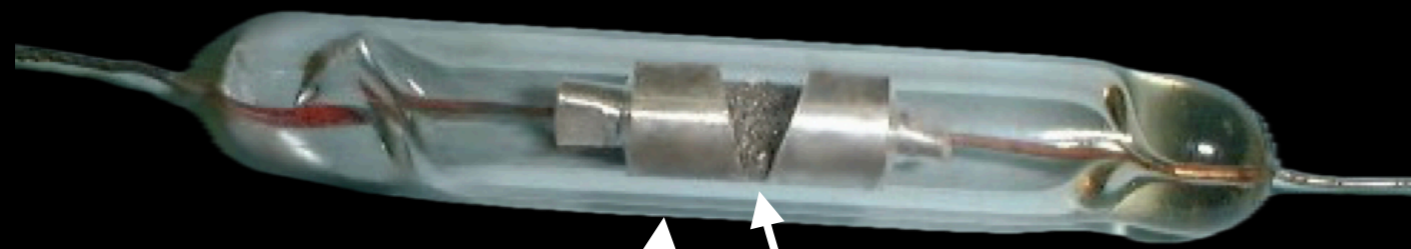
Marconi's "coherer" receiver



Metal contacts

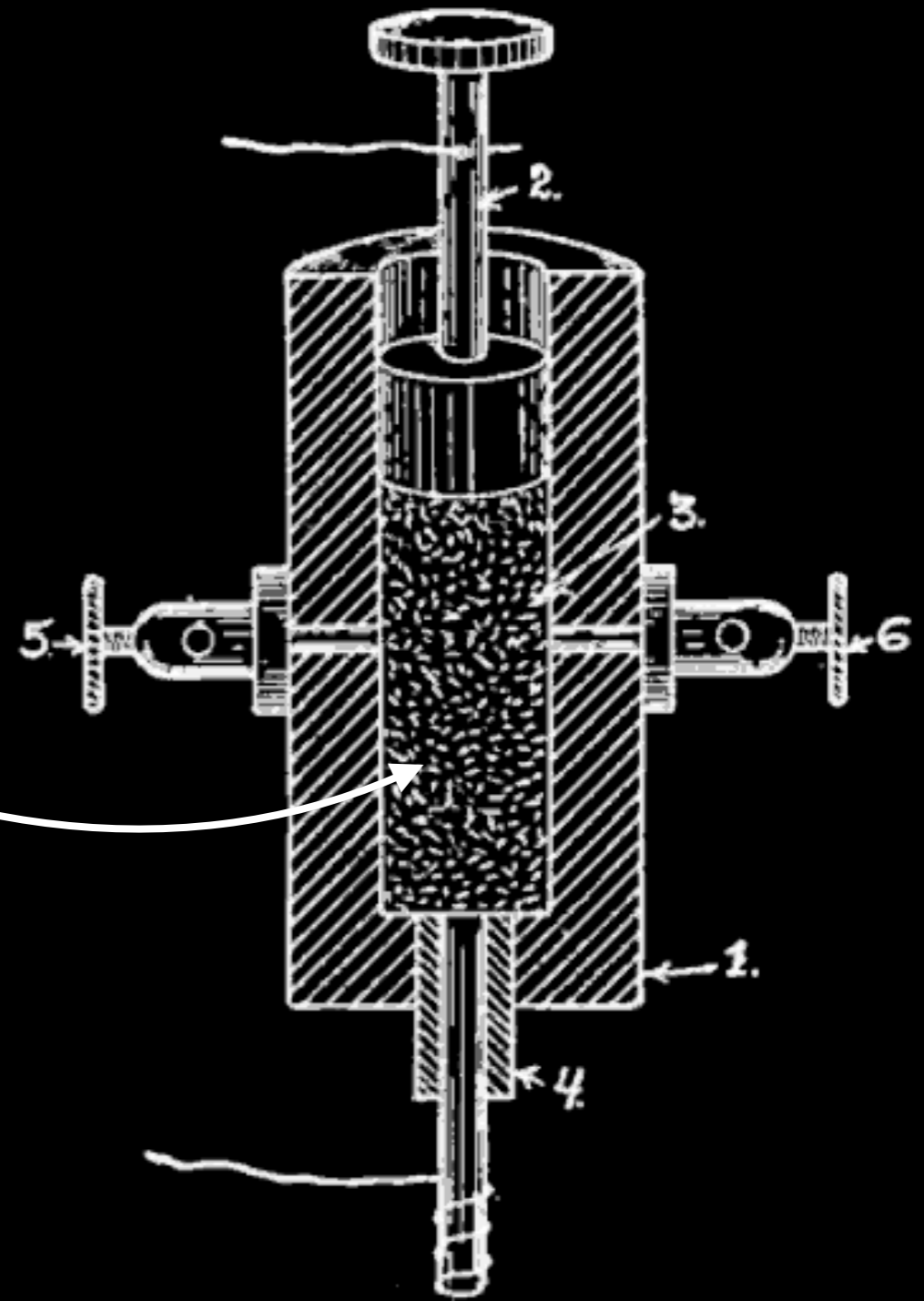


Marconi's "coherer" receiver

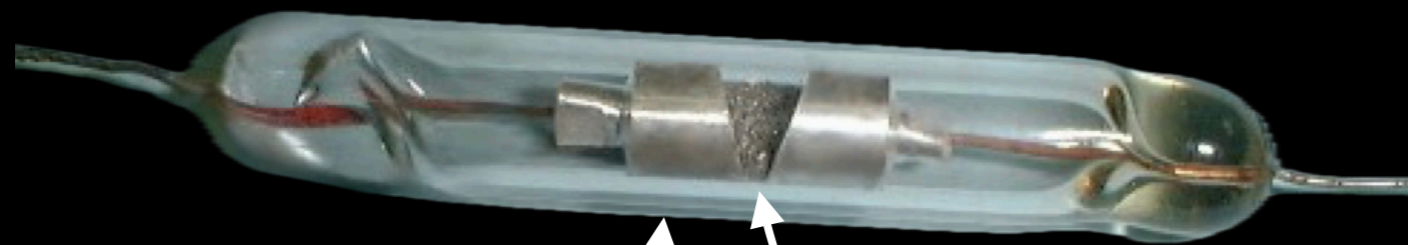


Metal contacts

Metal filings



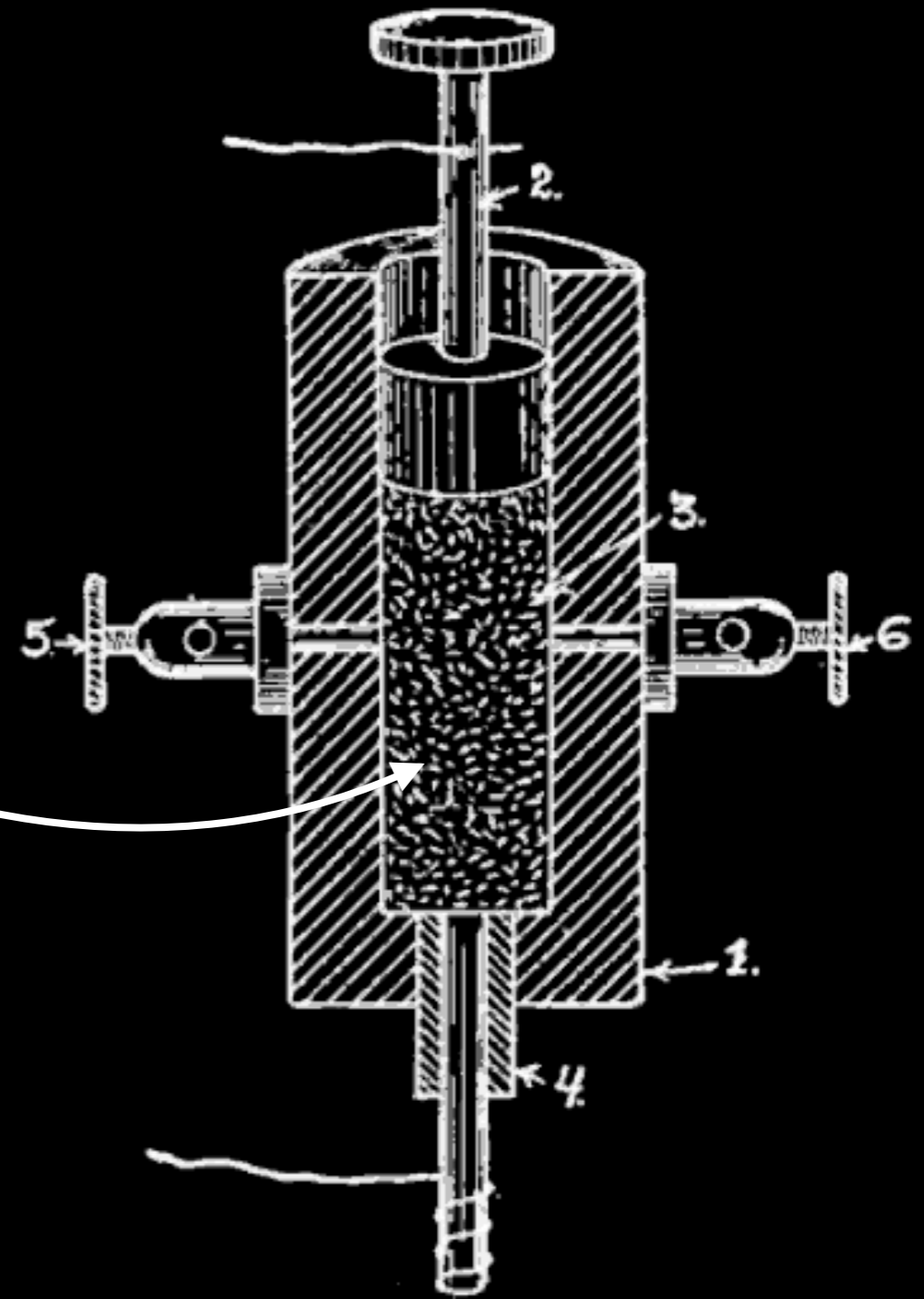
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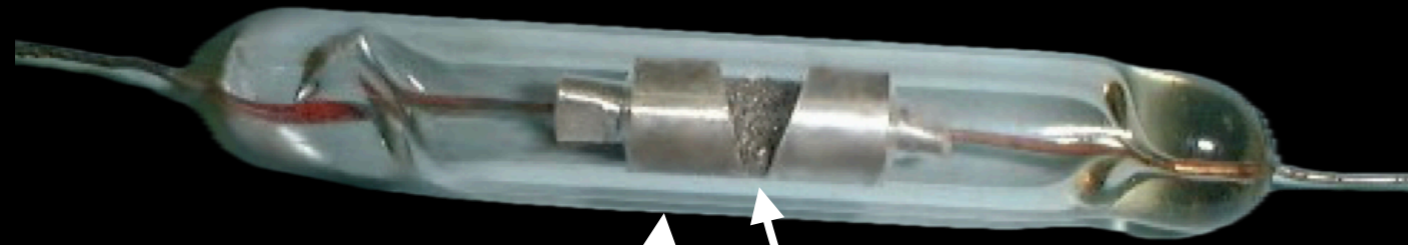
Metal contacts

Metal filings

Fast oscillations of "Hertzian waves" makes coherer conducting to non-oscillating currents ("direct current")



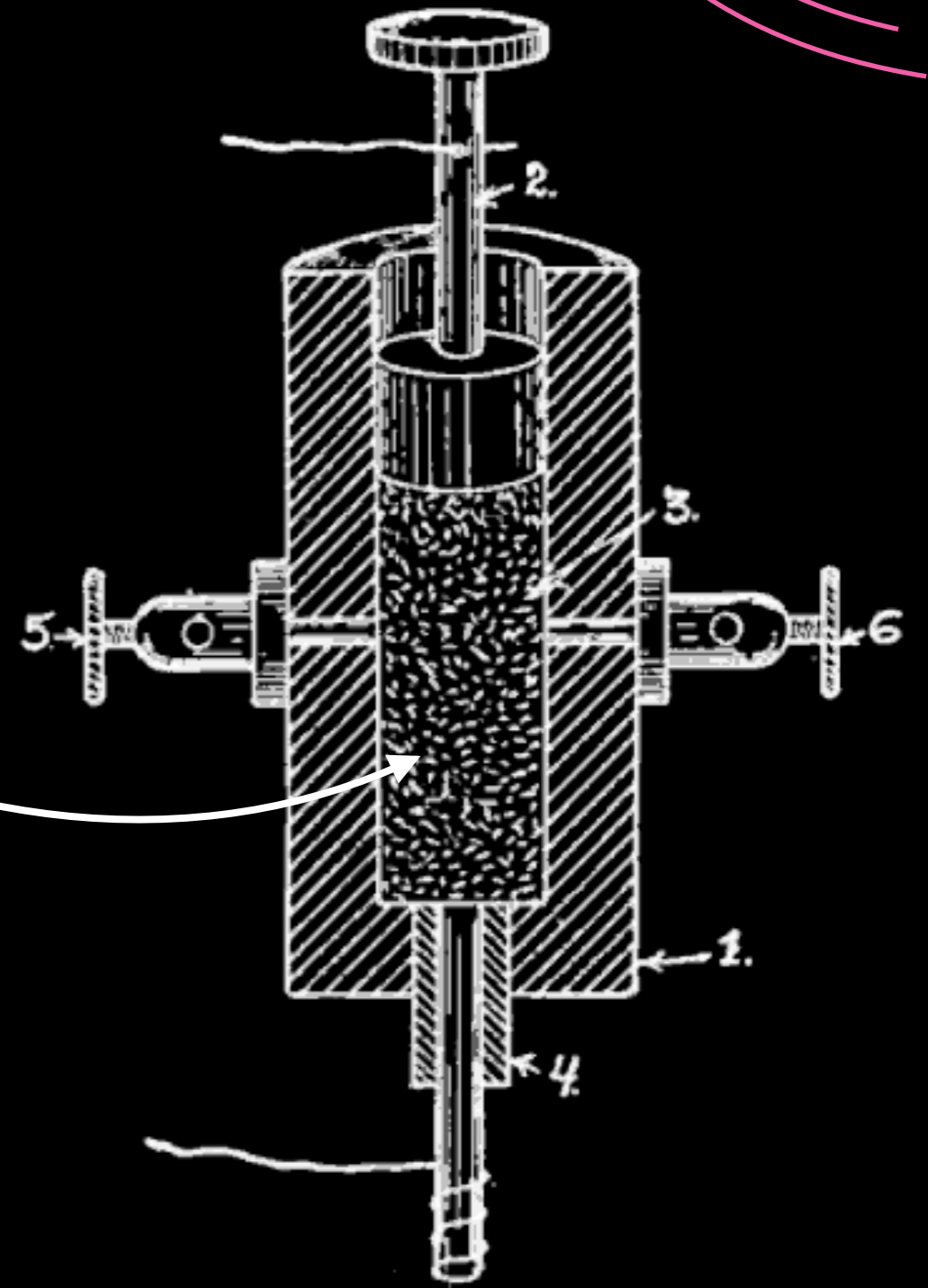
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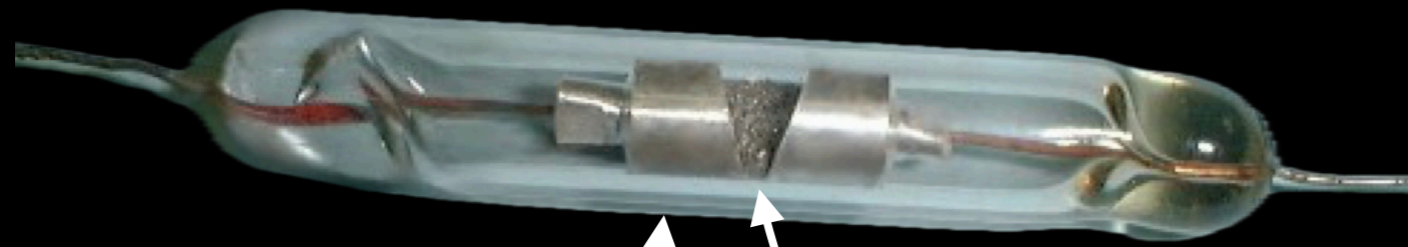
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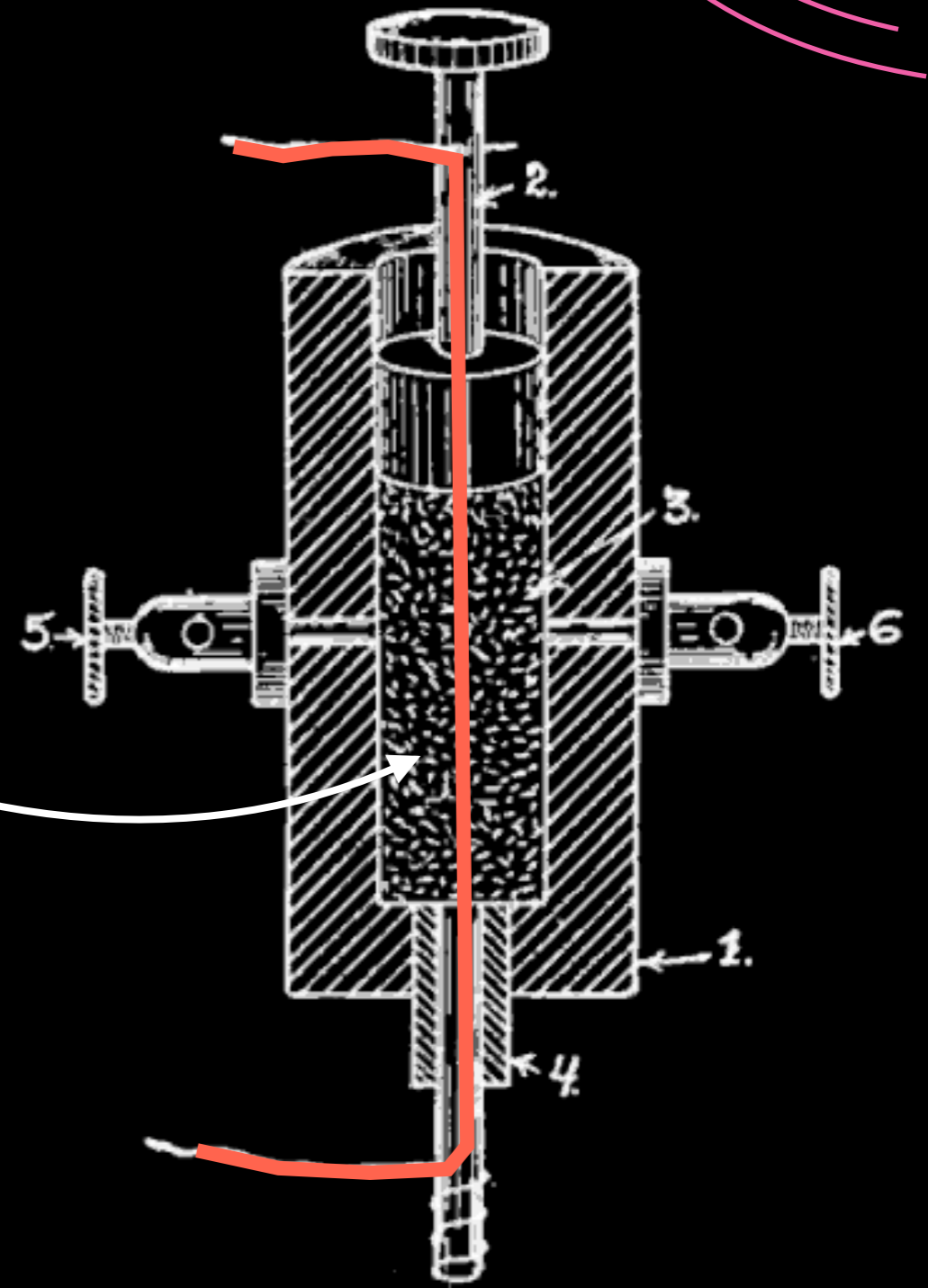
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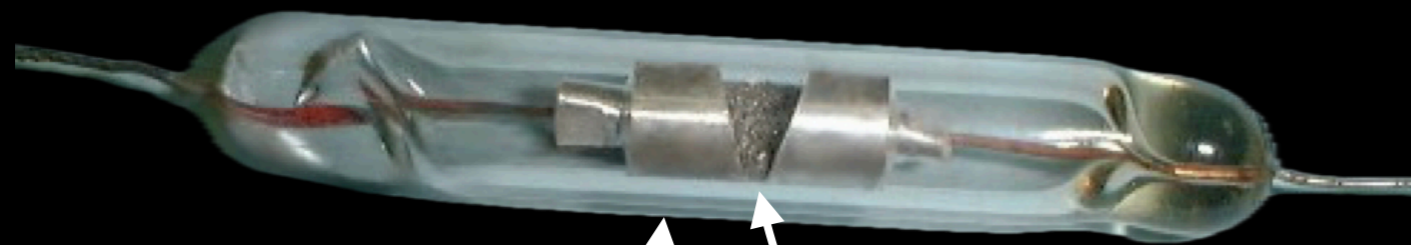
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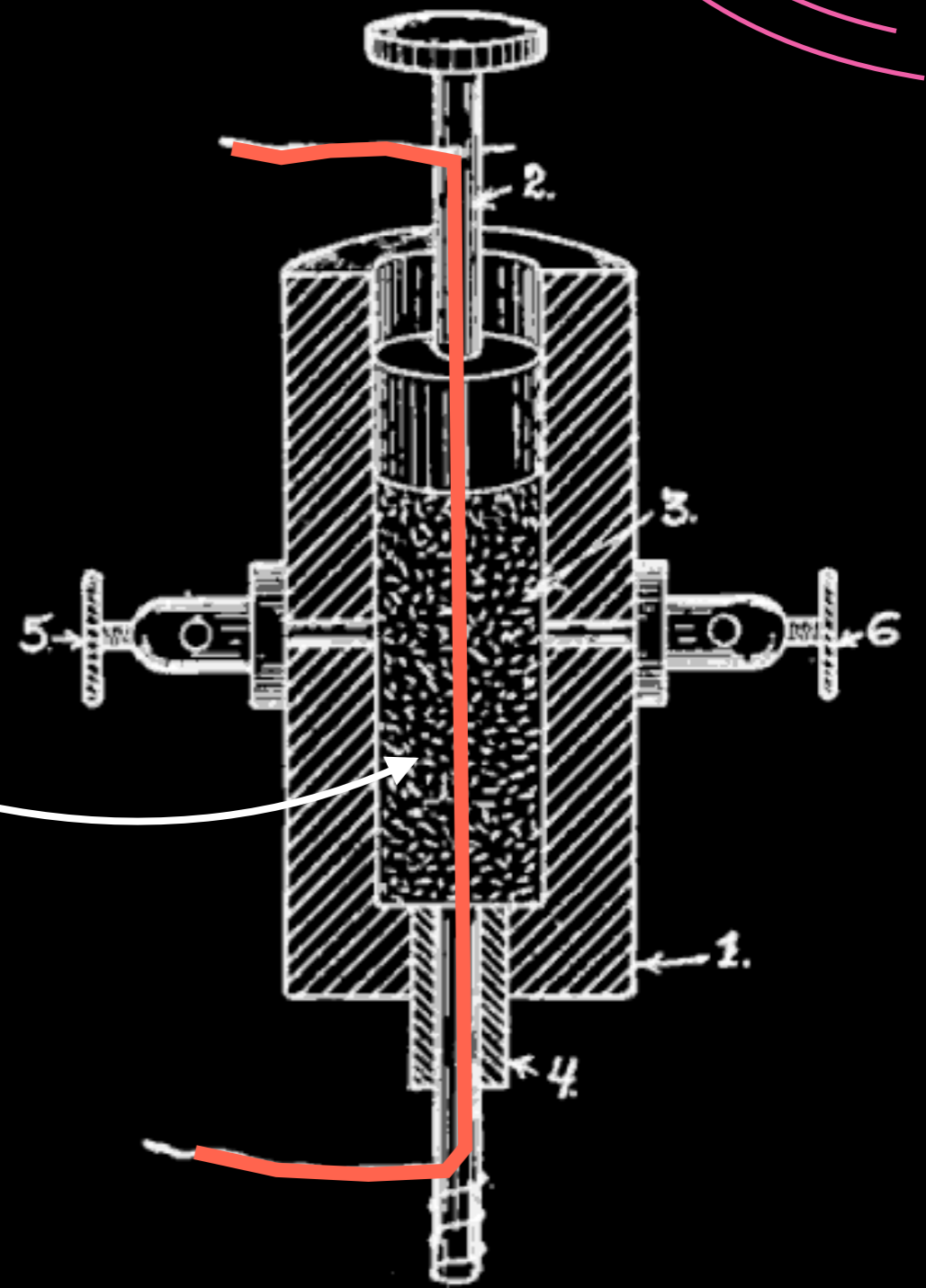


Metal contacts

Metal filings

Fast oscillations of "Hertzian waves" makes coherer conducting to non-oscillating currents ("direct current")

"The coherer was publicized as wonderful, and it was wonderfully erratic and bad. It would not work when it should, and it worked overtime when it should not have."



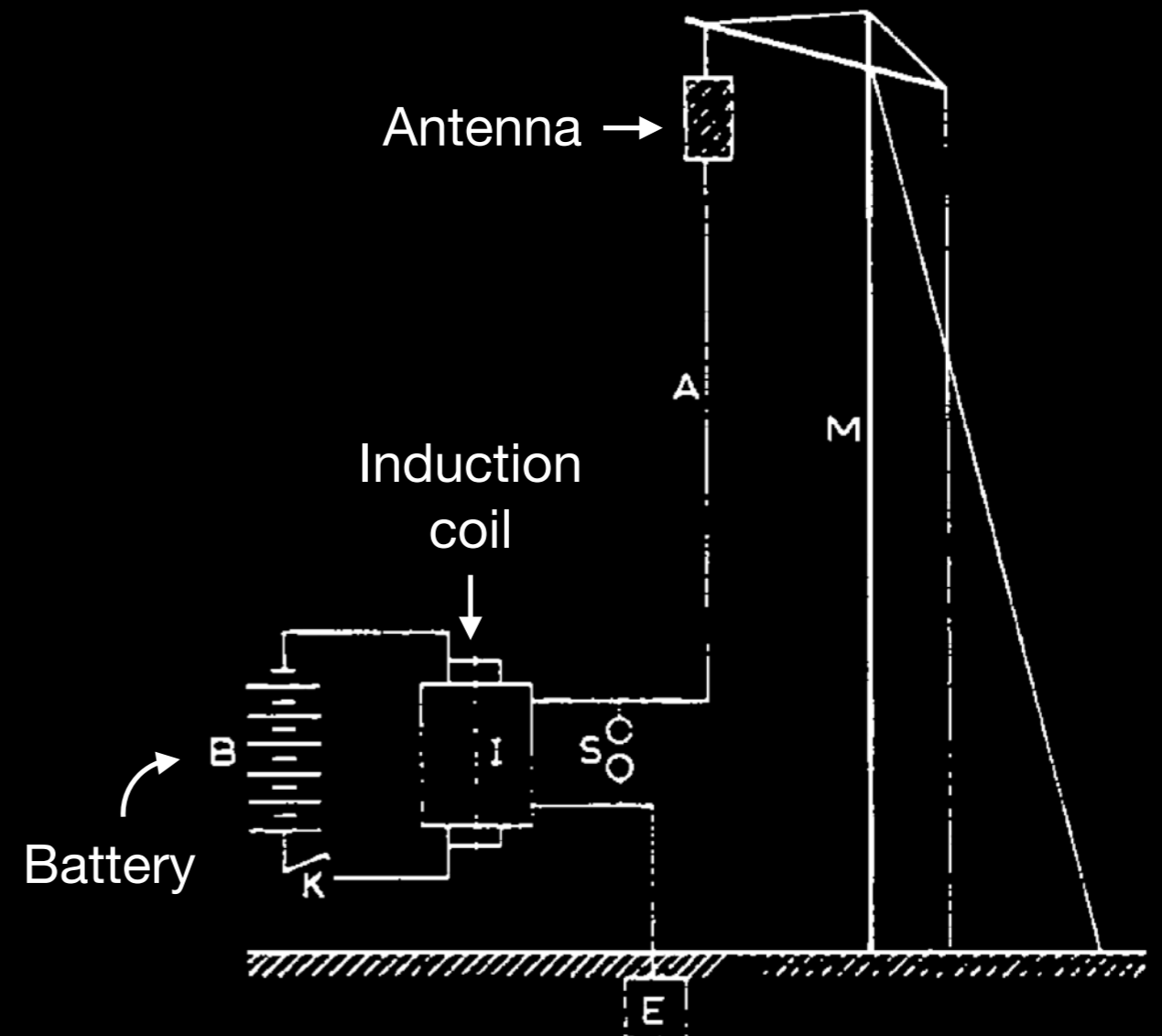
The first transmission stations

The first transmission stations

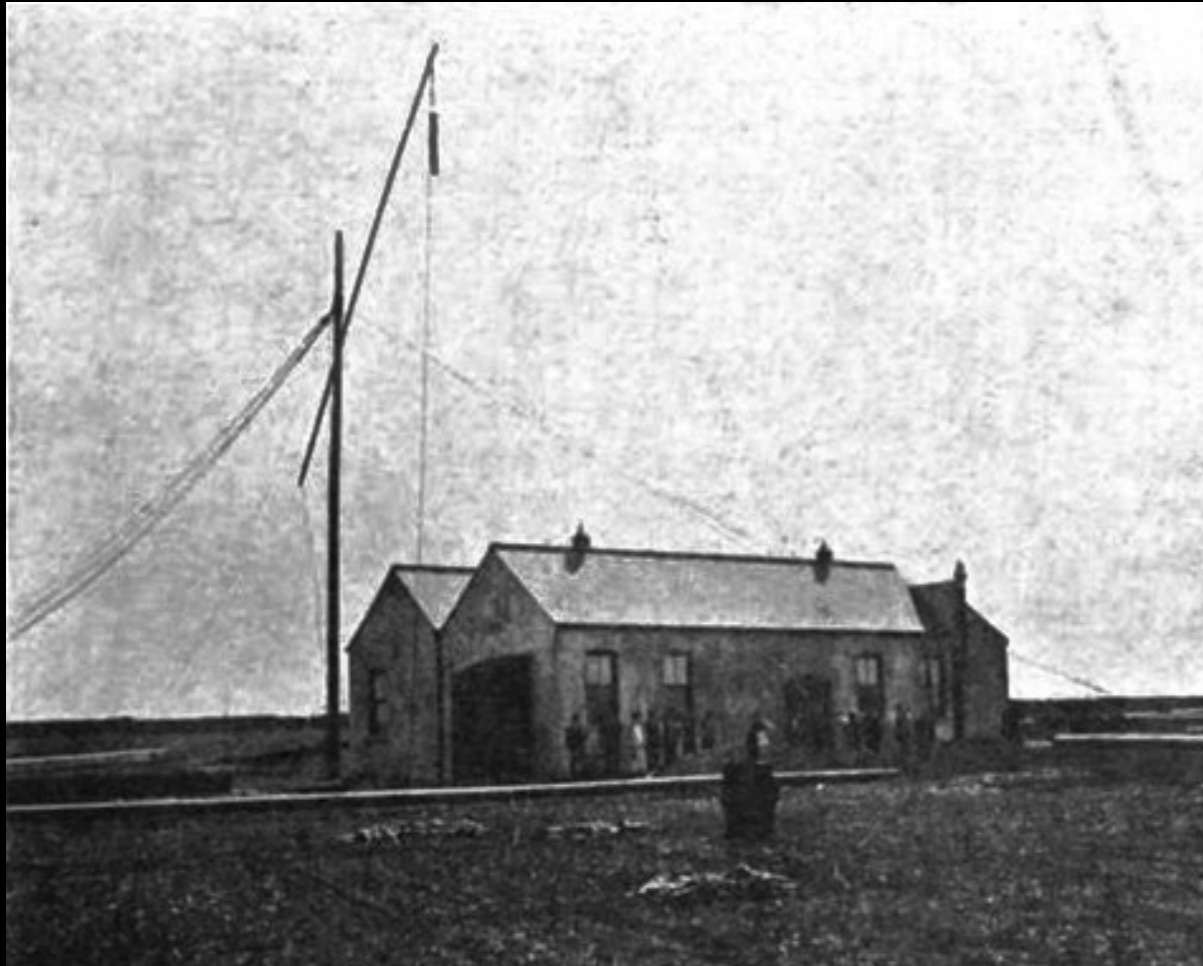
“In August 1895 I discovered a new arrangement which not only greatly increased the distance over which I could communicate ...”

The first transmission stations

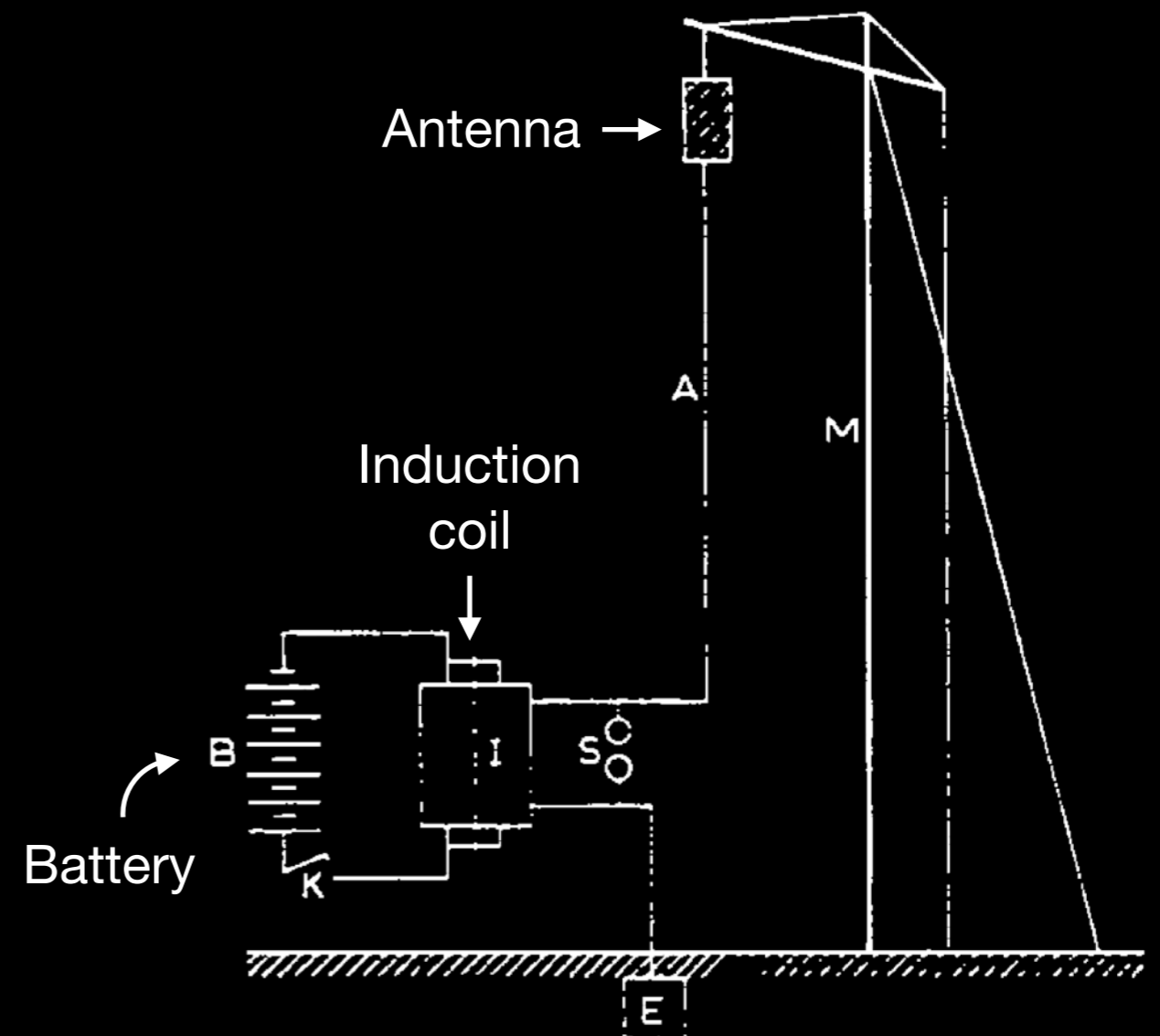
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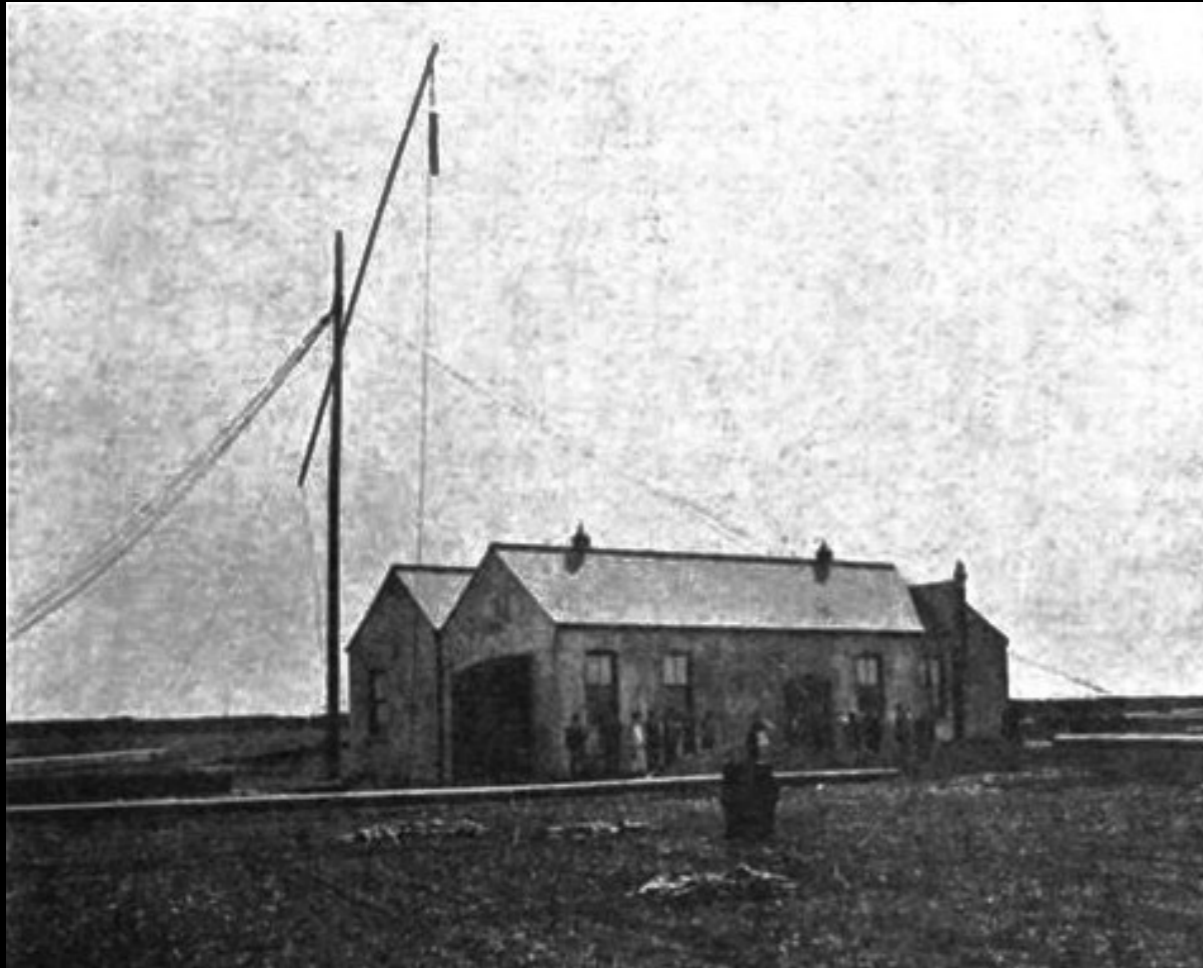
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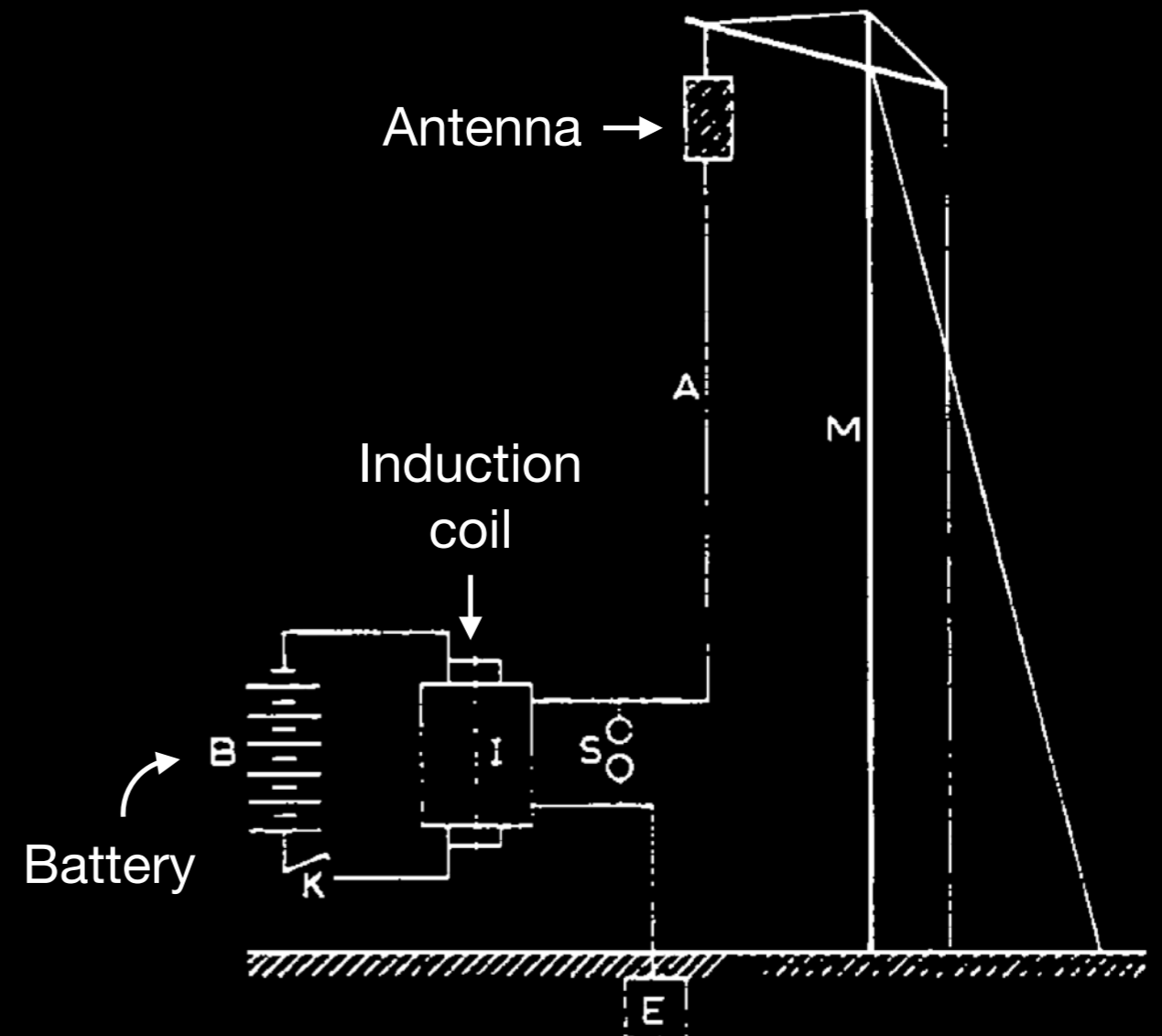


The first transmission stations



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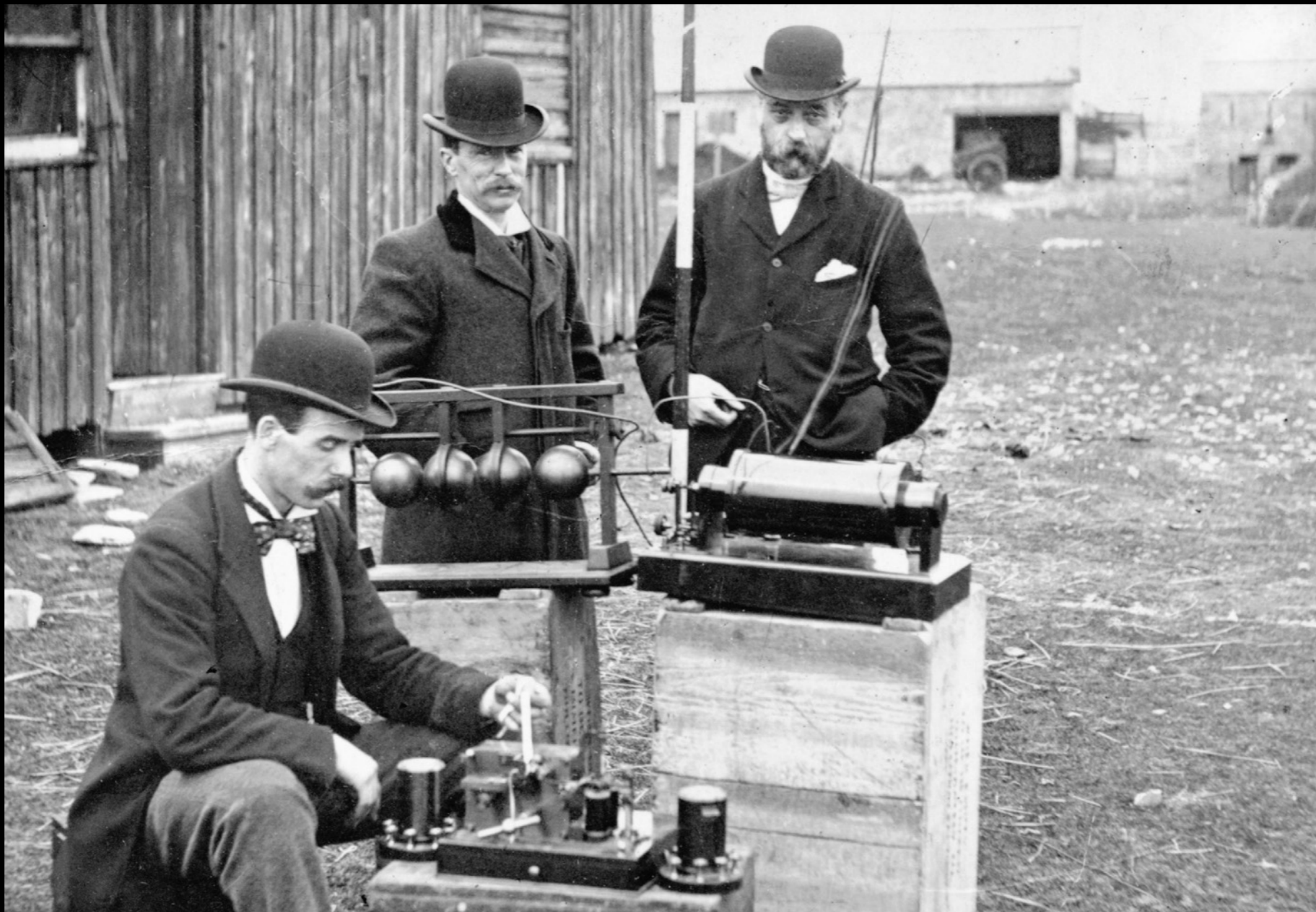
“... but also seemed to make the transmission independent from the effects of intervening obstacles.”



Scaling up

“The distance of communication was extended to 4 miles in March 1897 ...”

“... and in May of the same year to 9 miles.”



Bridging the English Channel

“After numerous tests and demonstrations, communication was established for the first time across the English Channel between England and France in March 1899.”

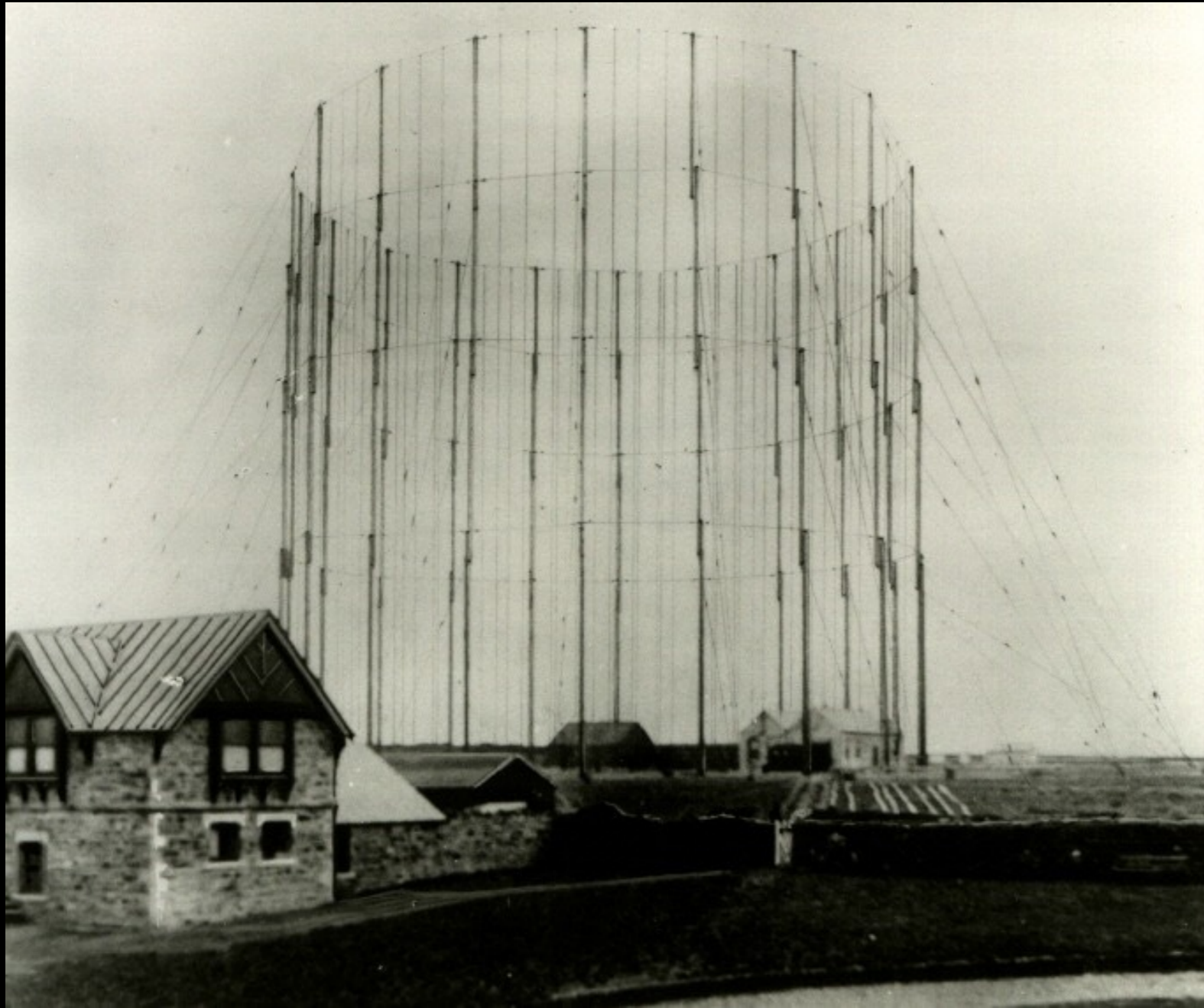


Transatlantic wireless telegraphy

December 12, 1901

*Only 43 years after the first
transatlantic cable!*

Transatlantic wireless telegraphy

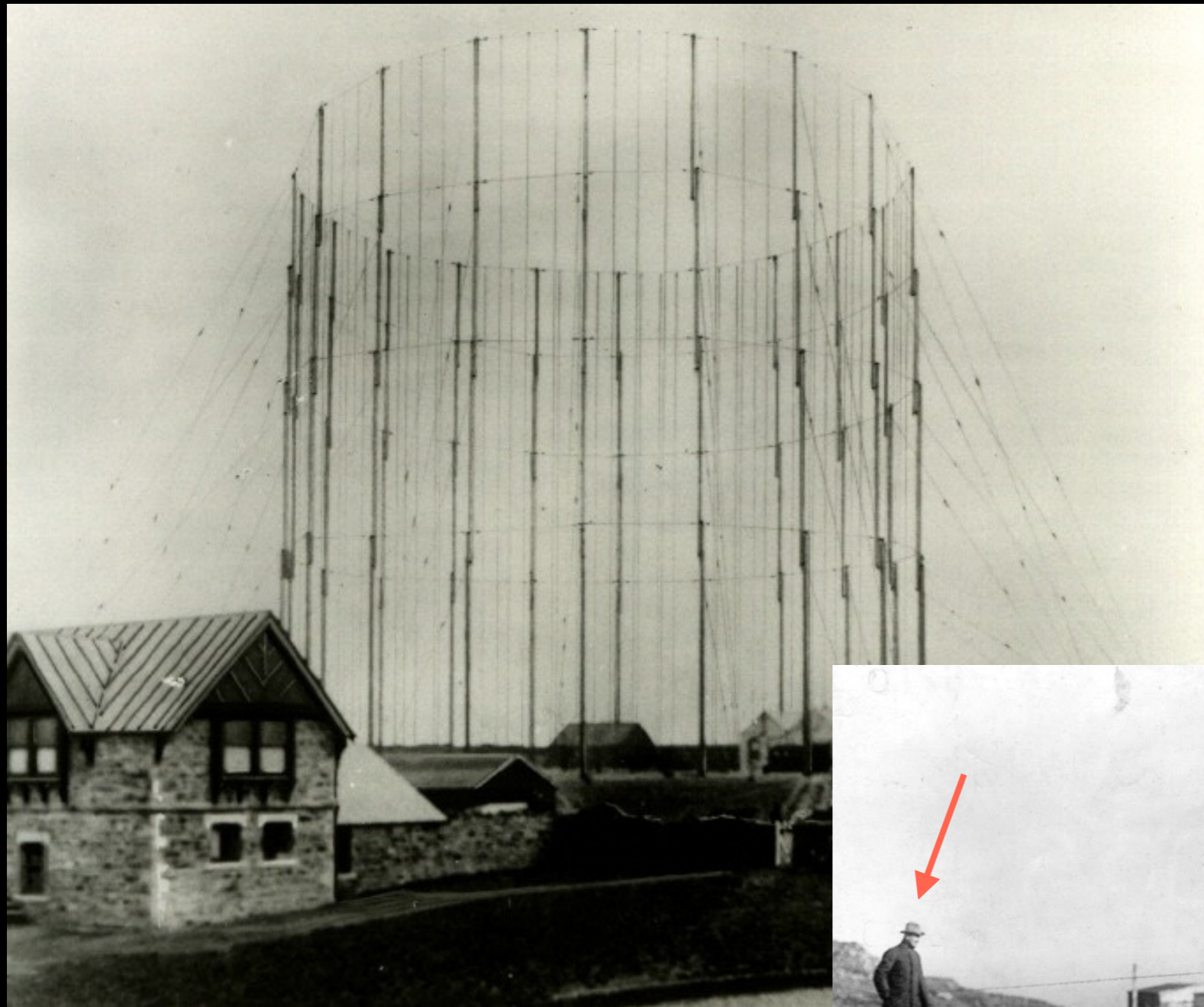


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*Only 43 years after the first
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Poldhu Wireless Station, England

Transatlantic wireless telegraphy



Poldhu Wireless Station, England

December 12, 1901

*Only 43 years after the first
transatlantic cable!*

St. John's, Newfoundland



And the rest is history ...

And the rest is history ...

**Pearl Street Station, New York City,
Edison Illuminating Company
1880-1901**



And the rest is history ...

**Pearl Street Station, New York City,
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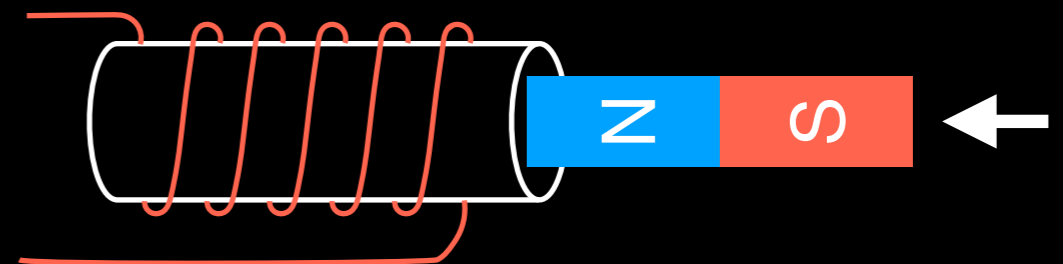
**Tennessee Centennial Exposition
1897**



And the rest is history ...

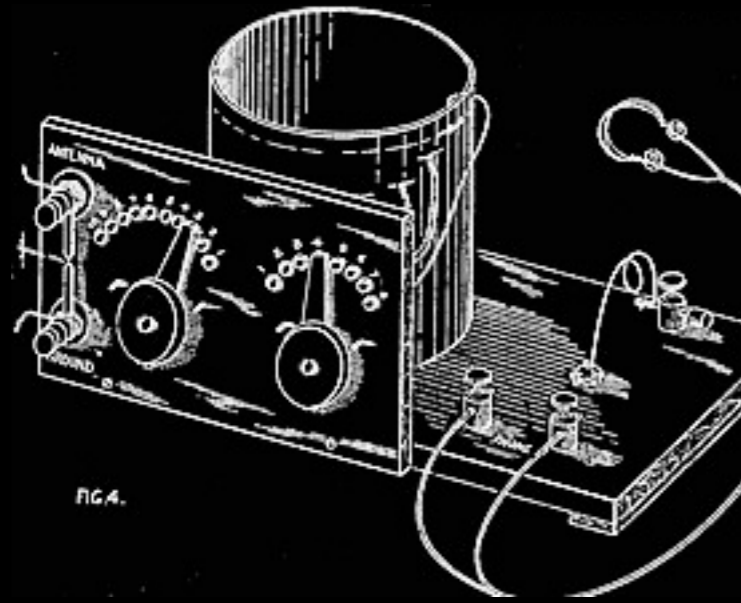
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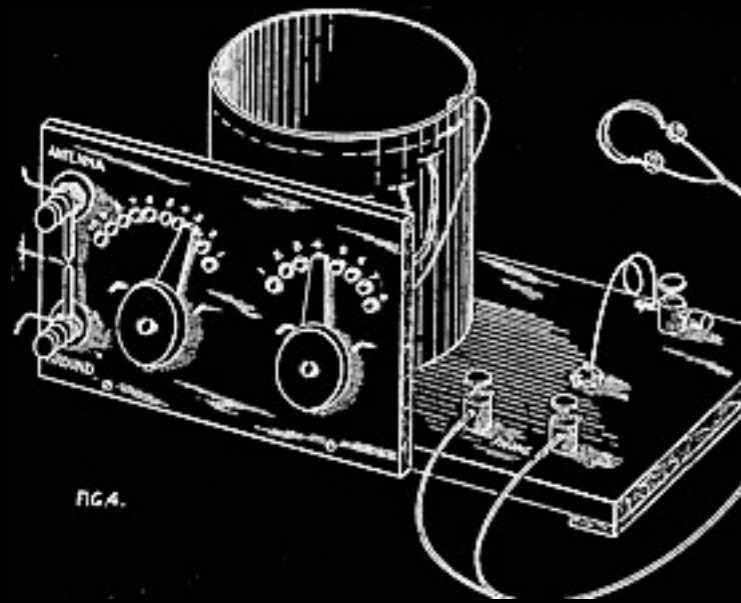
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And the rest is history



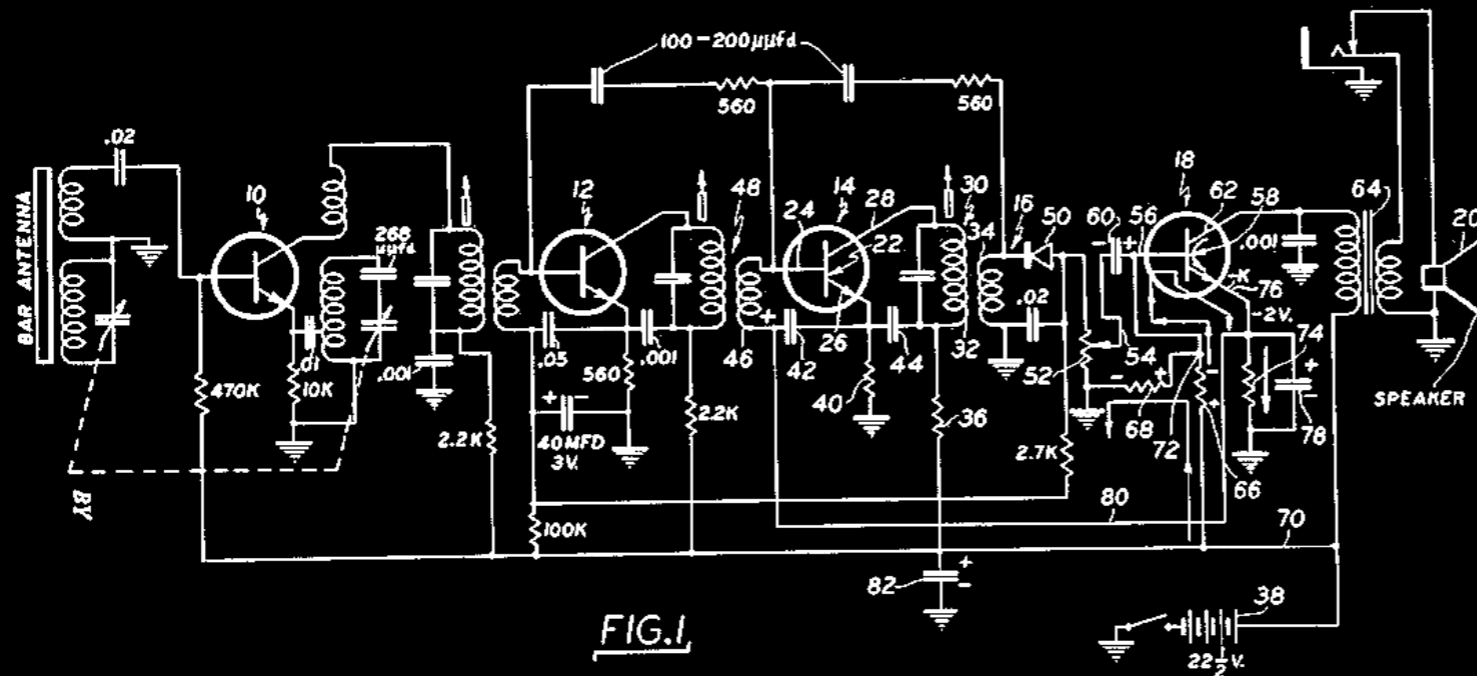
**US Patent: “Construction and Operation of a Simple
Homemade Radio Receiving Outfit”**
“Crystal receiver”, 1920

And the rest is history



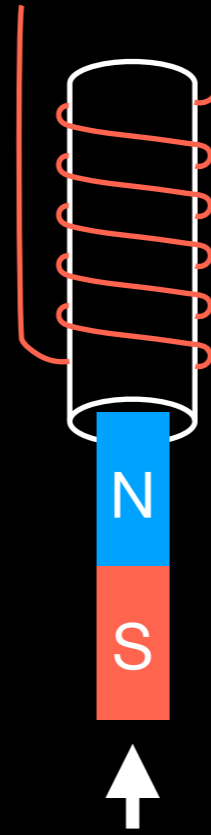
**US Patent: “Construction and Operation of a Simple
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“Crystal receiver”, 1920

First transistor radio
1954

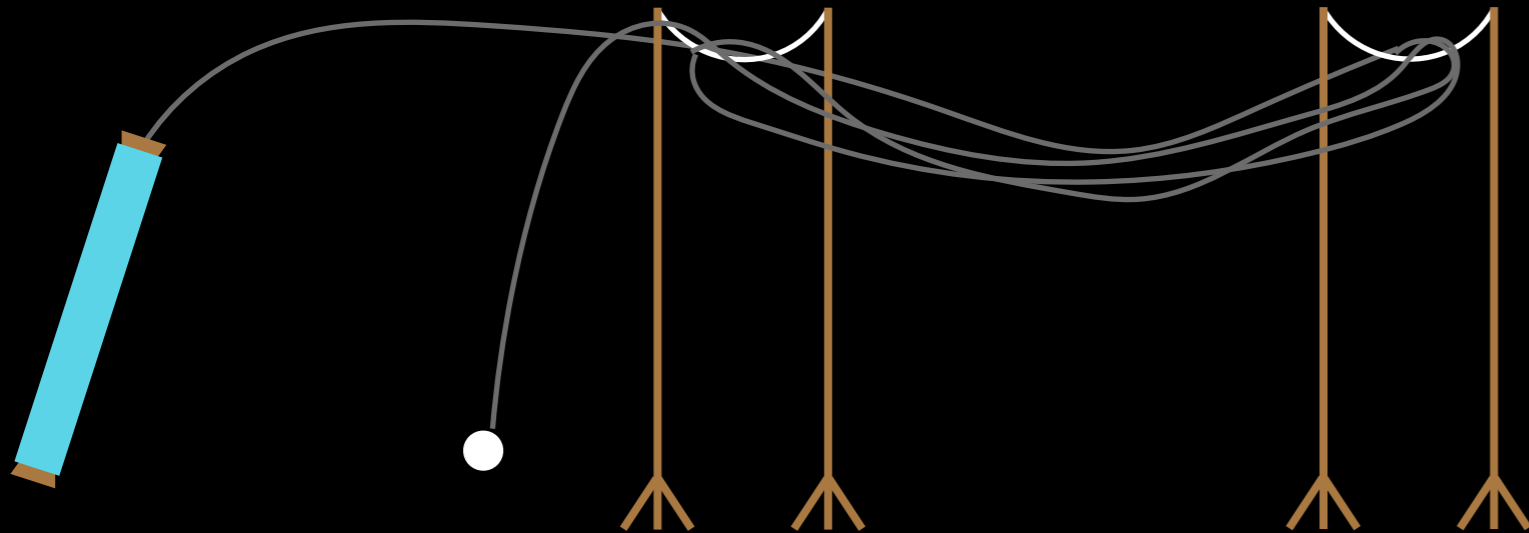
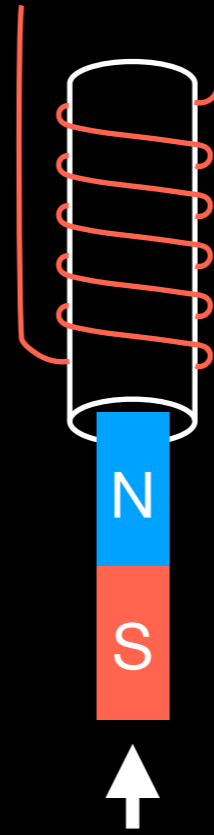


Electricity is everywhere

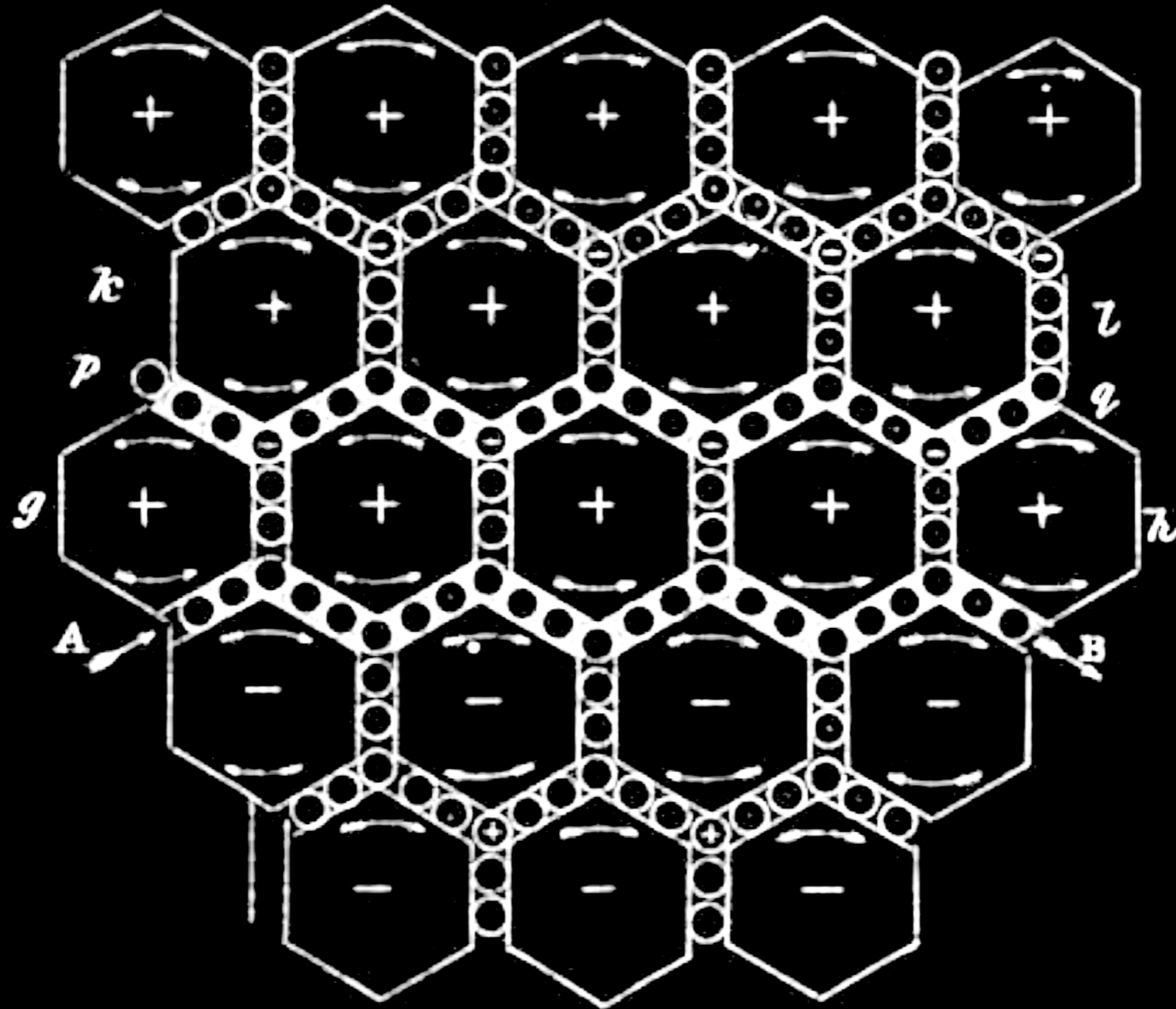
Electricity is everywhere



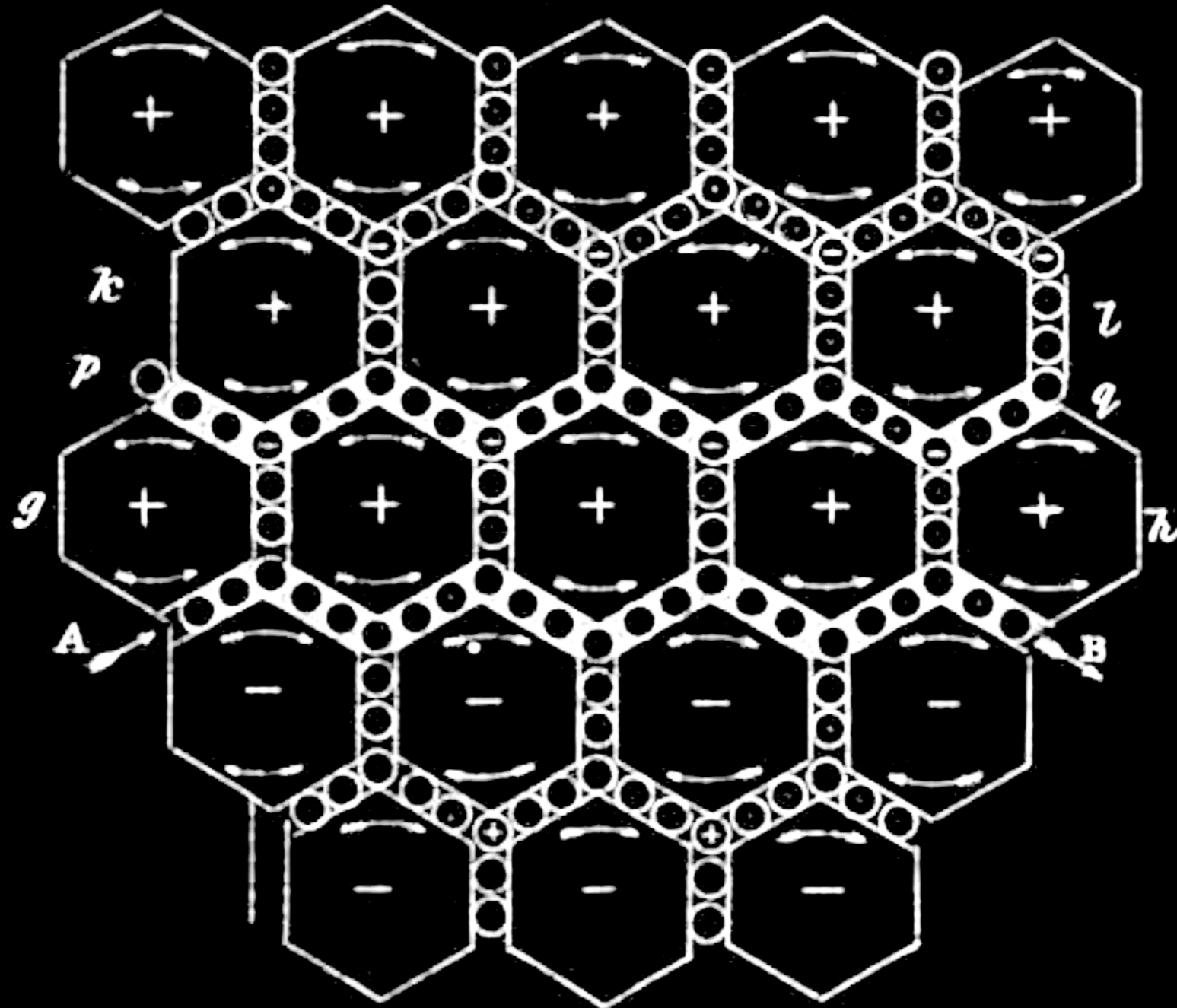
Electricity is everywhere



But what *is* the nature of electricity?



But what *is* the nature of electricity?



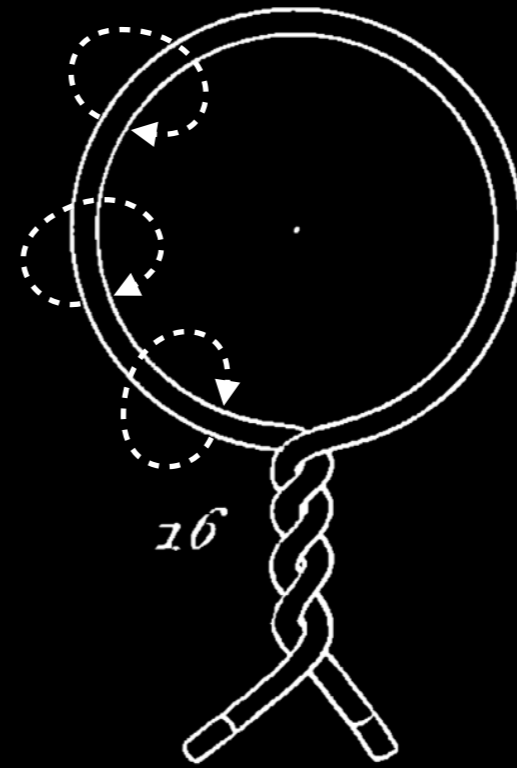
Is this all there is to it?

Back to Michael Faraday



Back to Michael Faraday

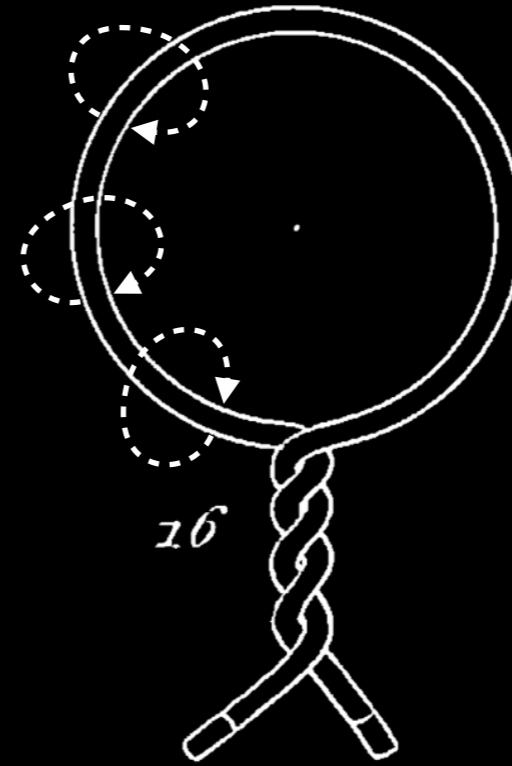
Magnetic "lines of force"



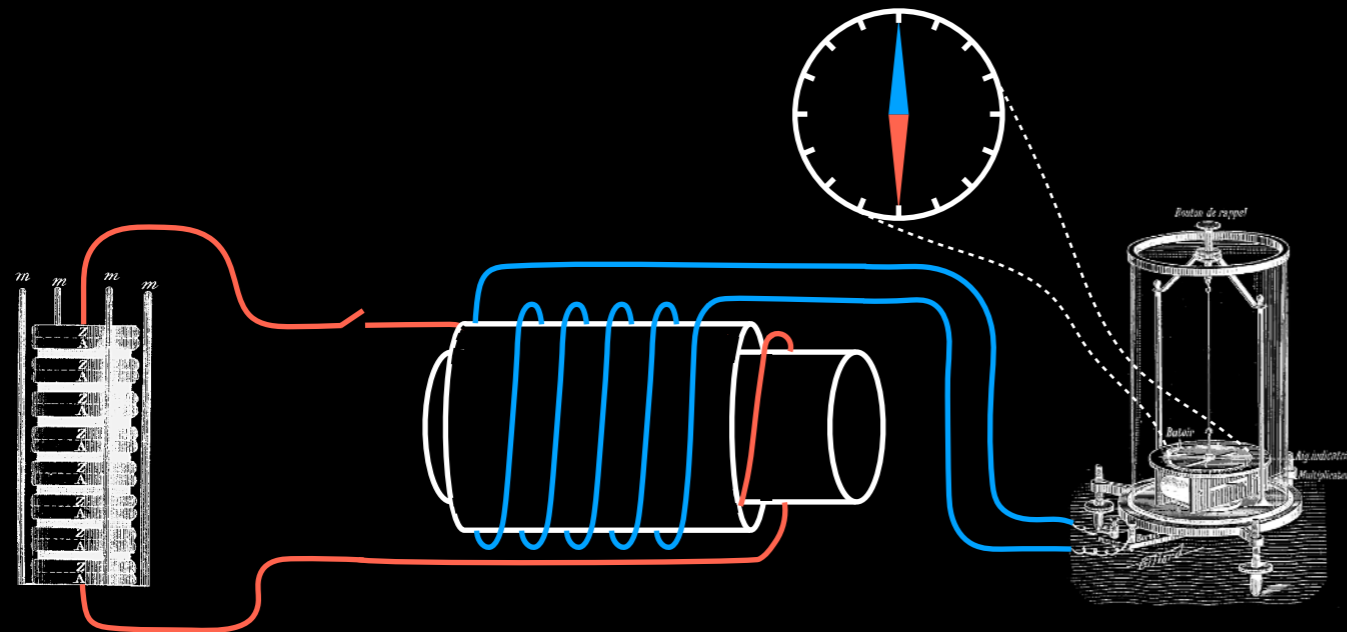
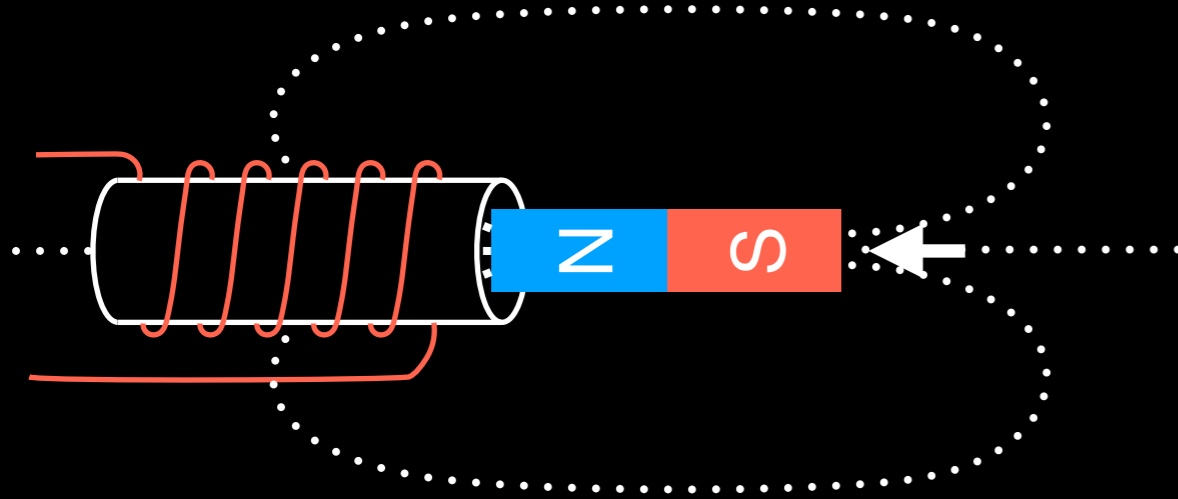
Back to Michael Faraday



Magnetic "lines of force"



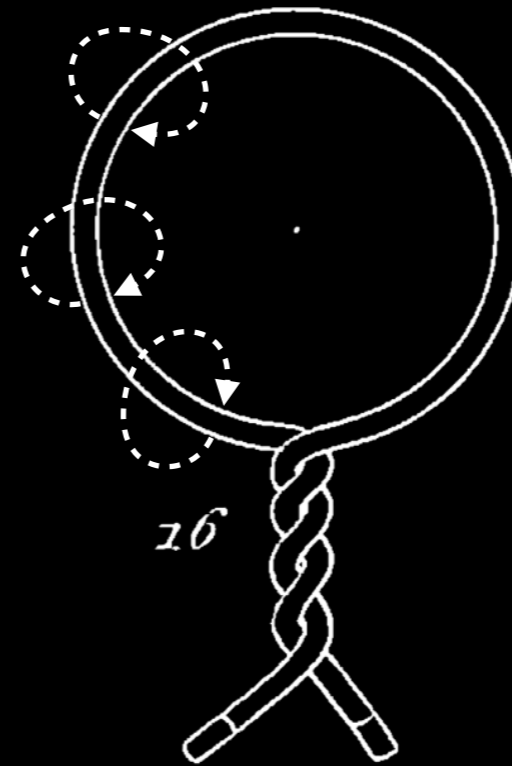
Electricity from magnetism in motion: *induction*



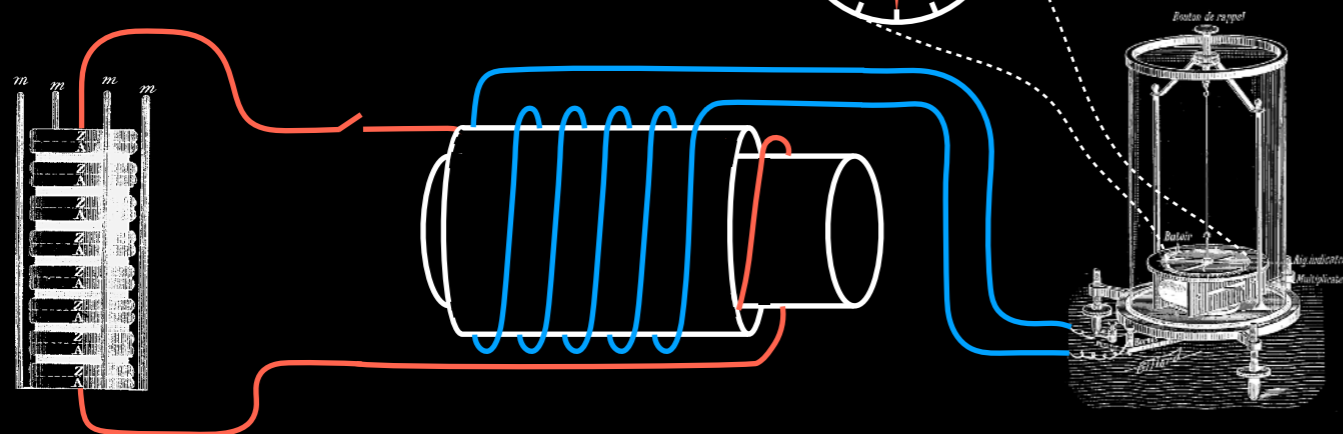
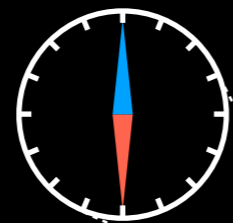
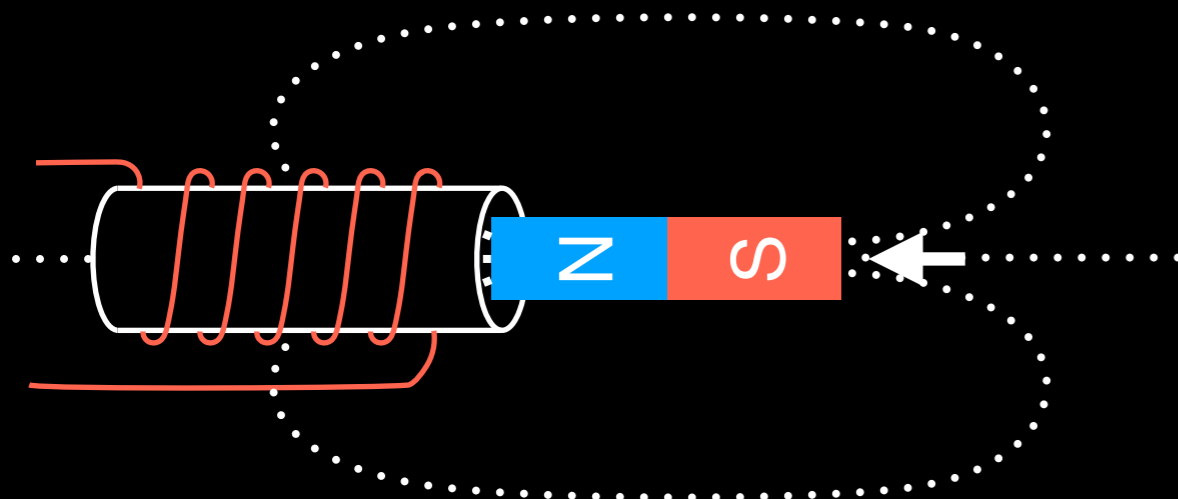
Back to Michael Faraday



Magnetic "lines of force"



Electricity from magnetism in motion: *induction*



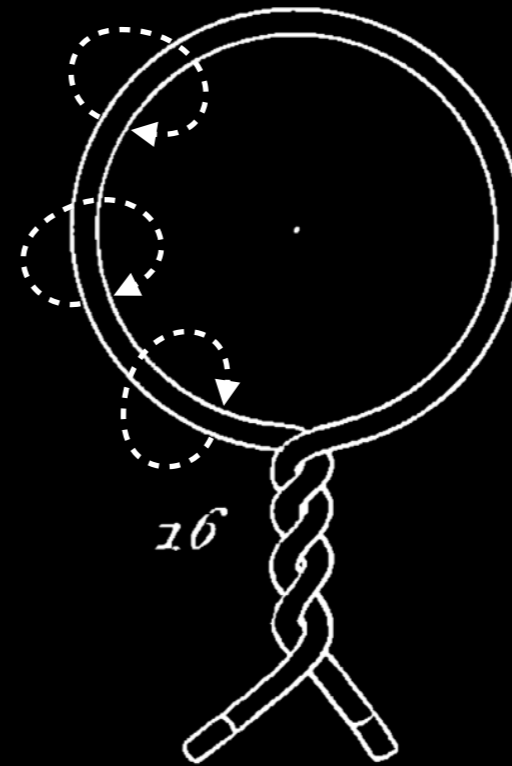
	Physiological Effects.	Magnetic Deflection.	Magnets made.	Spark.	Heating Power.	Attraction and Repulsion.	Discharge by Hot Air.
Voltaic electricity	×	×	×	×	×	×	×
Common electricity...	×	×	×	×	×	×	×
Magneto-Electricity..	×	×	×	×	×	×	
Animal Electricity...	×	×	×	+	+		

One kind of electricity

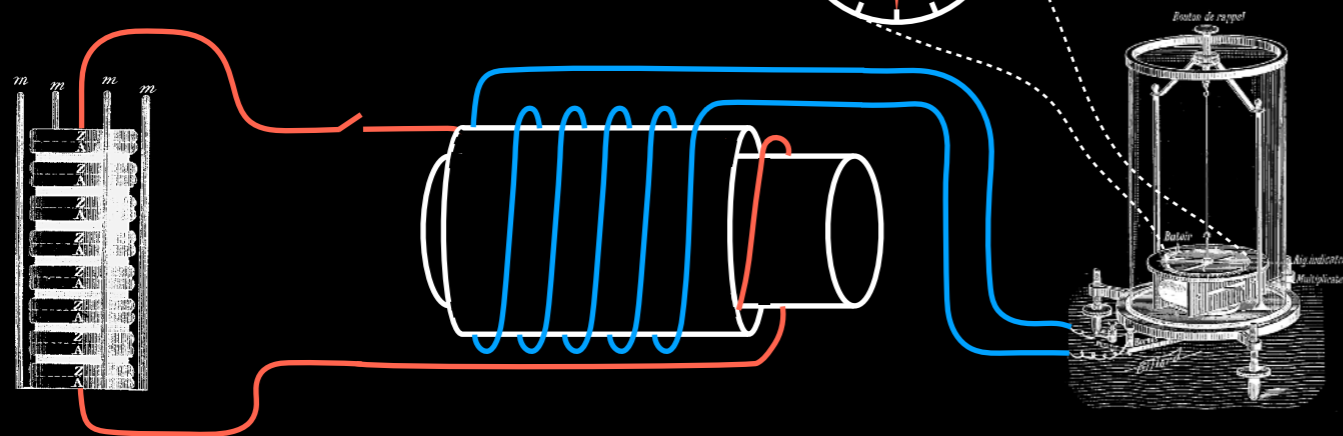
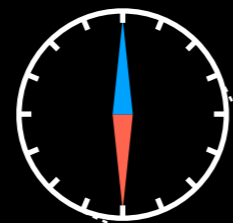
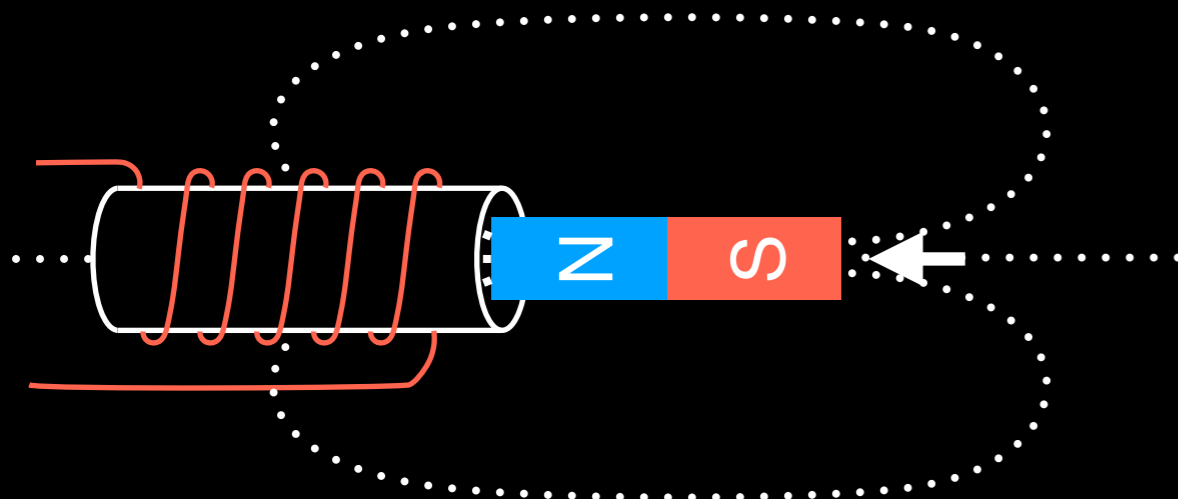
Back to Michael Faraday



Magnetic "lines of force"



Electricity from magnetism in motion: *induction*



	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	+	+		

One kind of electricity

Electrical sparks

Electrical sparks

“If two conducting surfaces in opposite states of electricity are brought nearer to each other, a spark at last appears.”



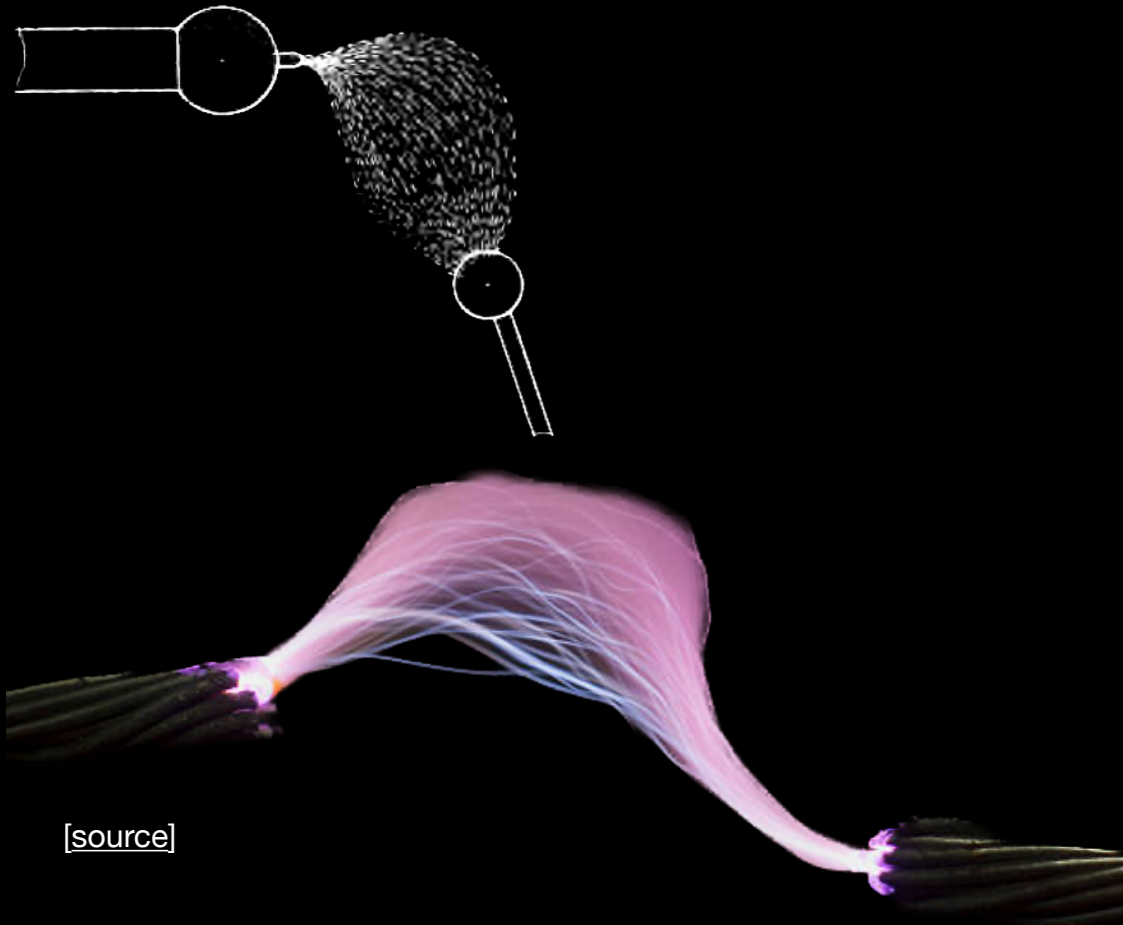
[source]

Electrical sparks

“If two conducting surfaces in opposite states of electricity are brought nearer to each other, a spark at last appears.”



“Some results obtained with brass balls were exceedingly interesting.”



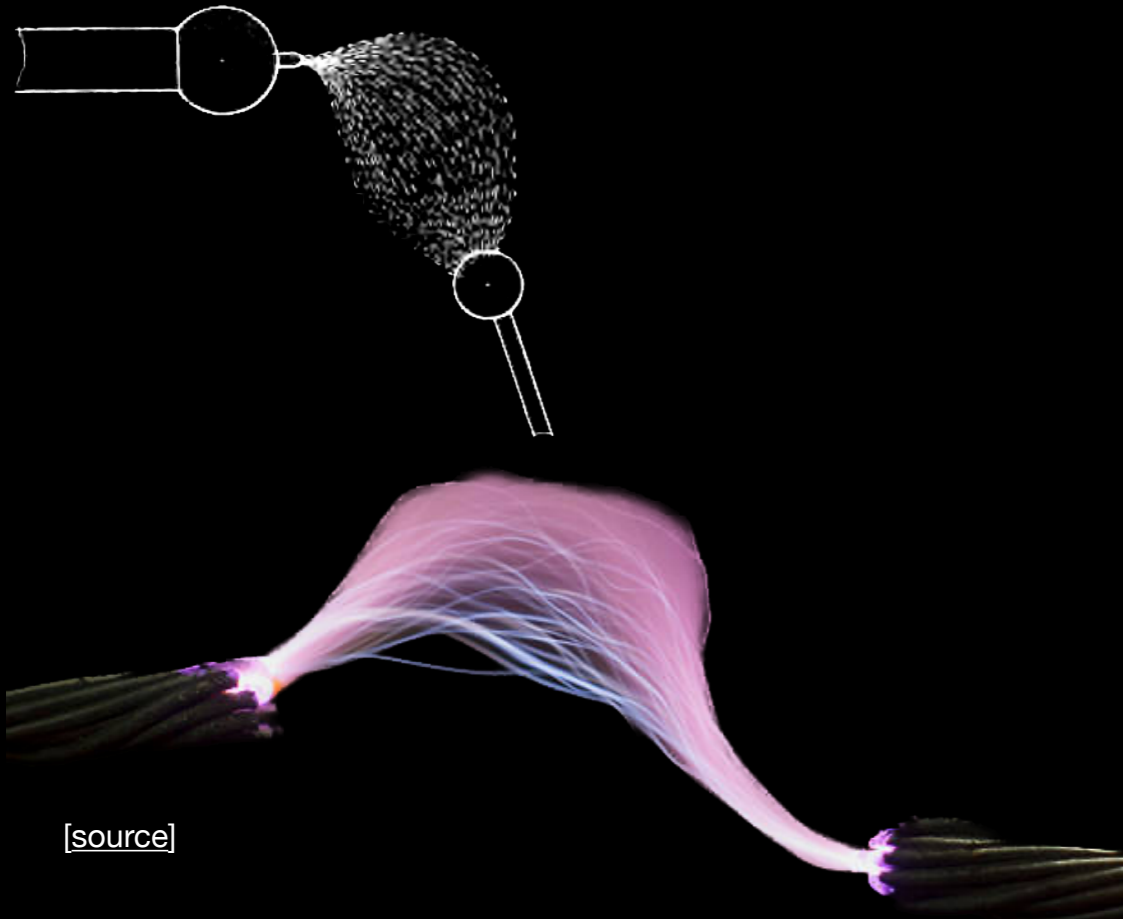
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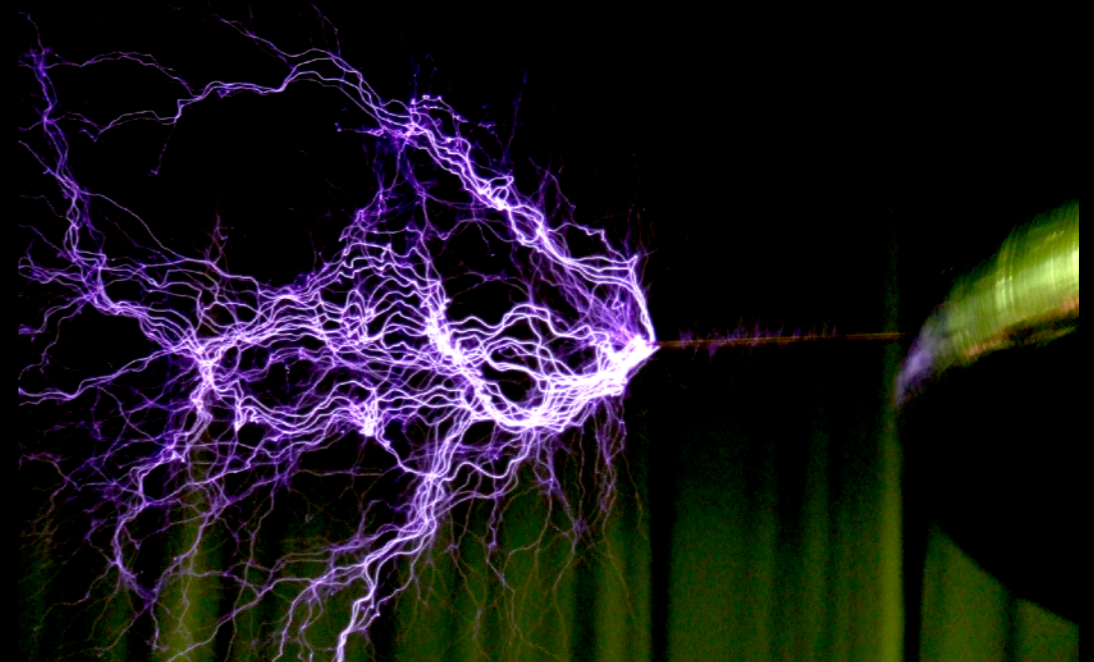
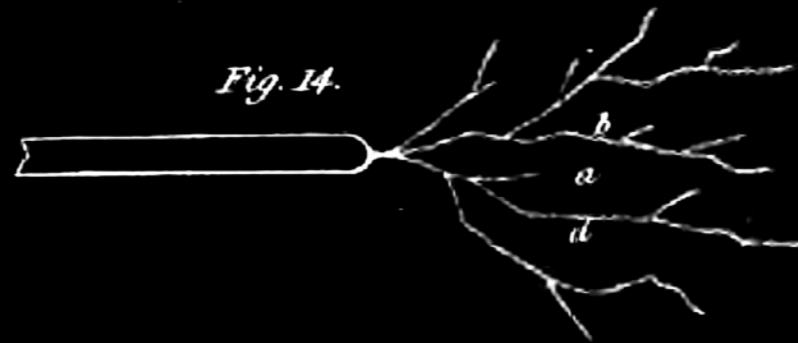
[source]

“Some results obtained with brass balls were exceedingly interesting.”



[source]

“The discharge is from the end of the rod outwards, in diverging lines towards the distant conductors, as the walls of the room, etc.”



Electricity in “rarefied” gases

1838

*“Rarefaction of the air wonderfully favors
the glow phenomena.”*

Electricity in “rarefied” gases

1838

“Rarefaction of the air wonderfully favors the glow phenomena.”

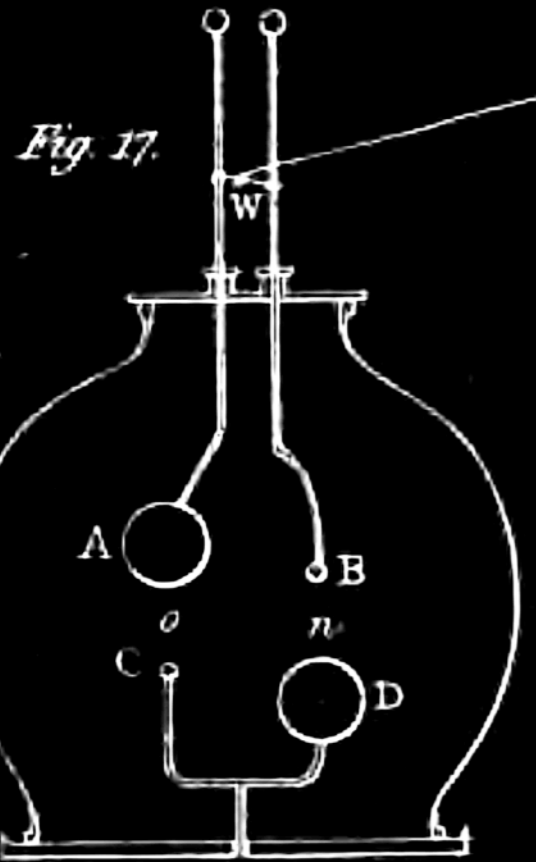


“A brass ball, being made positively electric in an air pump receiver could be covered all over with this light.”

Electricity in “rarefied” gases

1838

“Rarefaction of the air wonderfully favors the glow phenomena.”

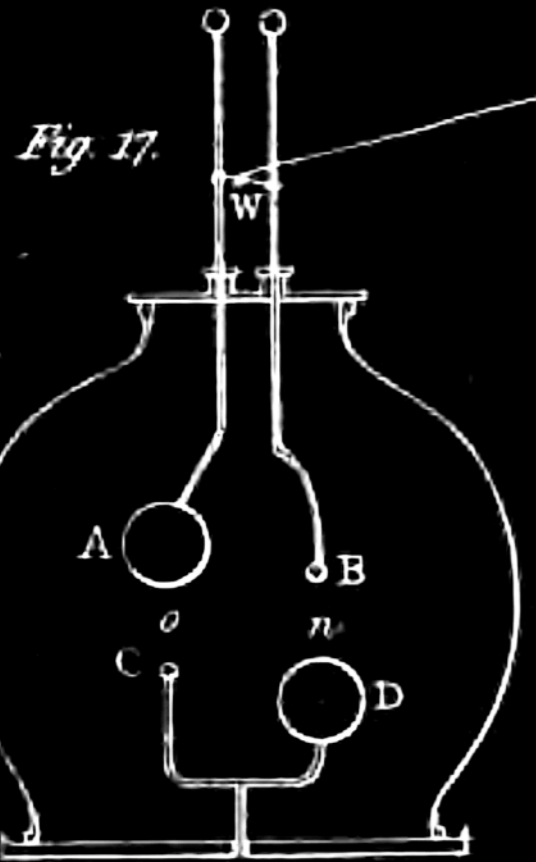


“A brass ball, being made positively electric in an air pump receiver could be covered all over with this light.”

Electricity in “rarefied” gases

1838

“Rarefaction of the air wonderfully favors the glow phenomena.”

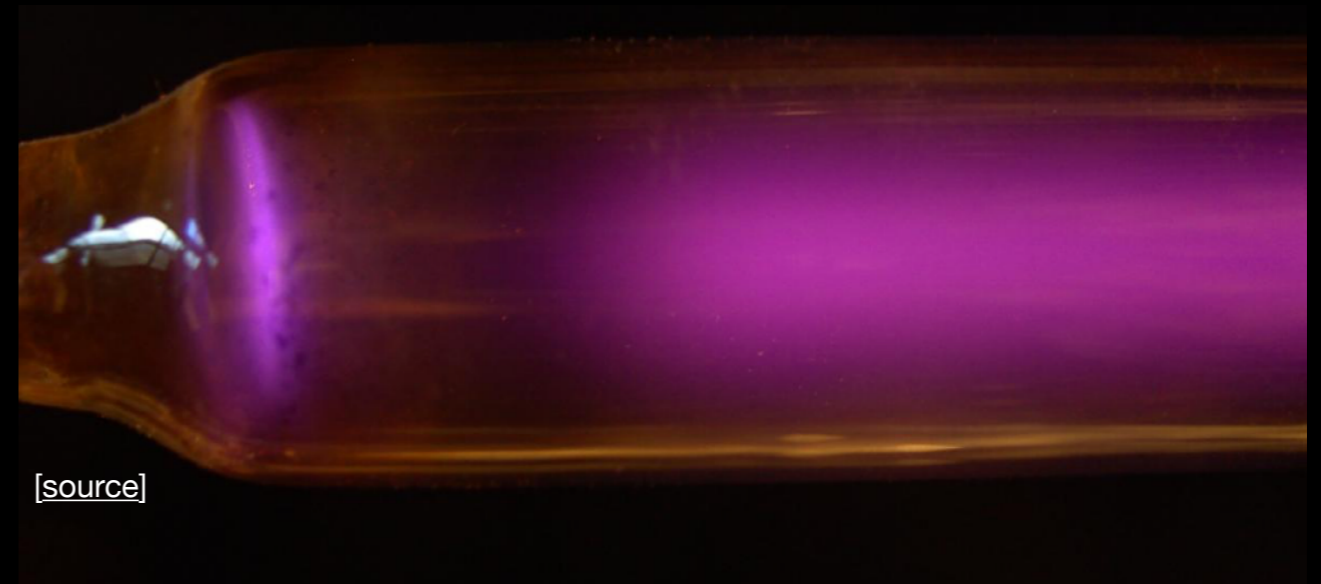


“A brass ball, being made positively electric in an air pump receiver could be covered all over with this light.”

Fig. 19.



“When two balls were used in a large air pump receiver, with the rarefaction high, the dark space appeared.”

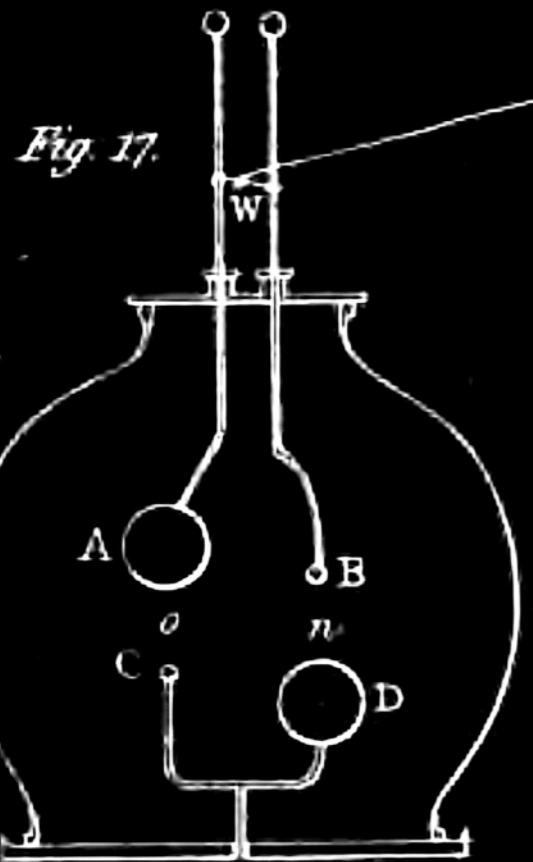


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Electricity in “rarefied” gases

1838

“Rarefaction of the air wonderfully favors the glow phenomena.”

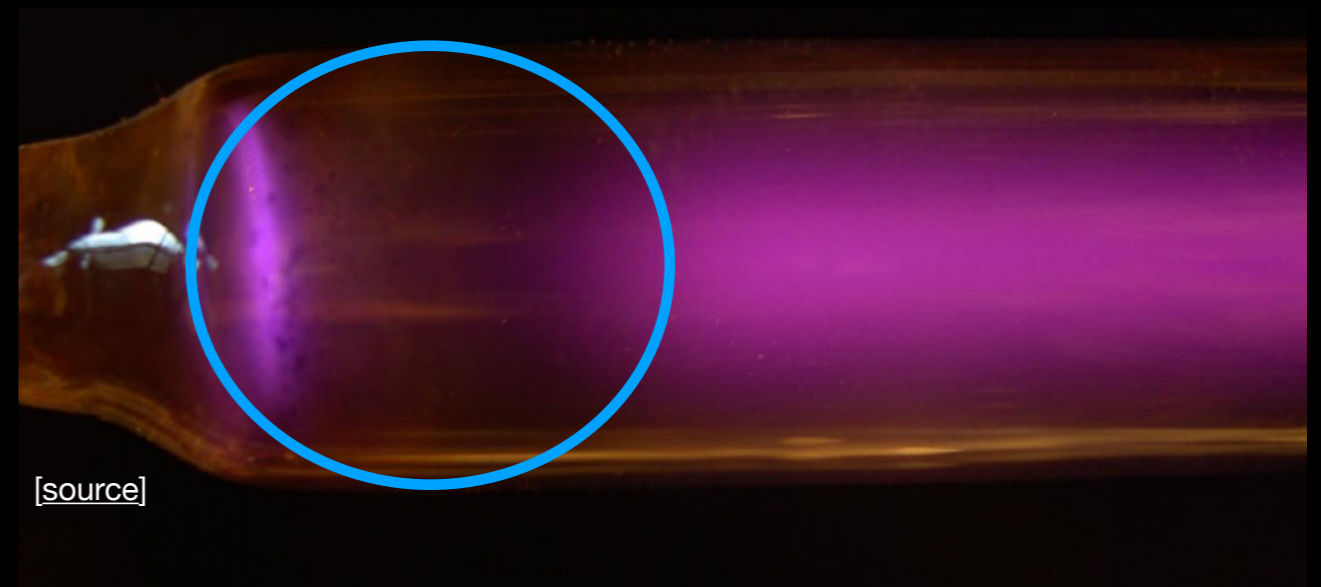


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Fig. 19.



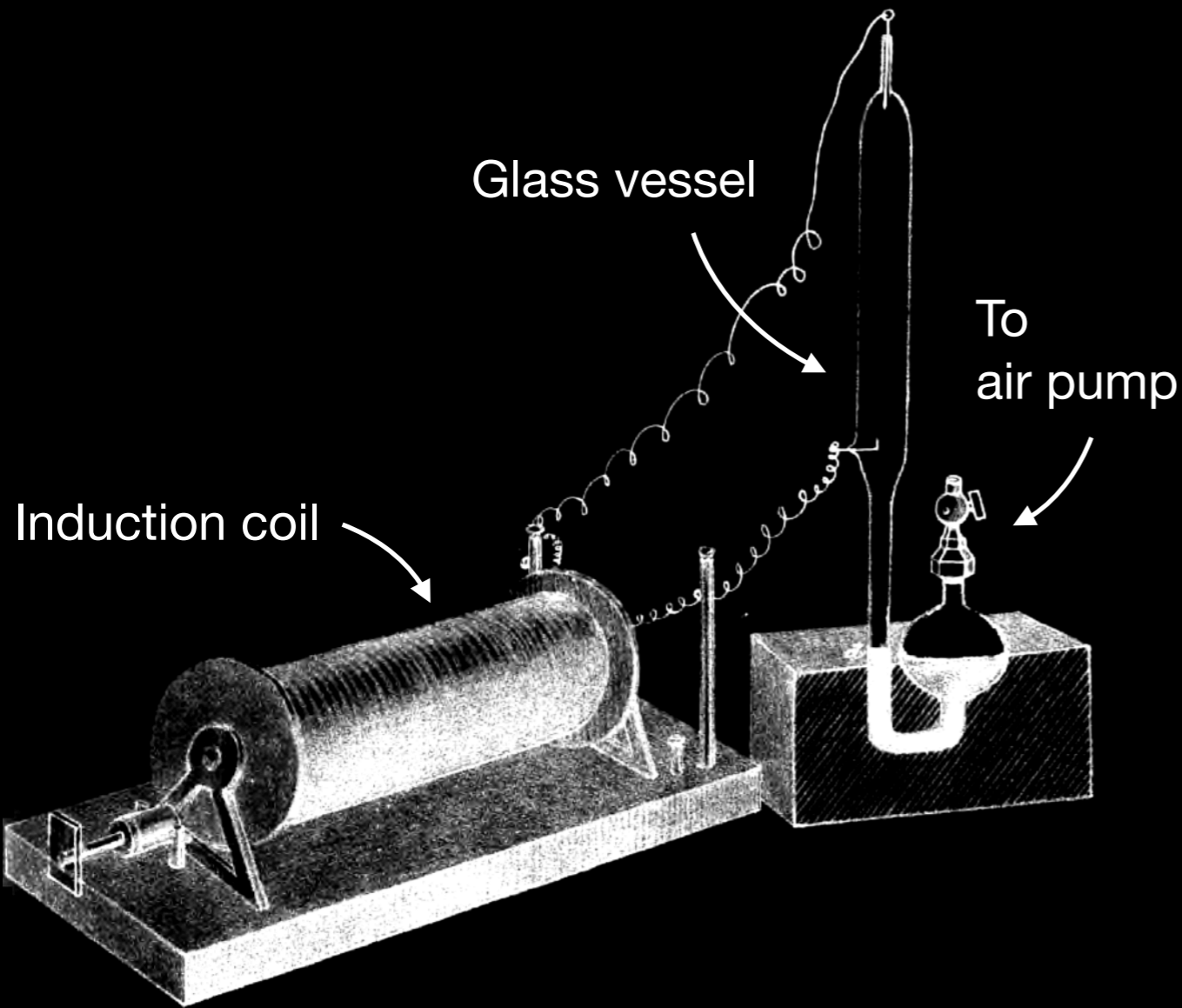
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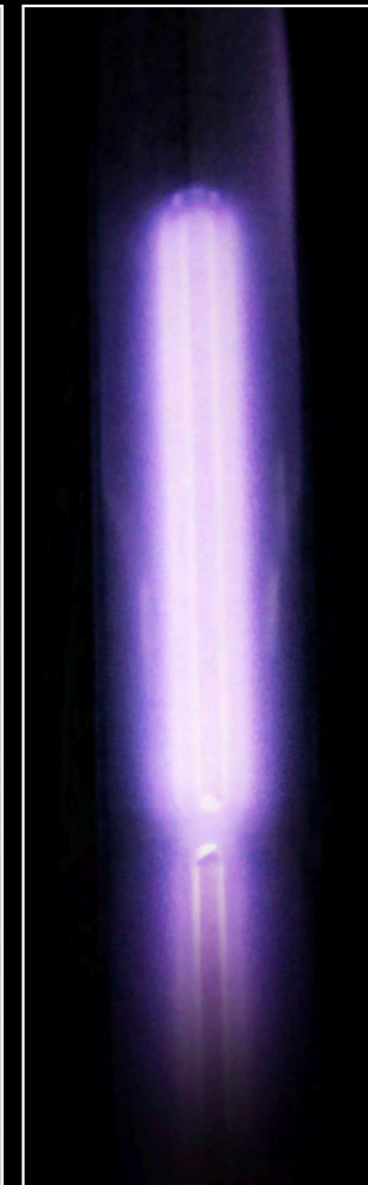
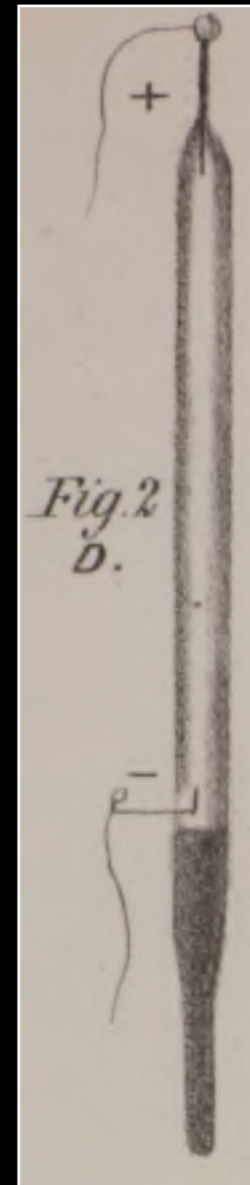
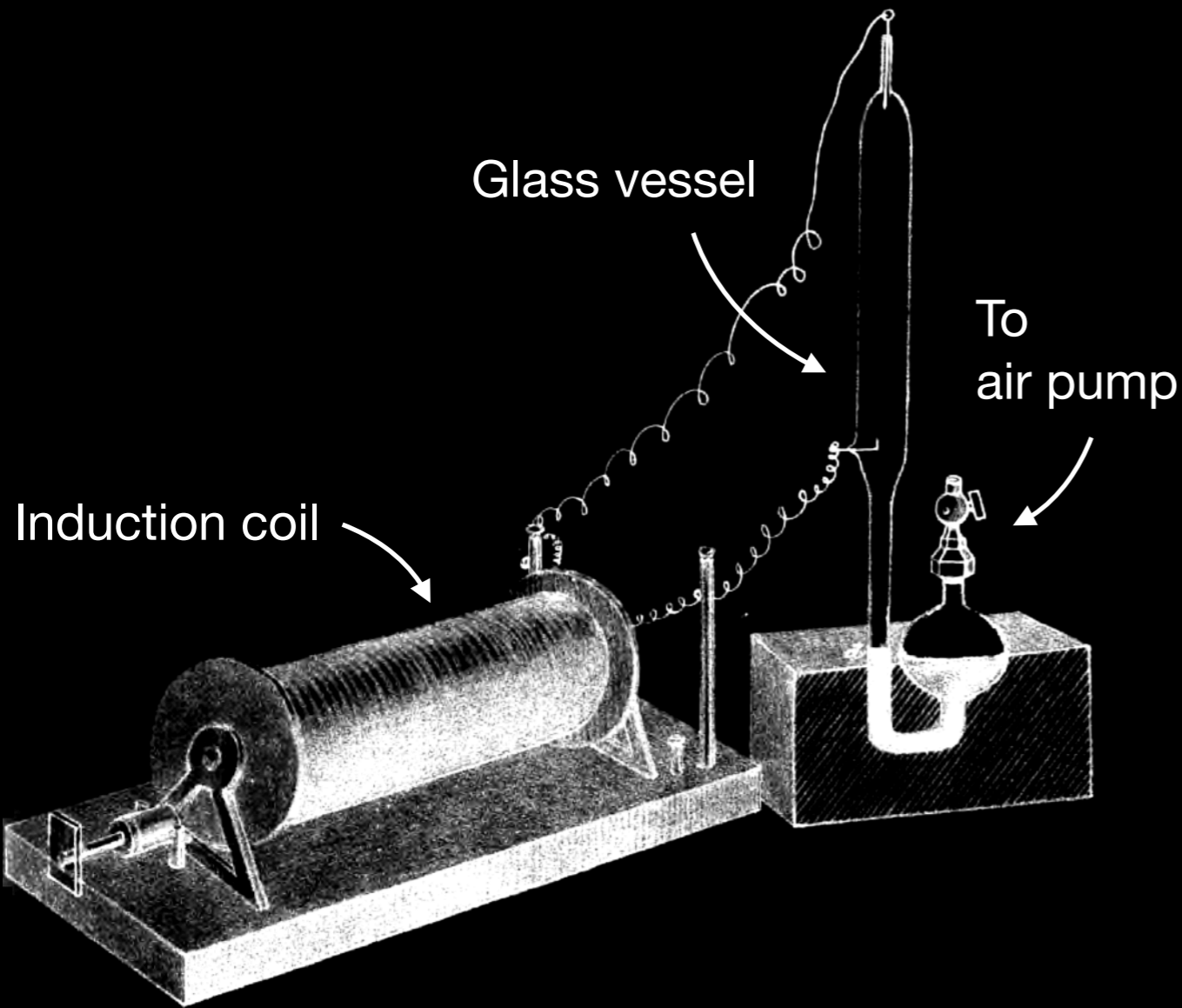
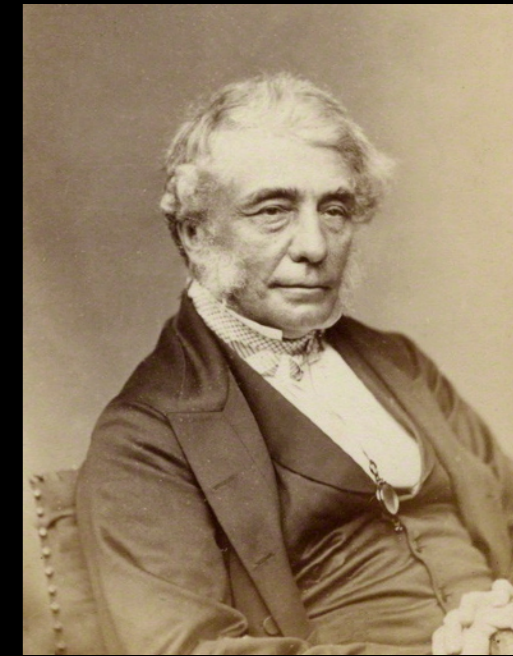
John Peter Gassiot takes over

Wine merchant, amateur scientist



John Peter Gassiot takes over

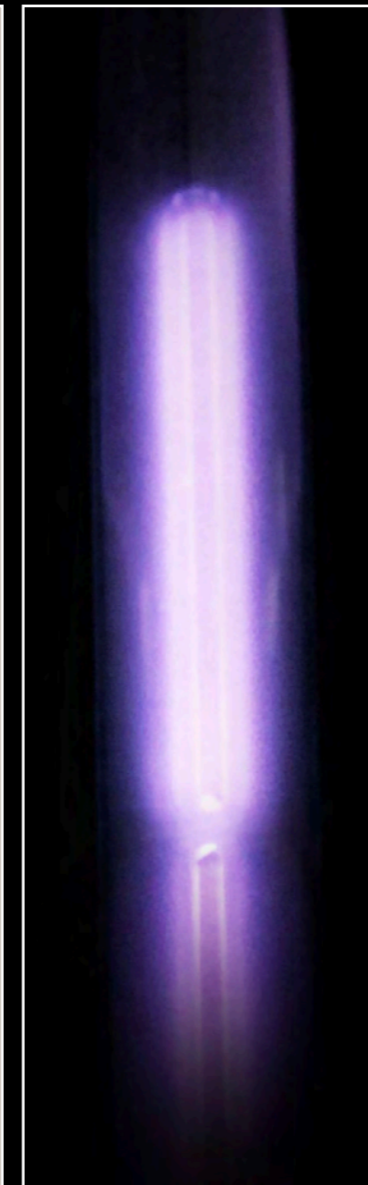
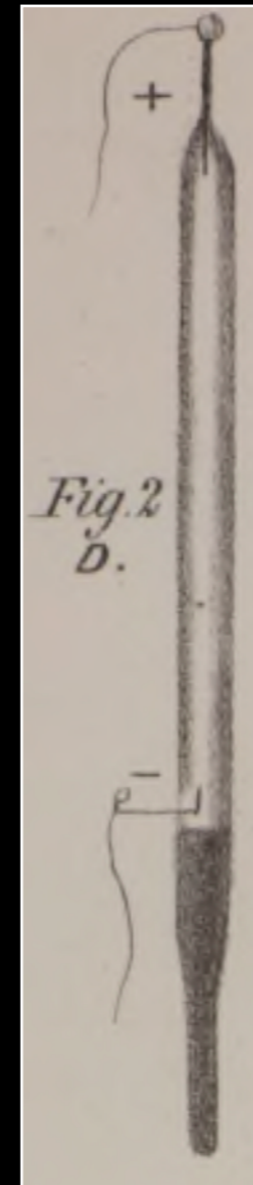
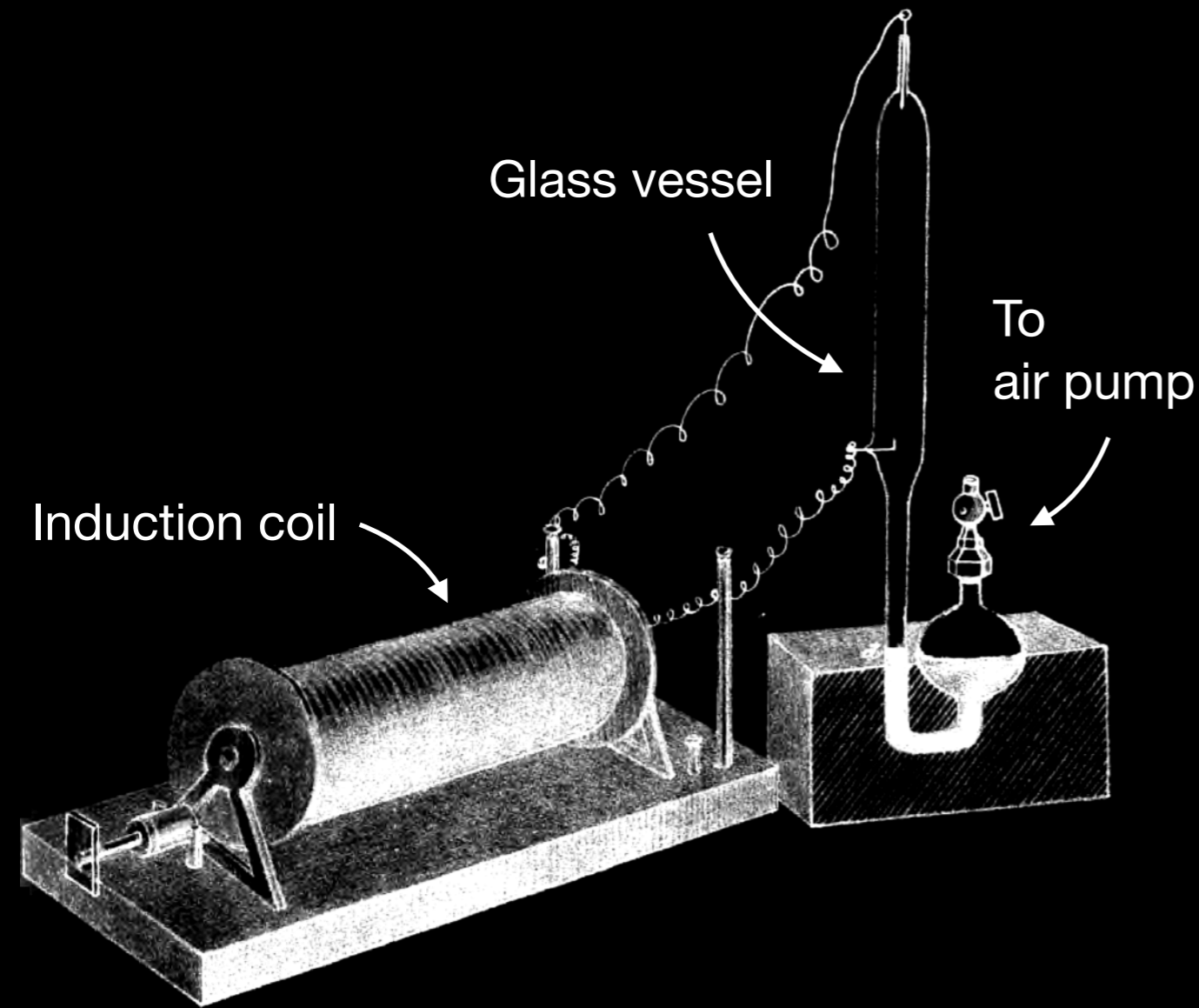
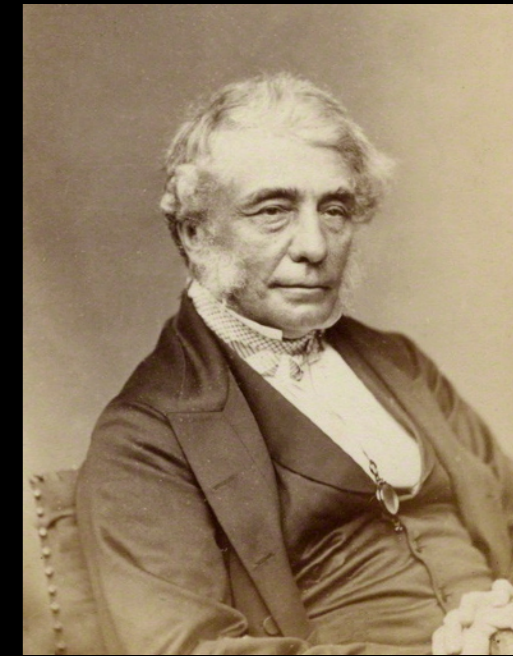
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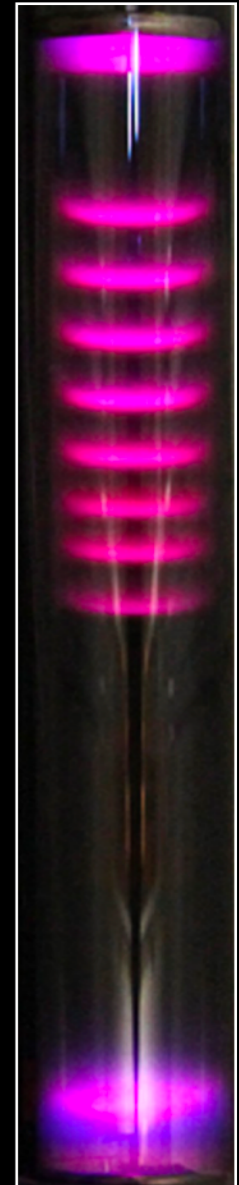
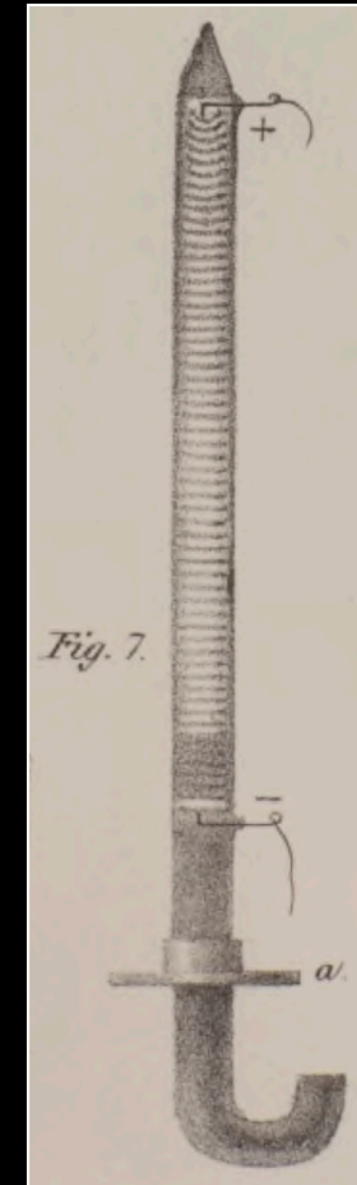
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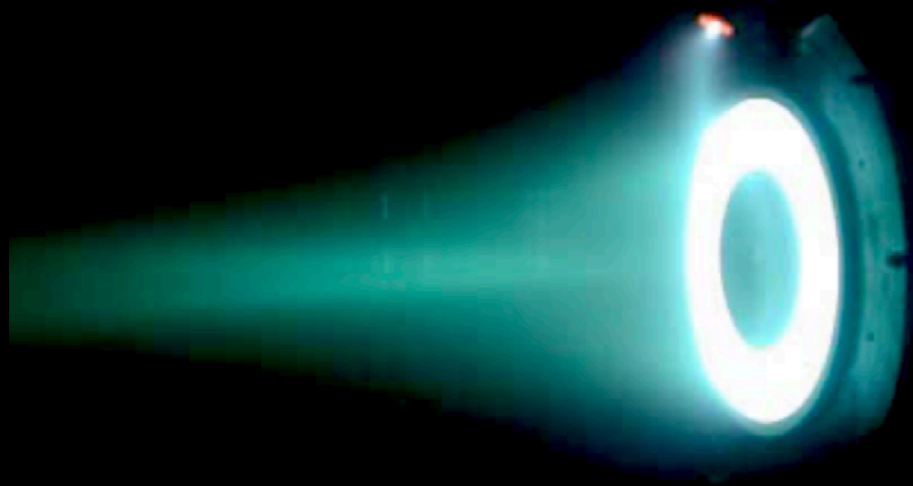
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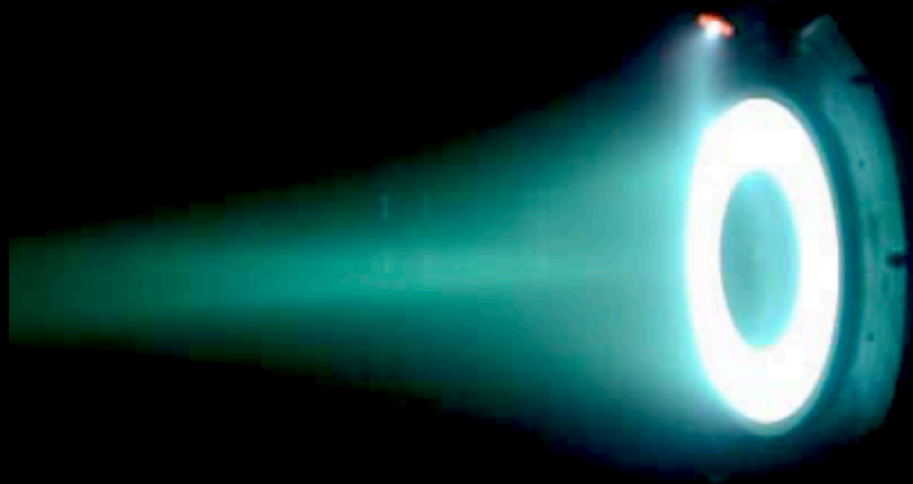
Plasma physics today

Plasma physics today

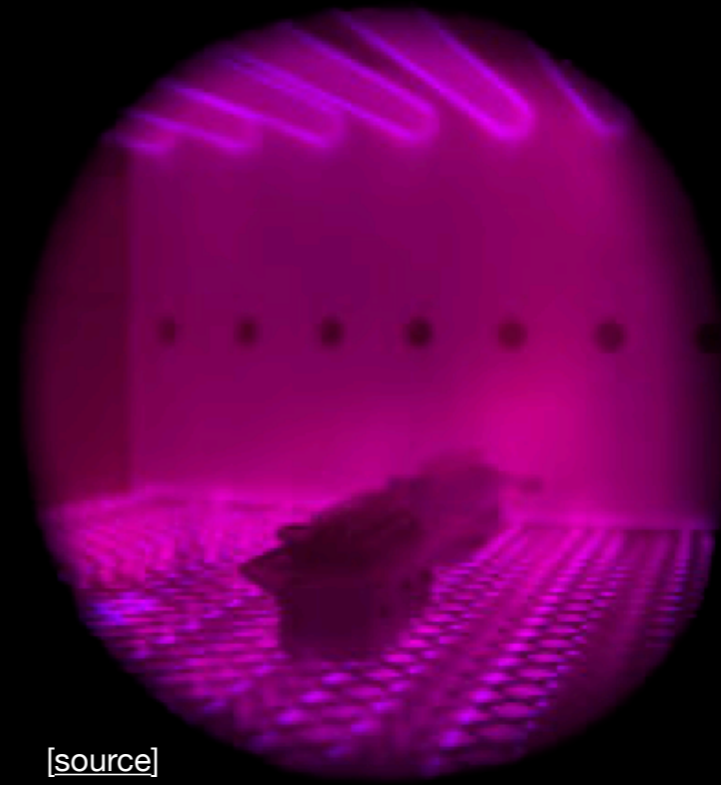


Plasma thruster
(communications satellites, space probes)

Plasma physics today



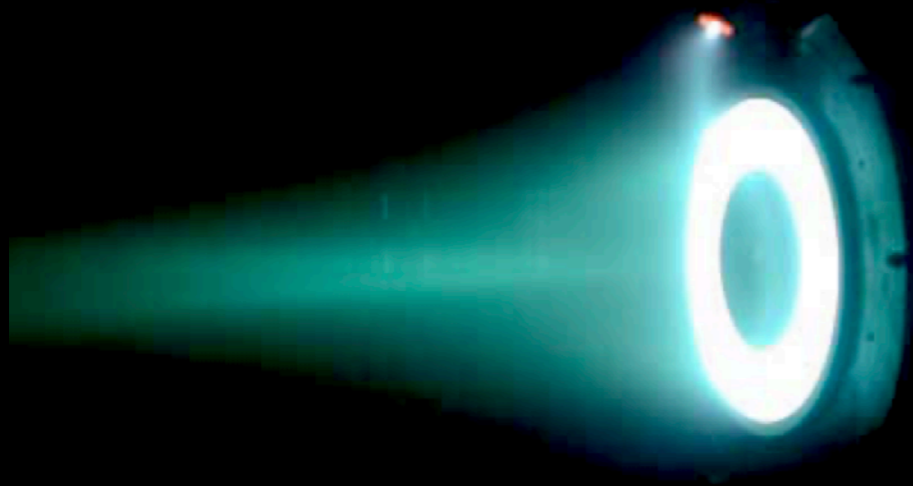
Plasma thruster
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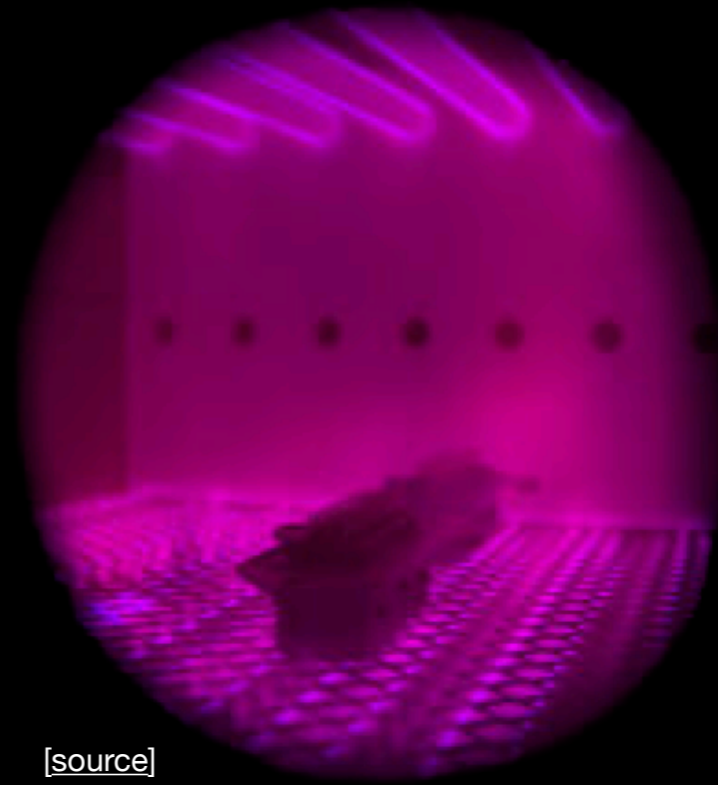
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Plasma etching
(“How can you print on plastic?”)

Plasma physics today



Plasma thruster
(communications satellites, space probes)



[source]

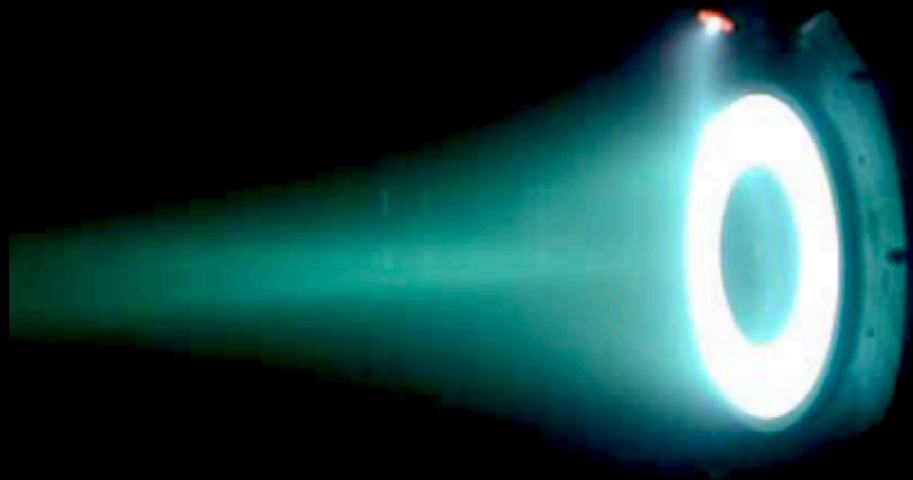
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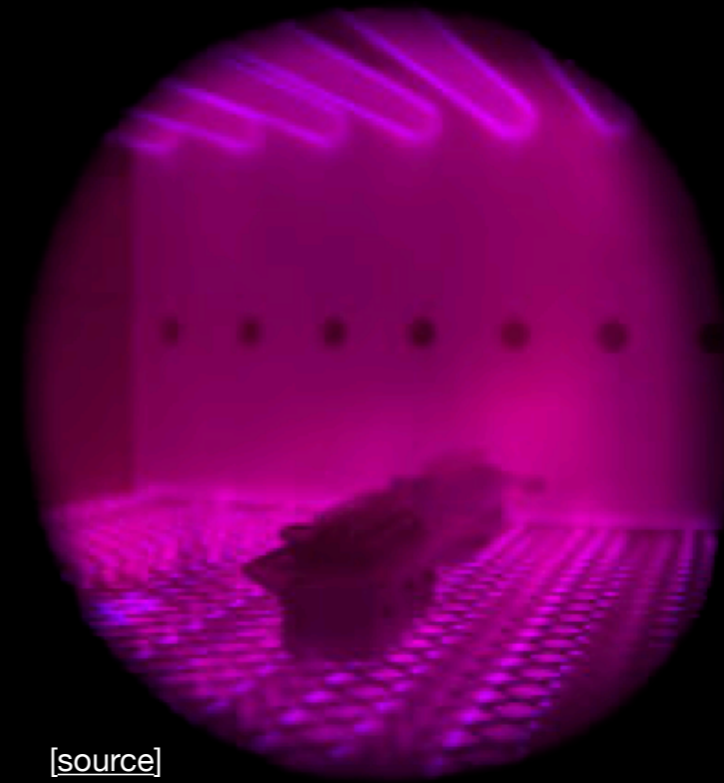
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Plasma cutting

Plasma physics today

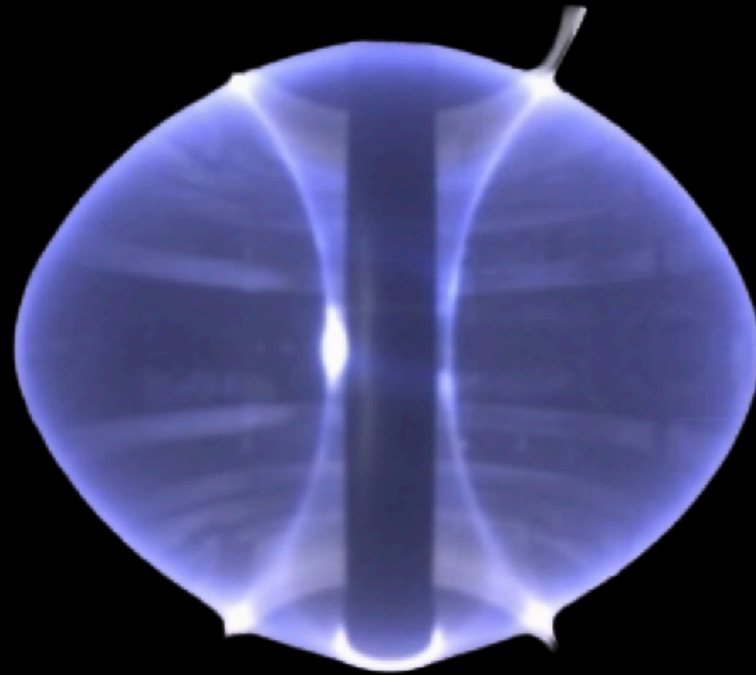


Plasma thruster
(communications satellites, space probes)



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Plasma etching
("How can you print on plastic?")



Fusion plasma

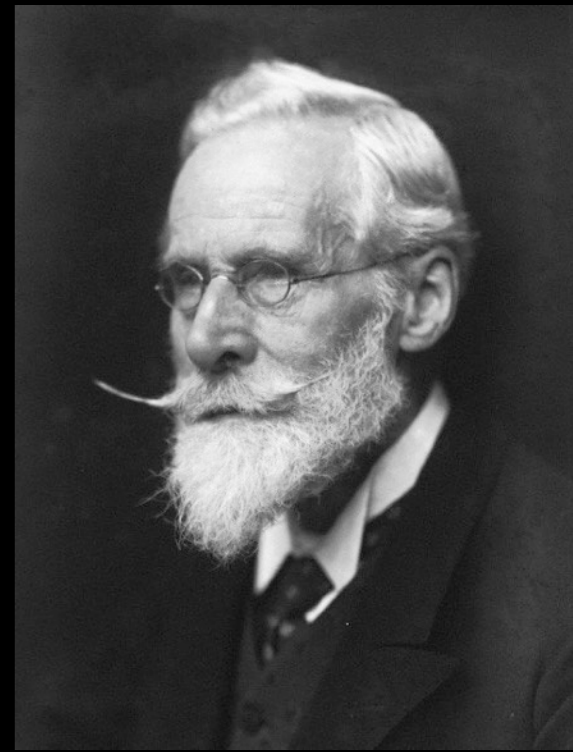


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Plasma cutting

William Crookes

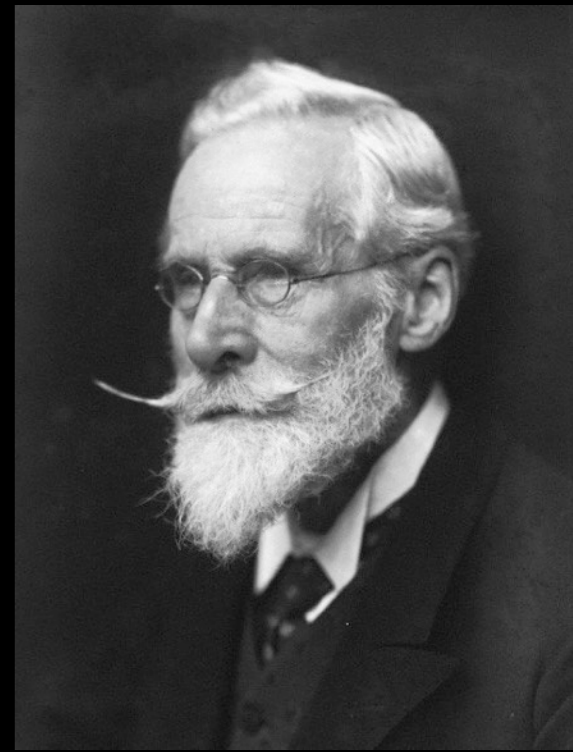
Chemist, physicist, vacuum experimenter



William Crookes

Chemist, physicist, vacuum experimenter

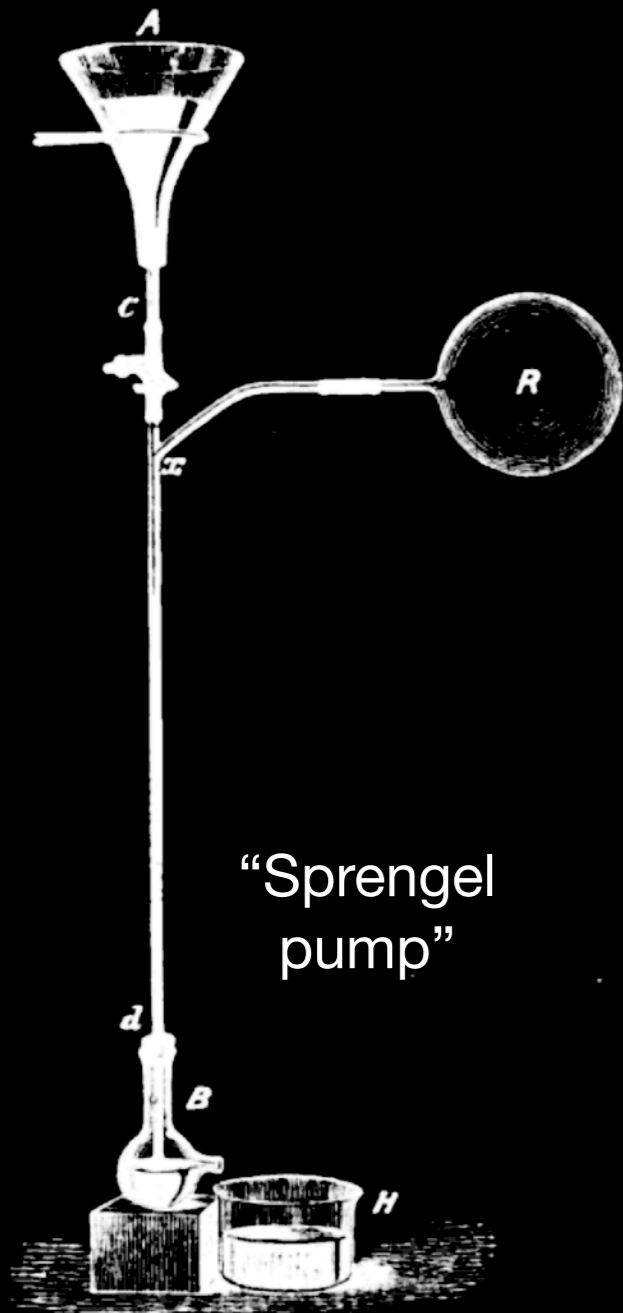
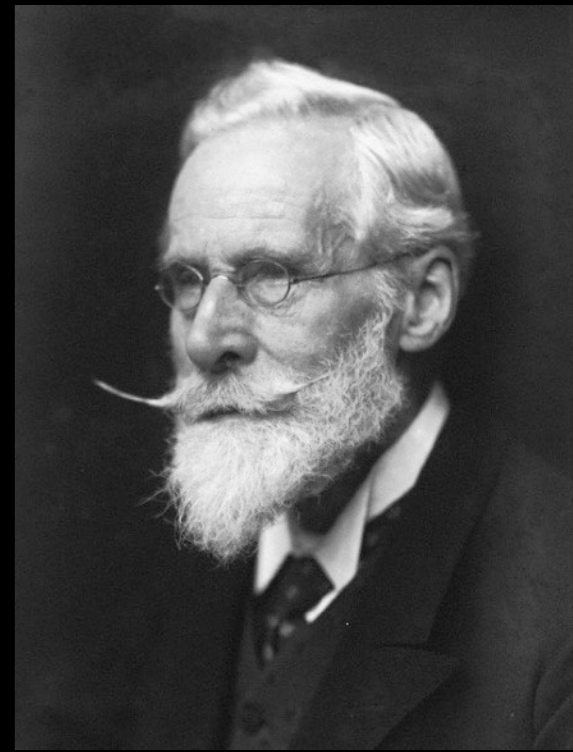
“When the spark from a good induction coil traverses a glass tube containing a rarefied gas, certain phenomena are observed which vary greatly with the kind of gas and the degree of exhaustion.”



William Crookes

Chemist, physicist, vacuum experimenter

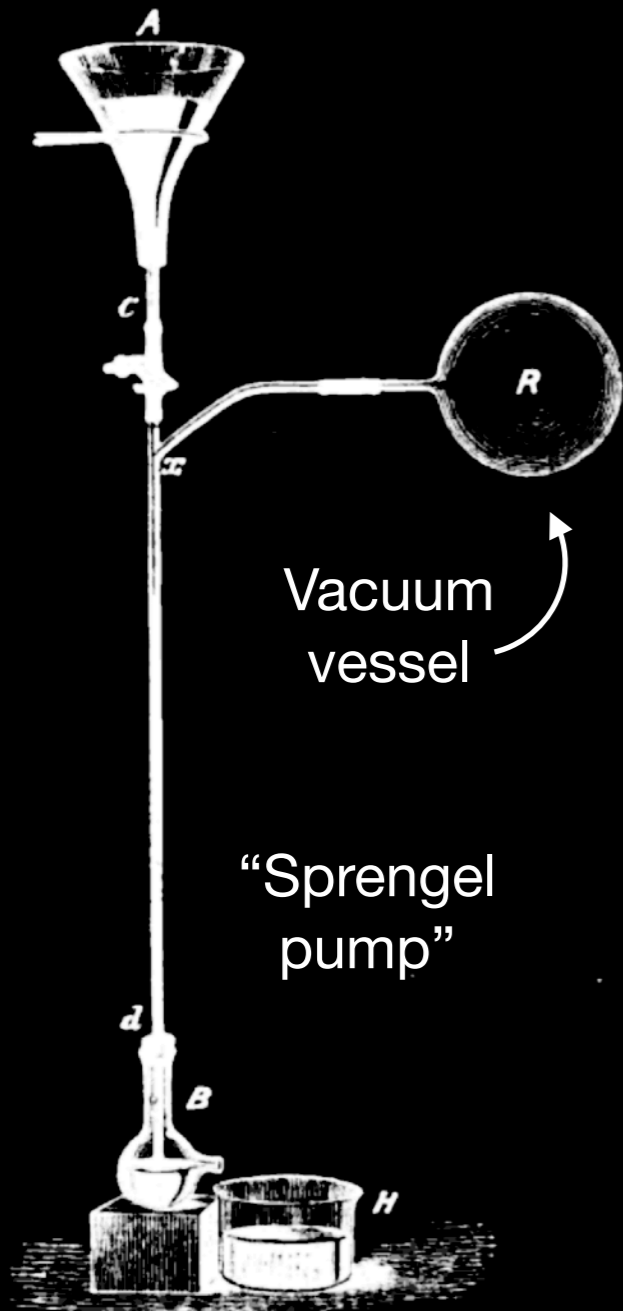
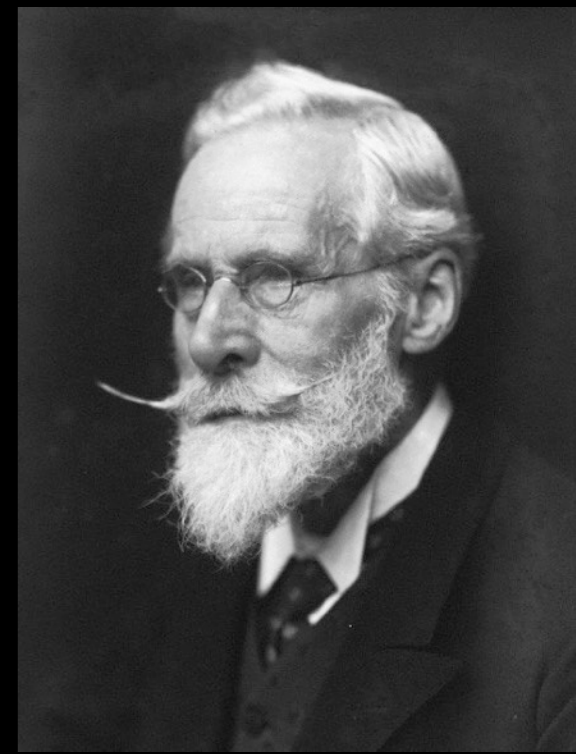
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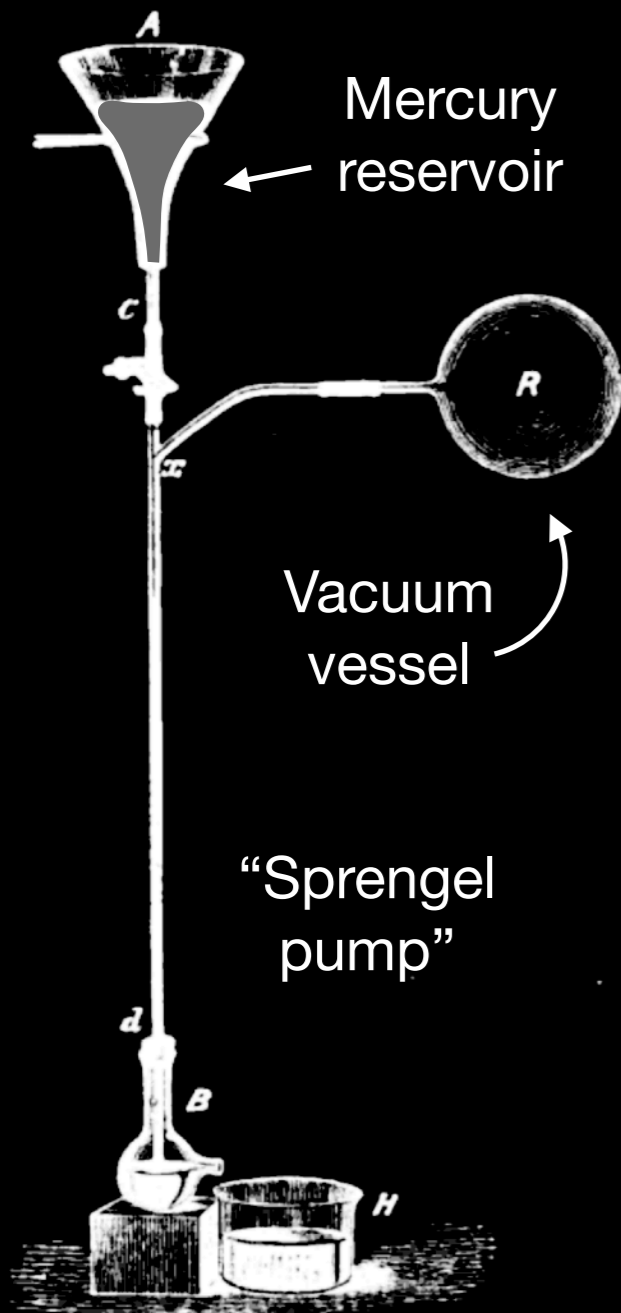
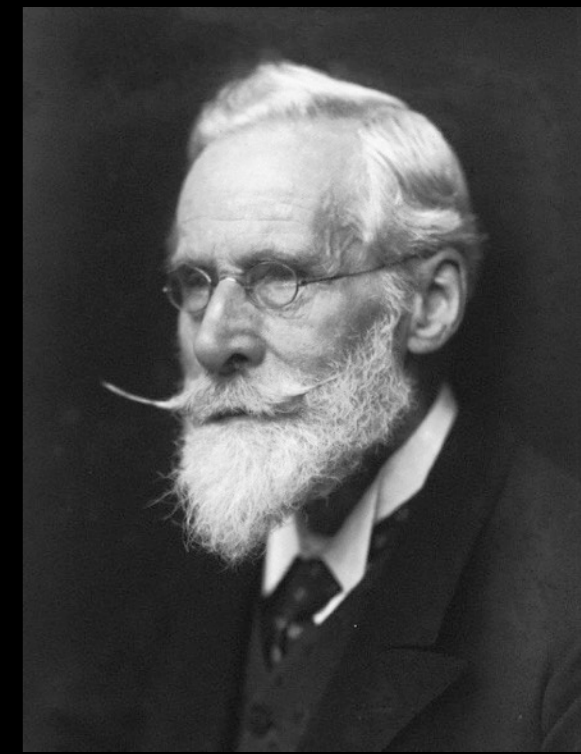
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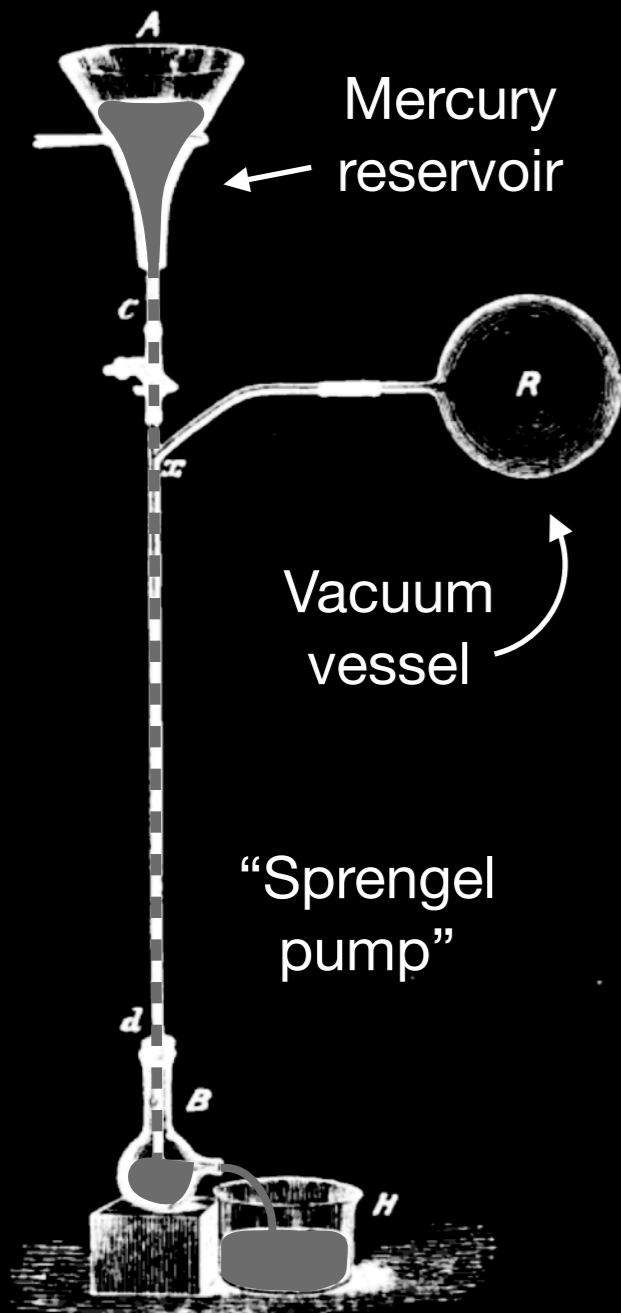
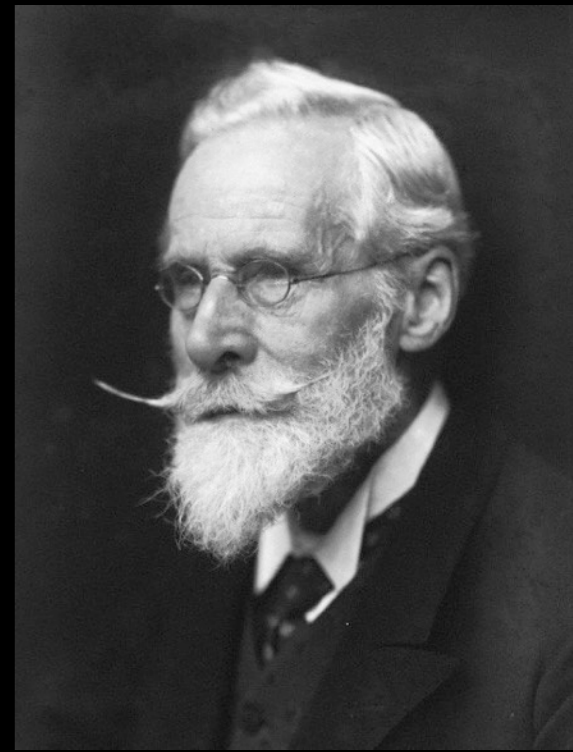
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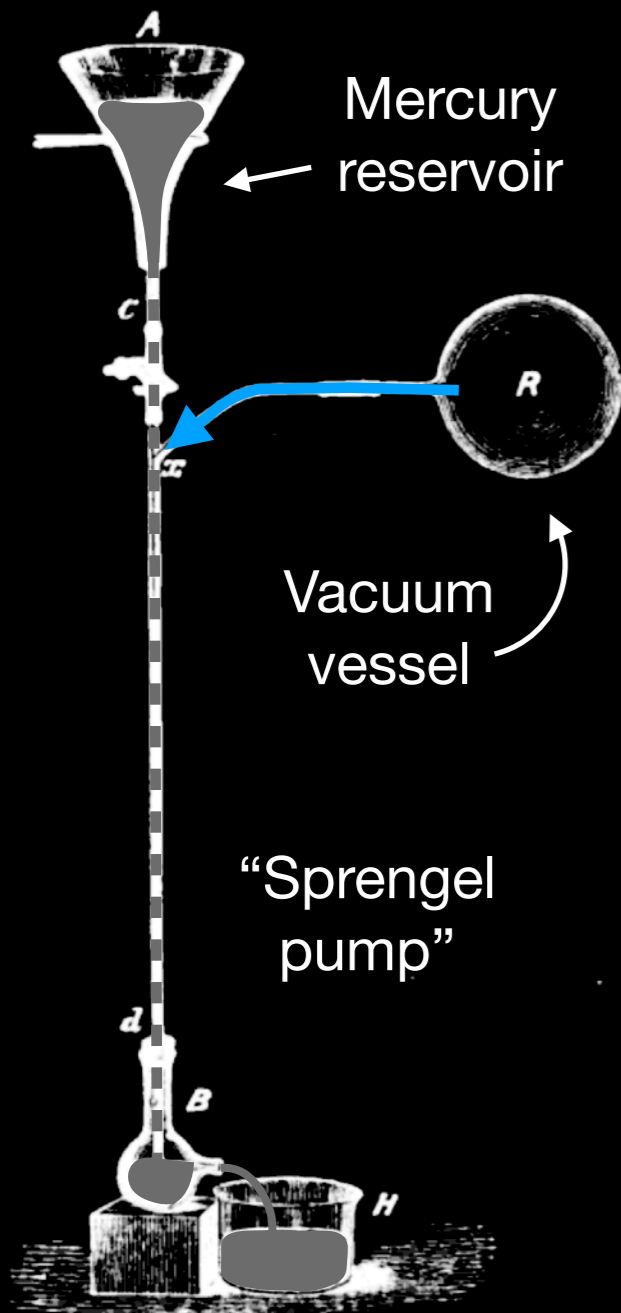
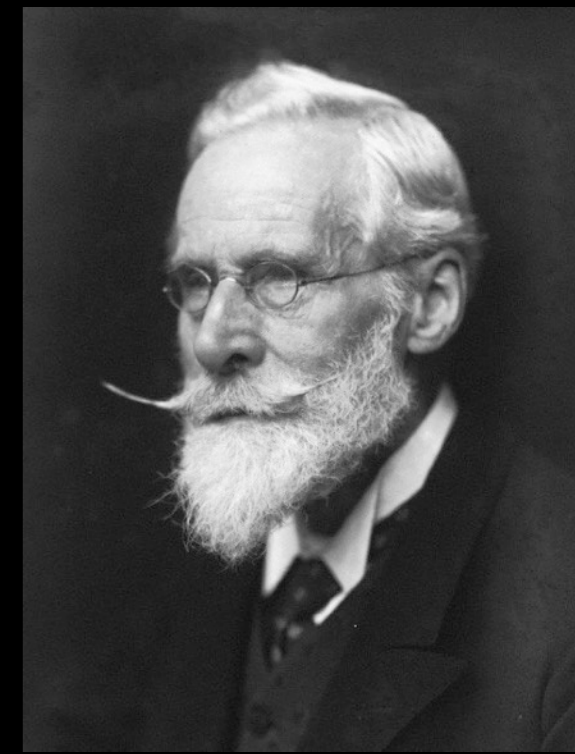
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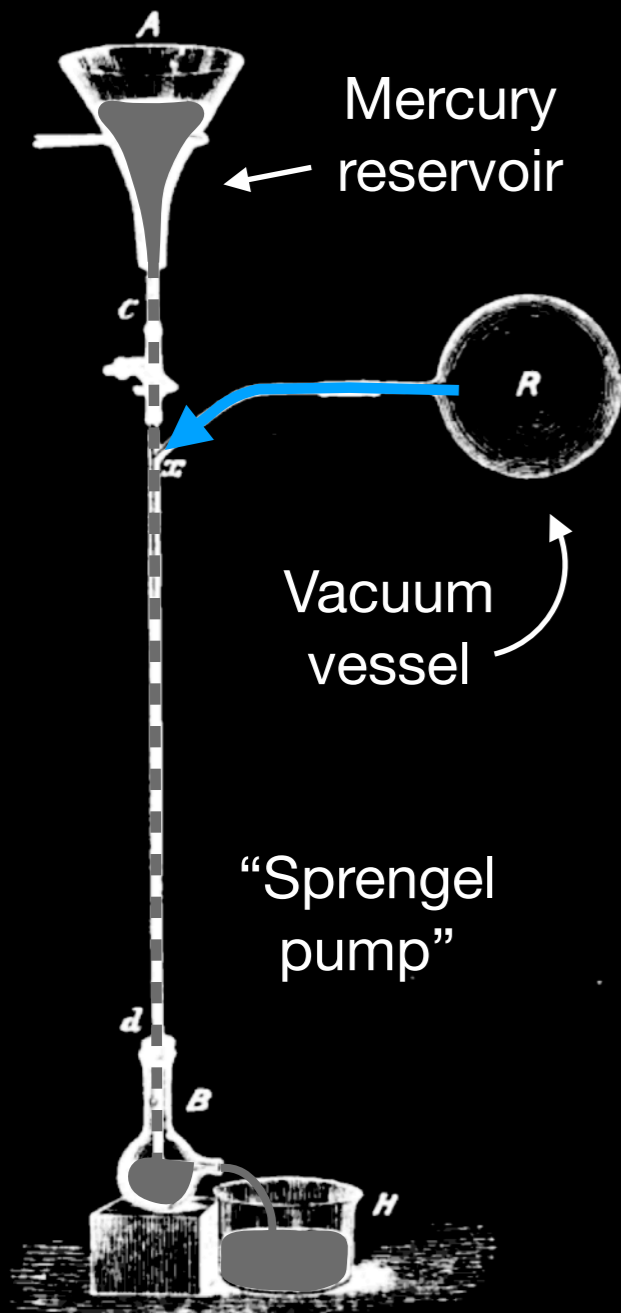
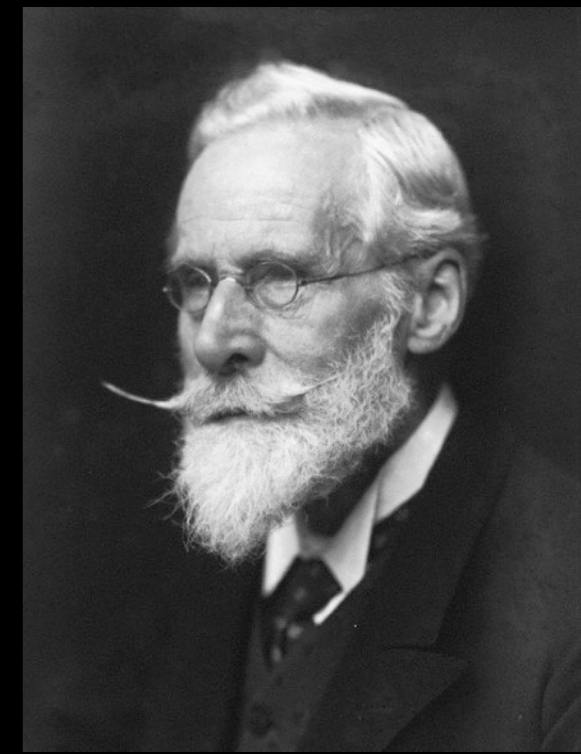
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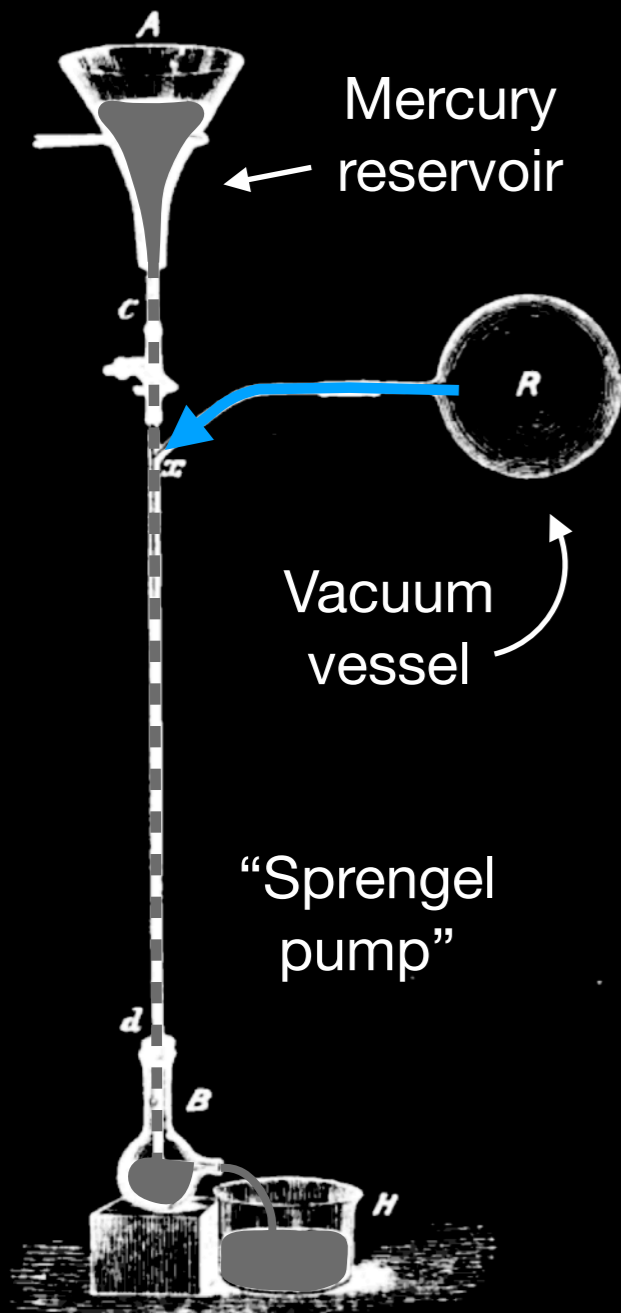
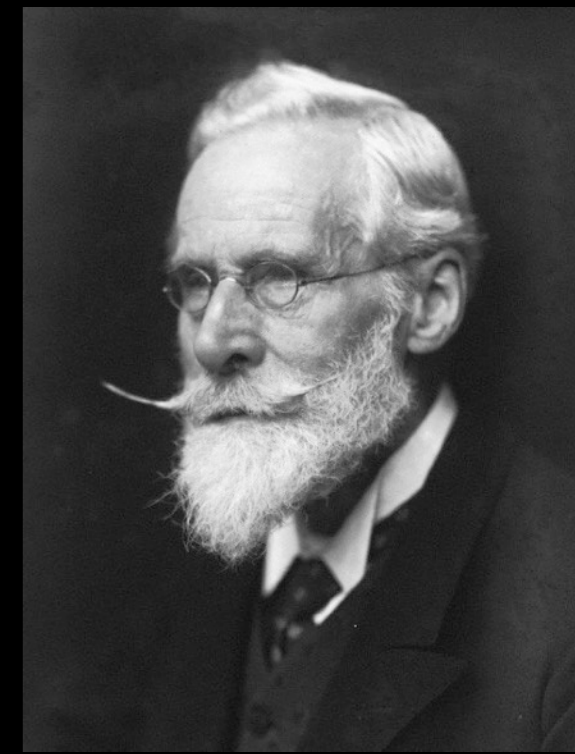


“When the exhaustion approaches 30 millionth of an atmosphere, a new phenomenon makes an appearance.”

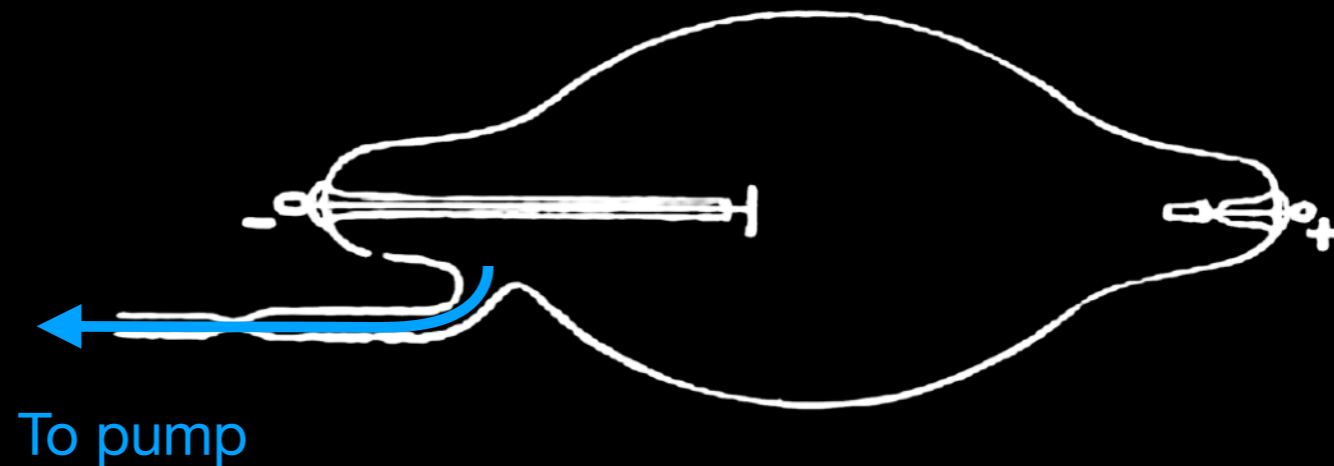
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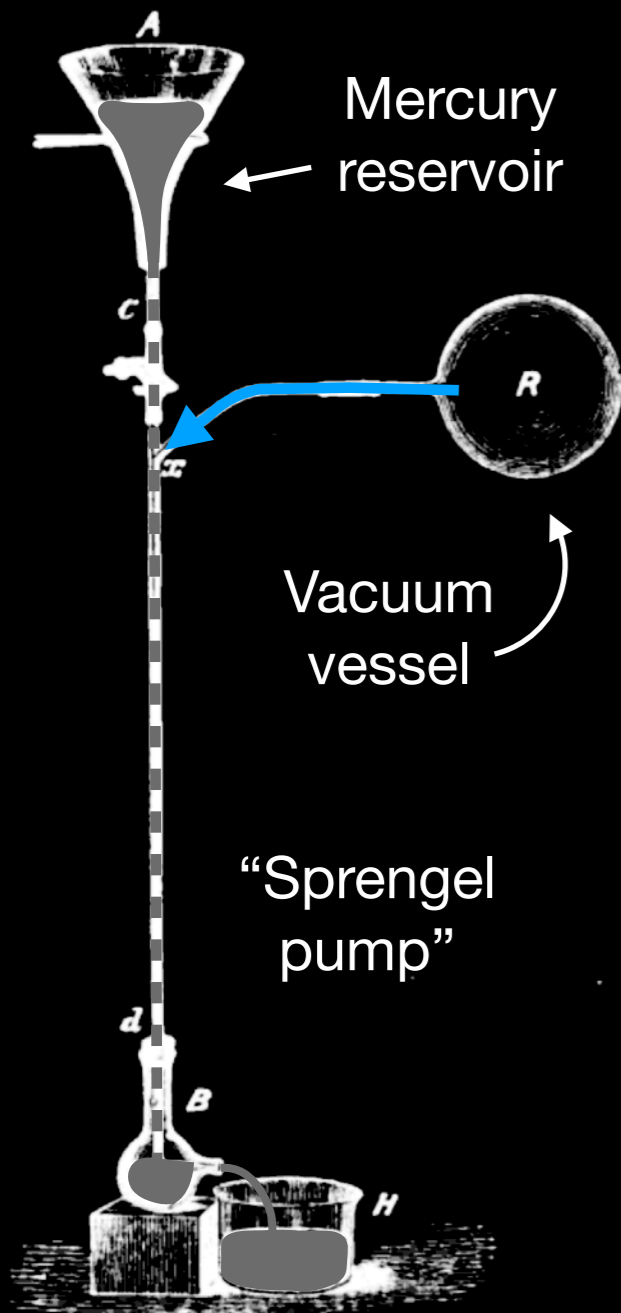
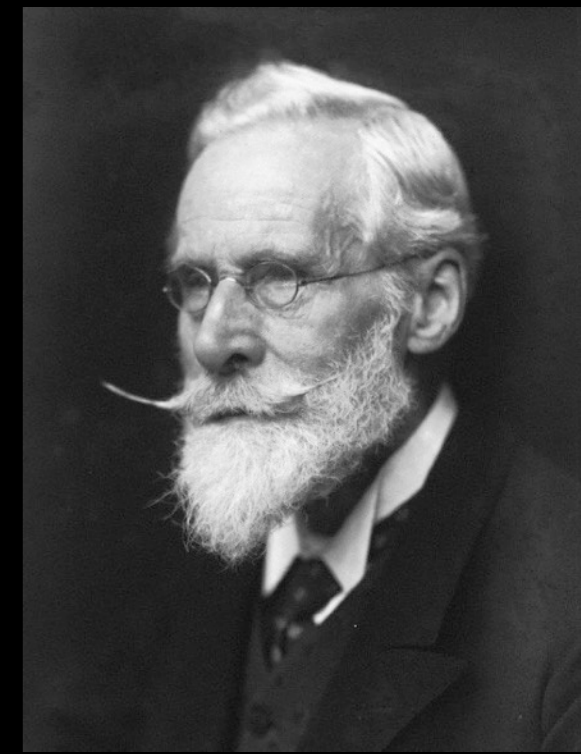
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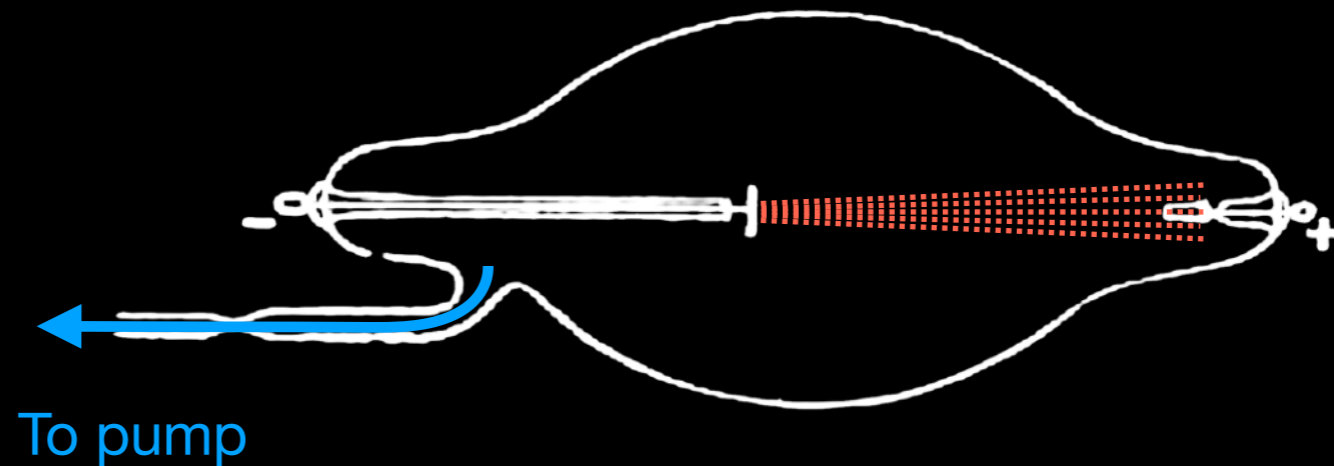
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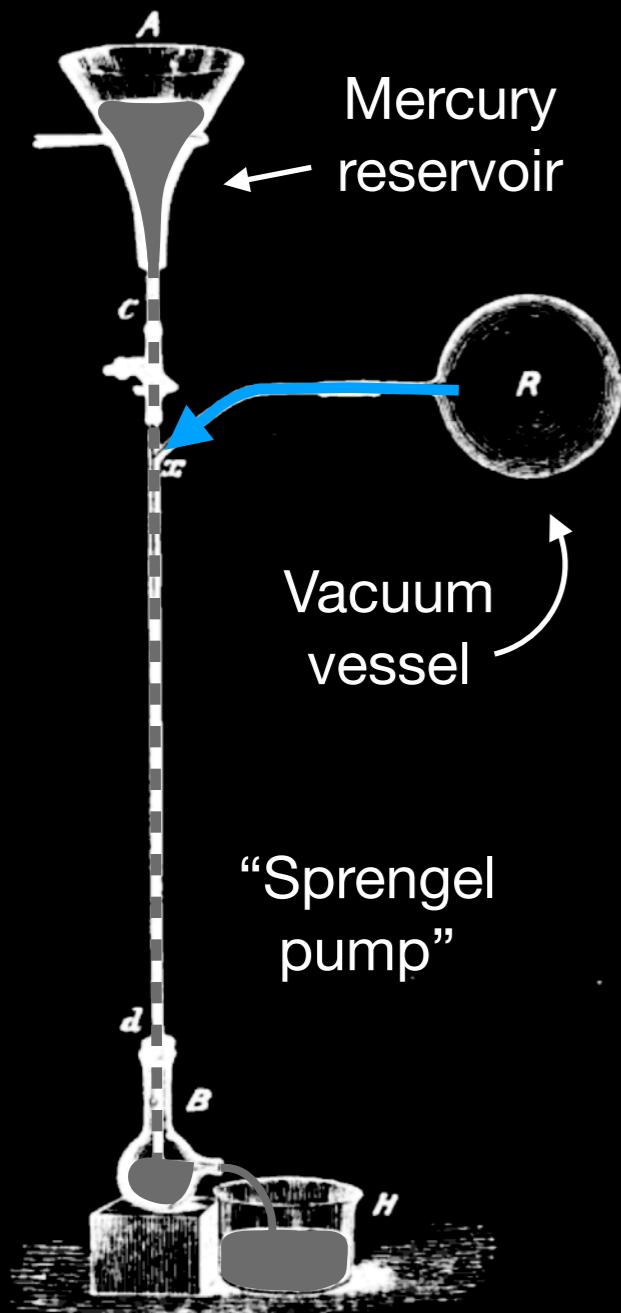
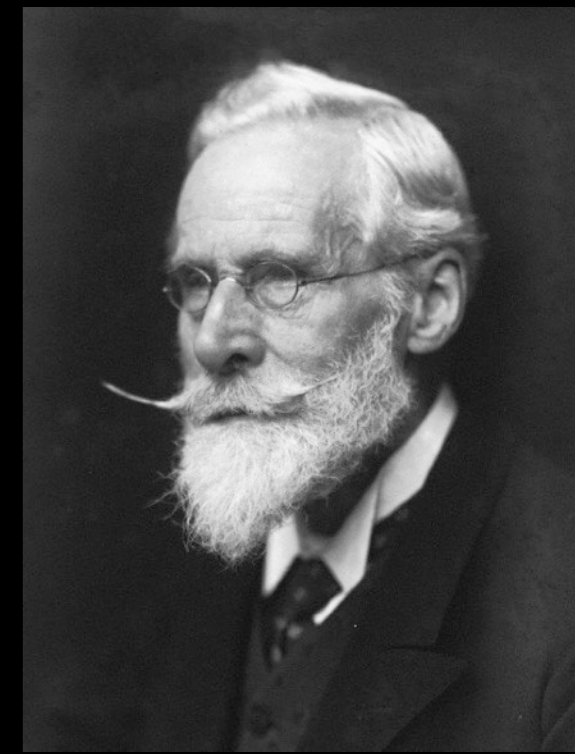
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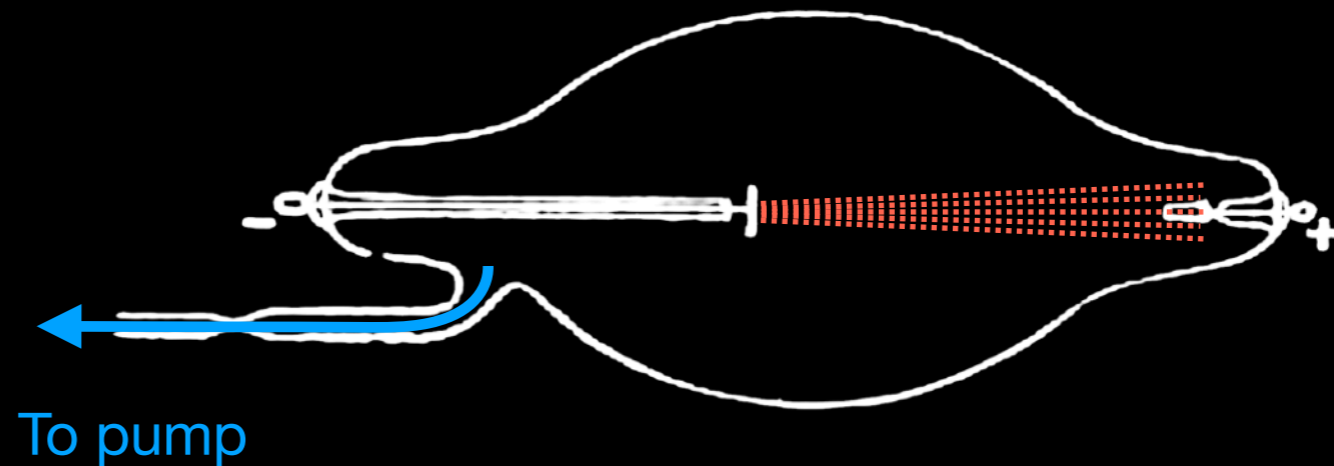
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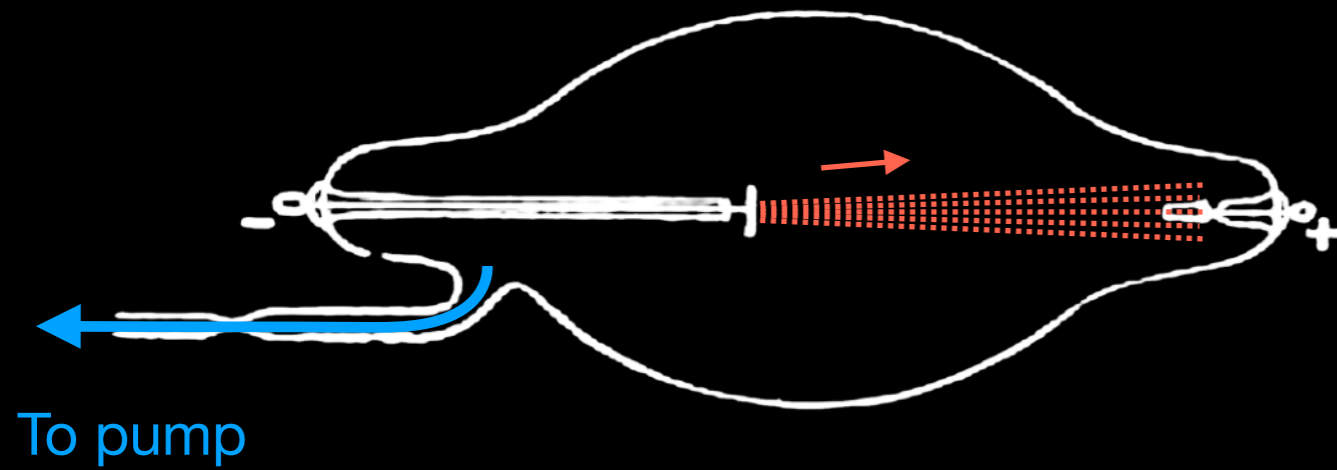


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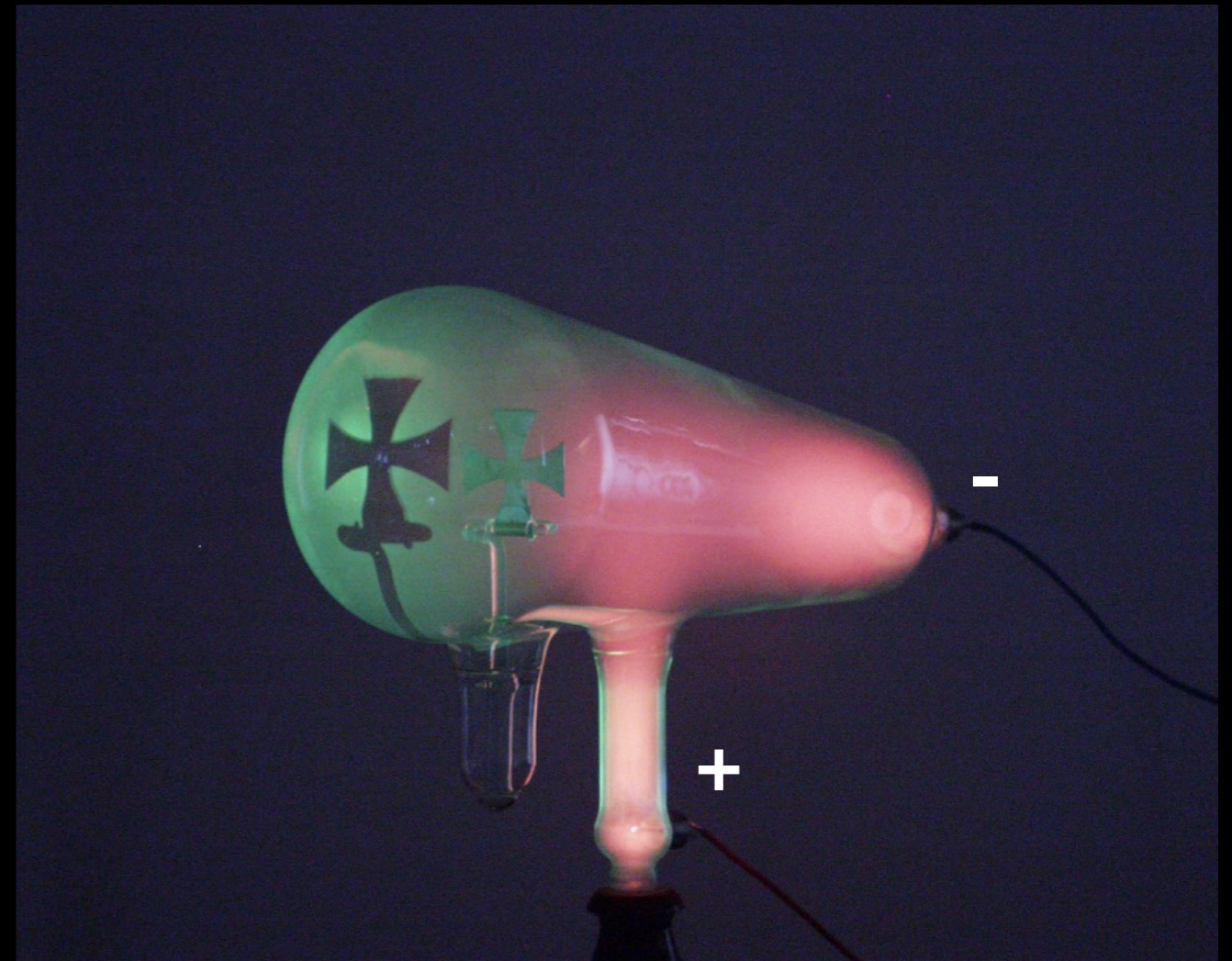


“Molecular rays” leave the negative terminal!

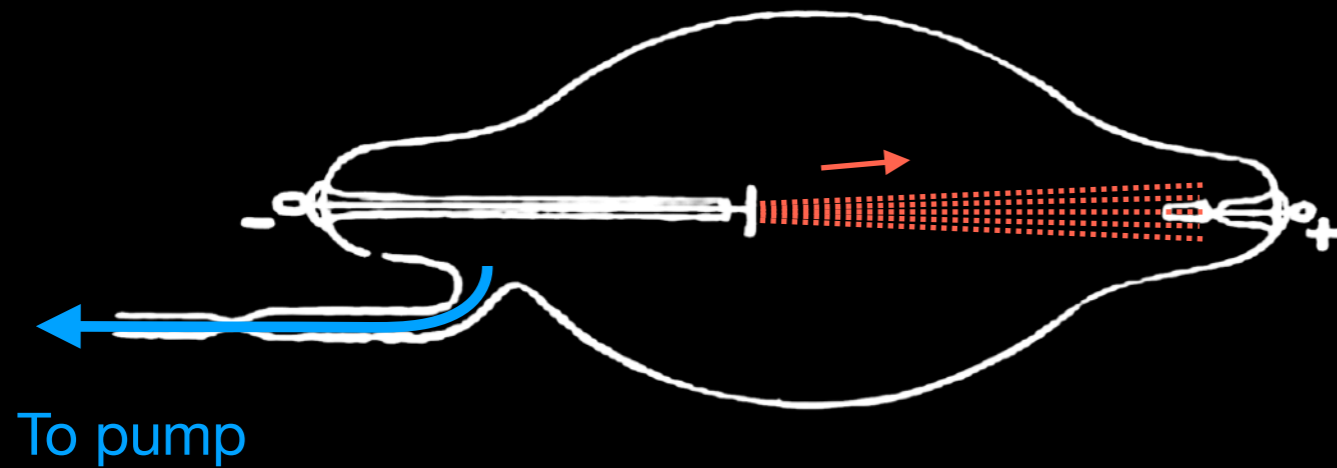
“Molecular rays” (1878)



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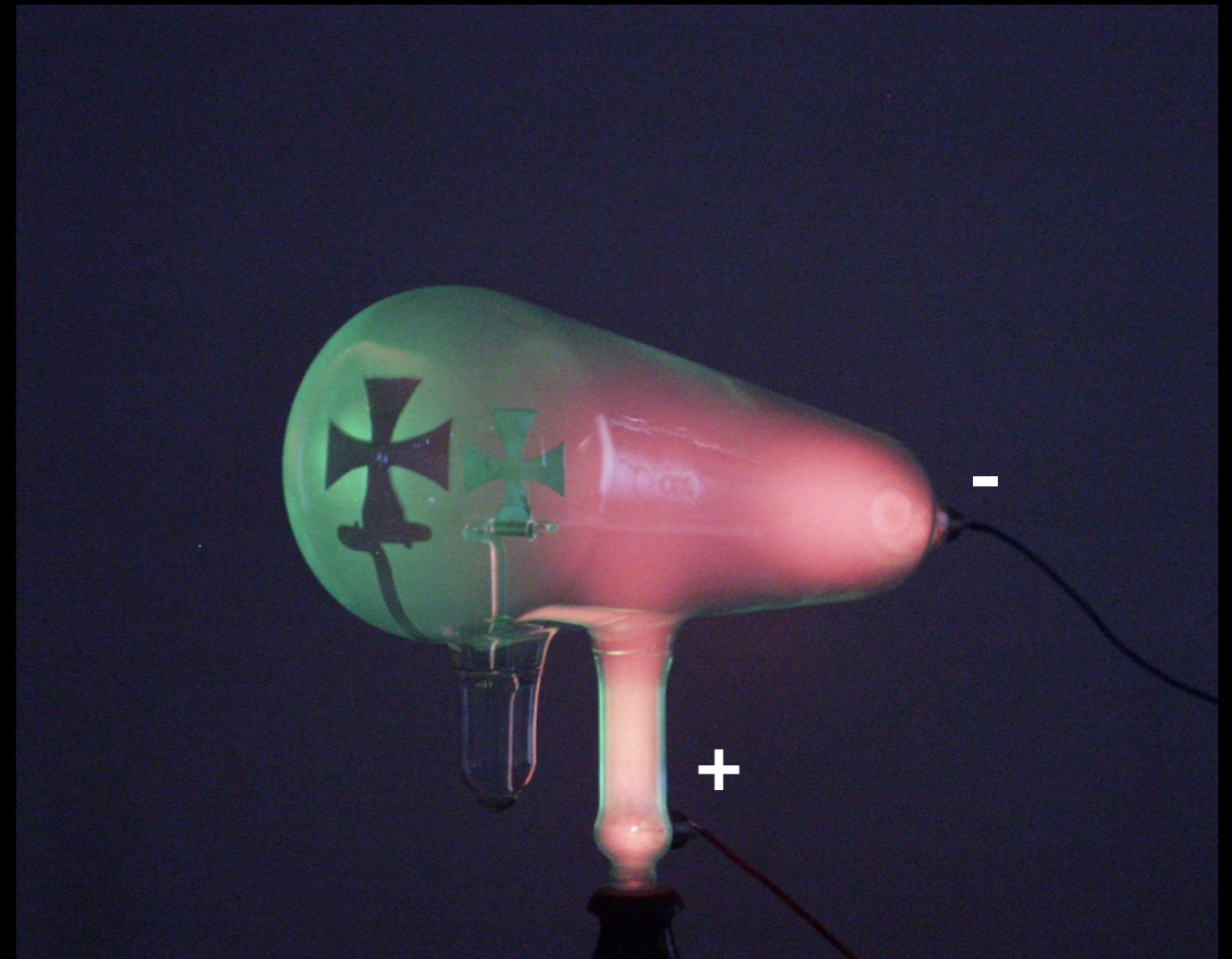


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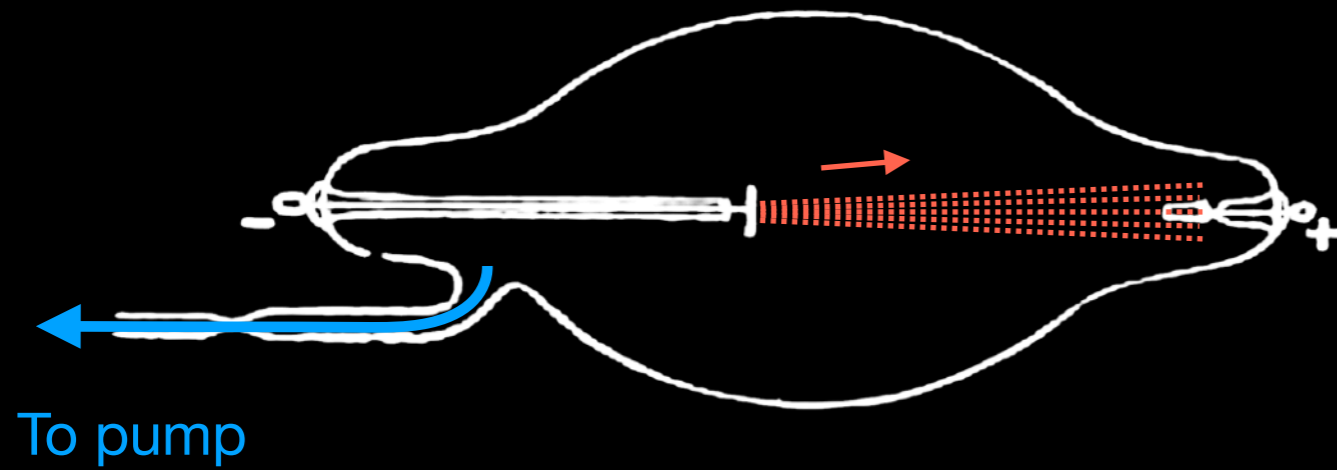


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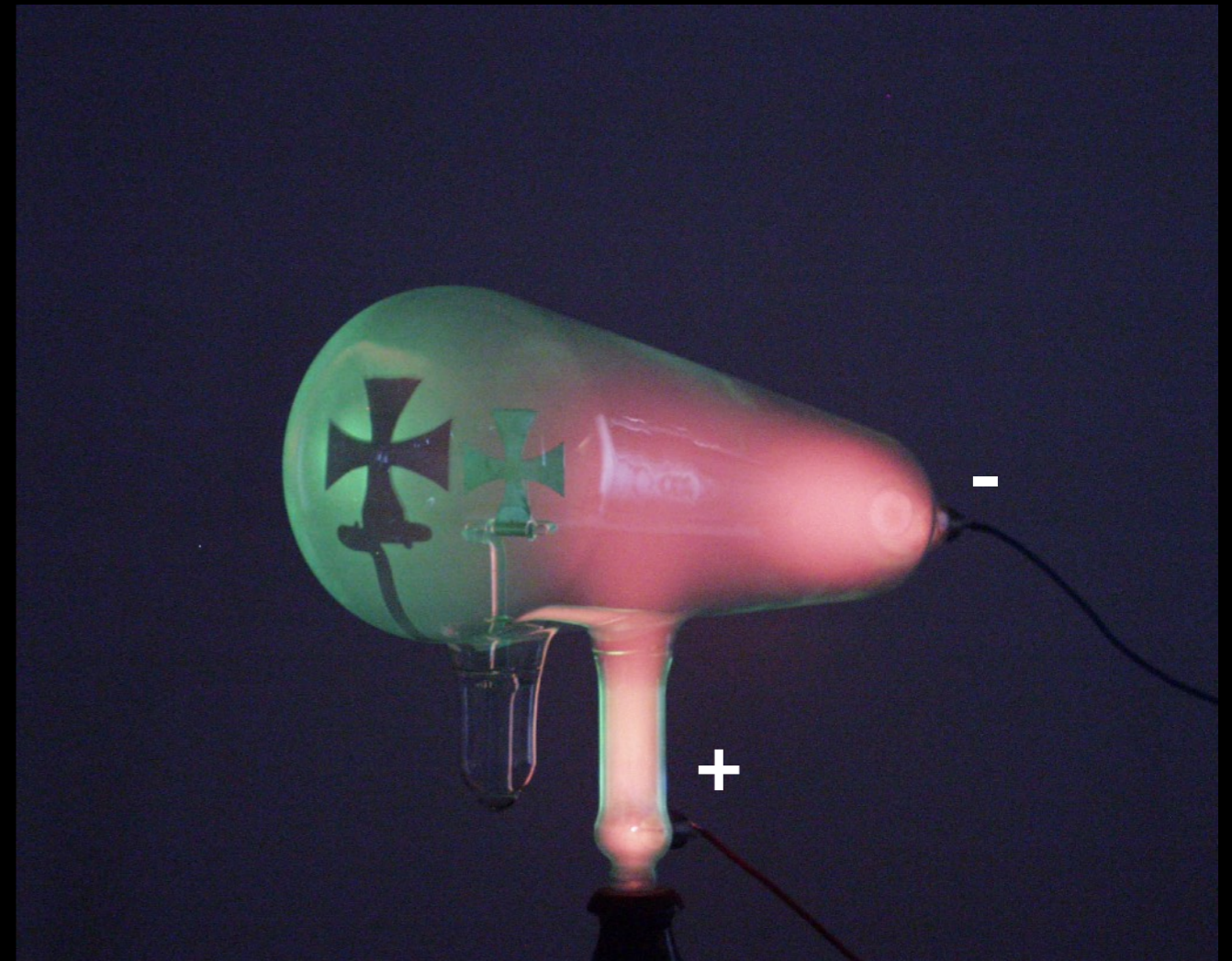
“On the part of the bulb on which the rays impinge, a faint greenish-yellow light is observed.”



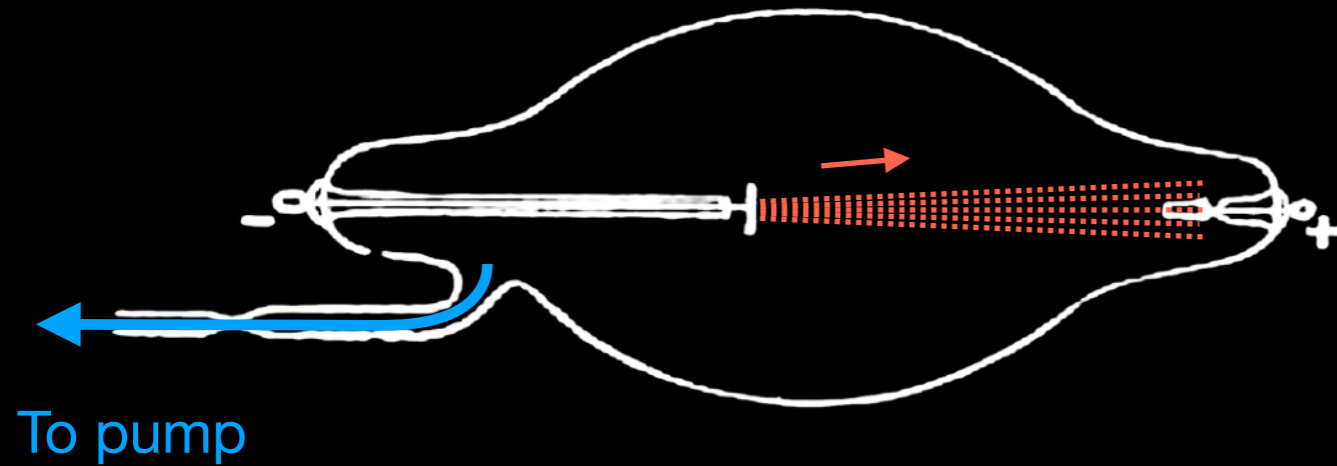
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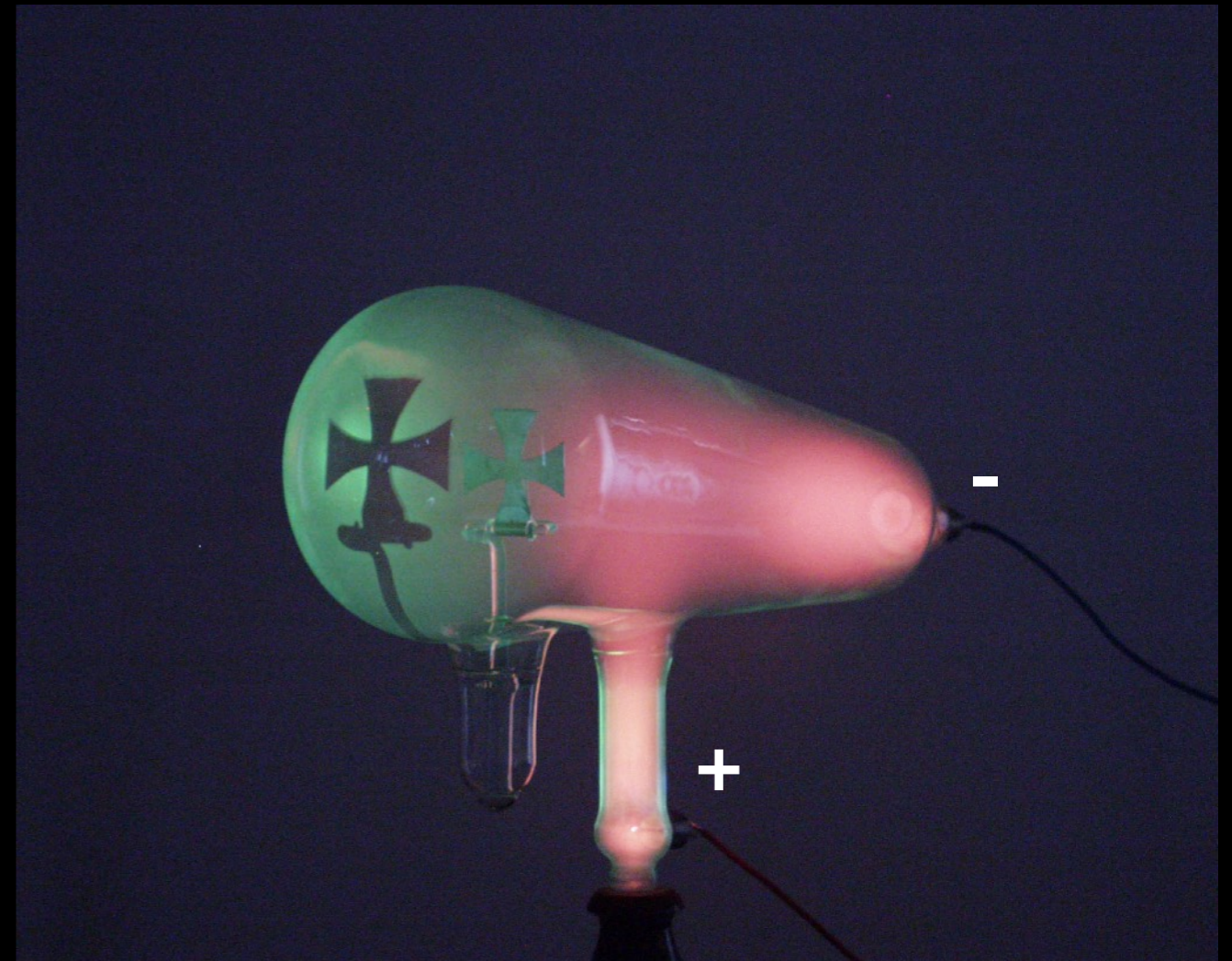


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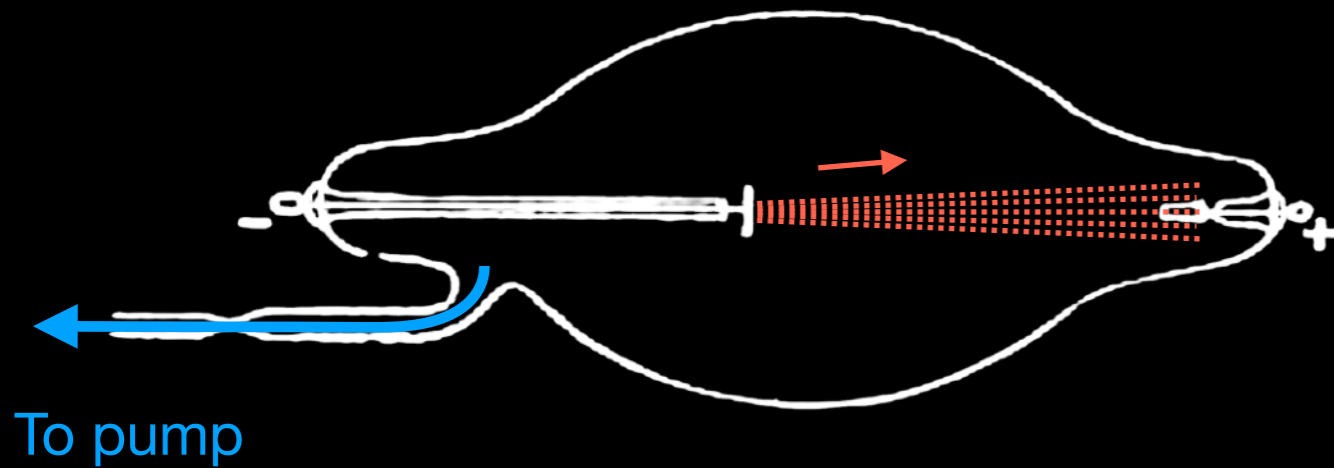


“Molecular rays” leave the negative terminal!

“The molecular ray which gives birth to the light absolutely refuses to take a corner, and radiates from the negative pole in straight lines ...”



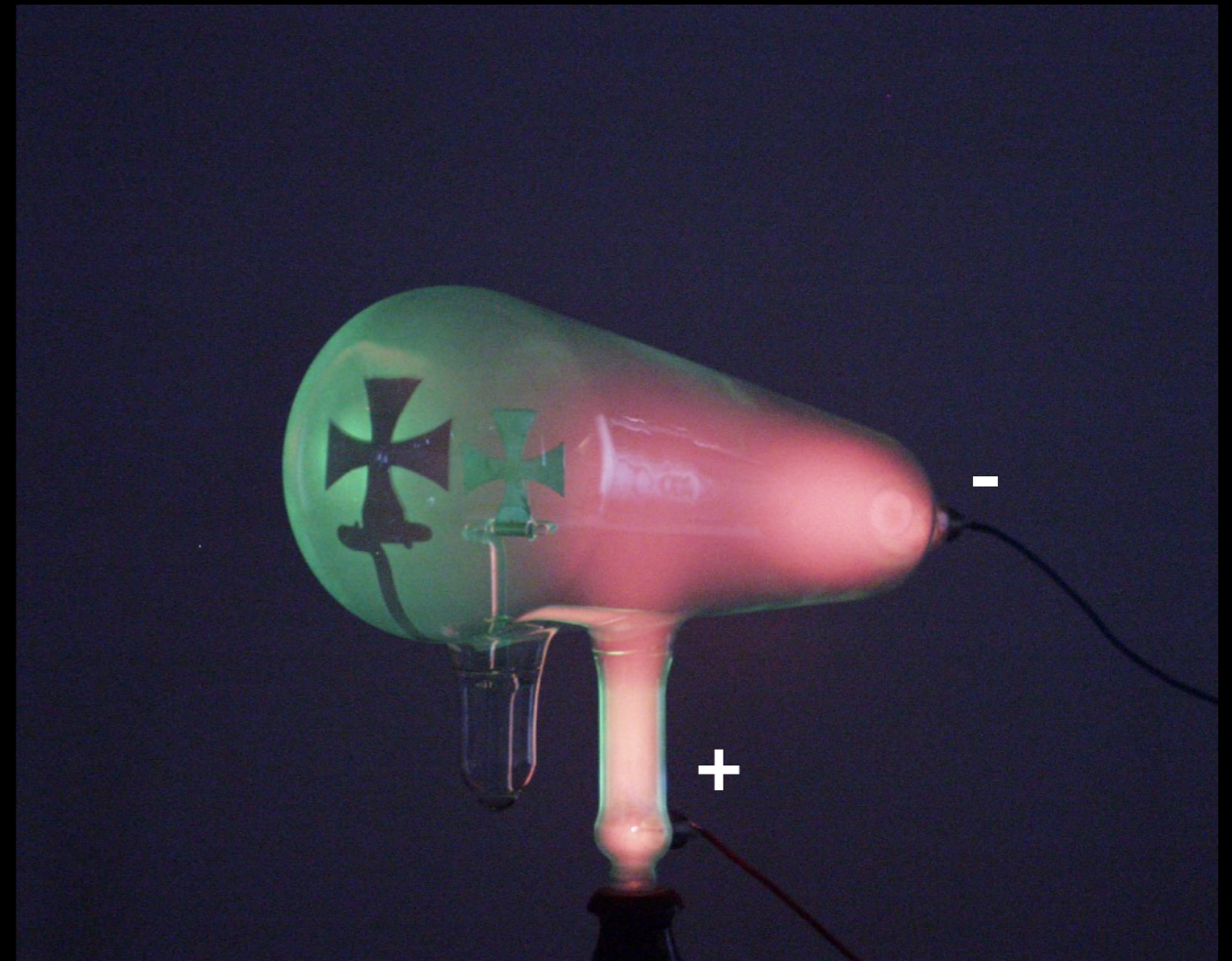
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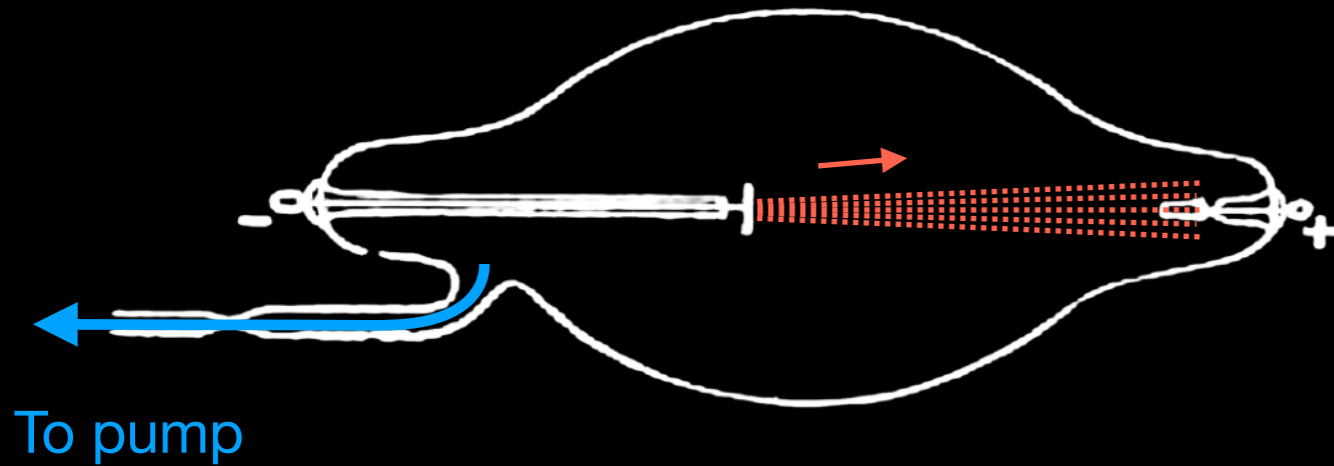
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“... casting strong and sharply-defined shadows of anything which happens to be in its path.”



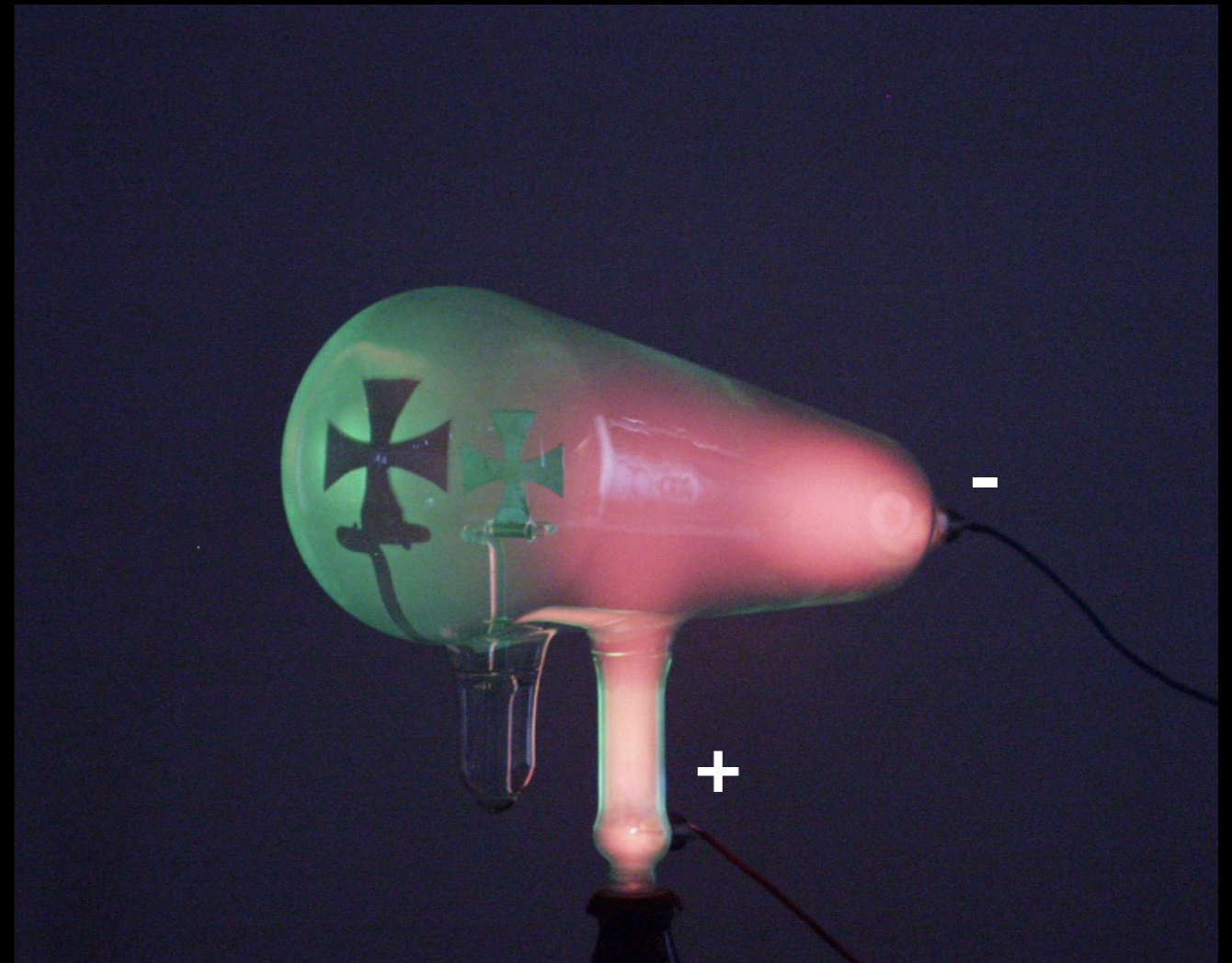
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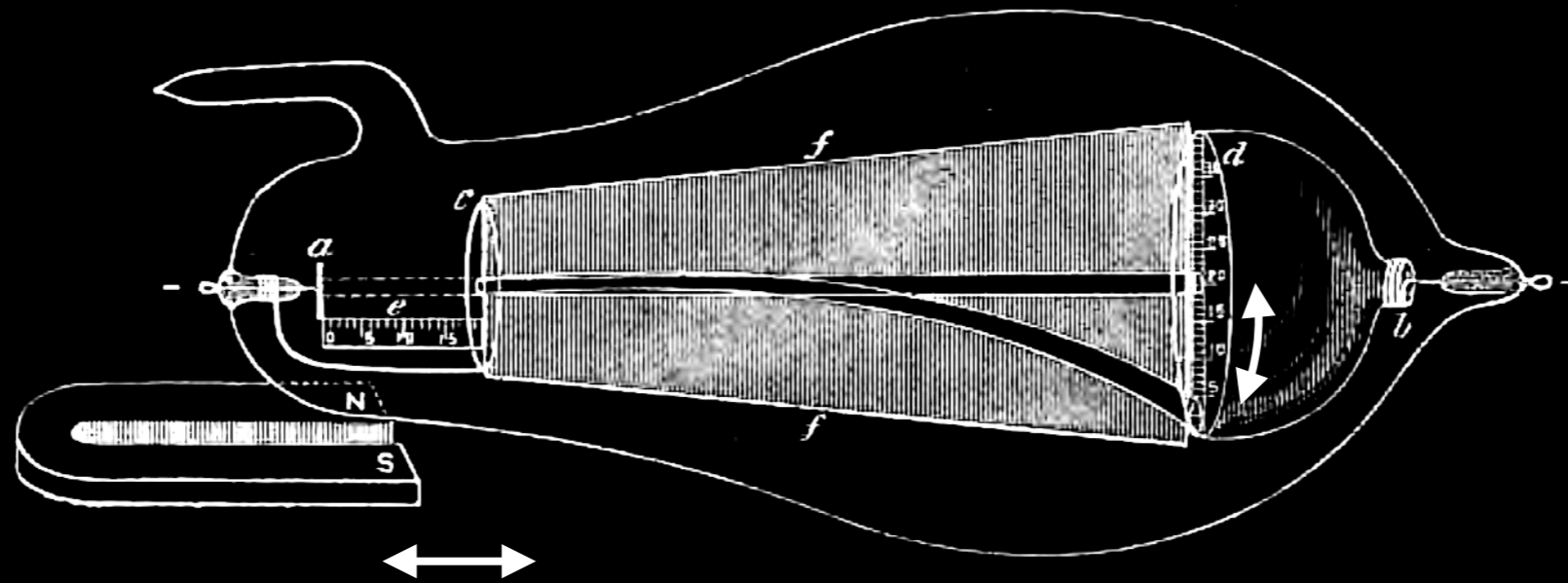
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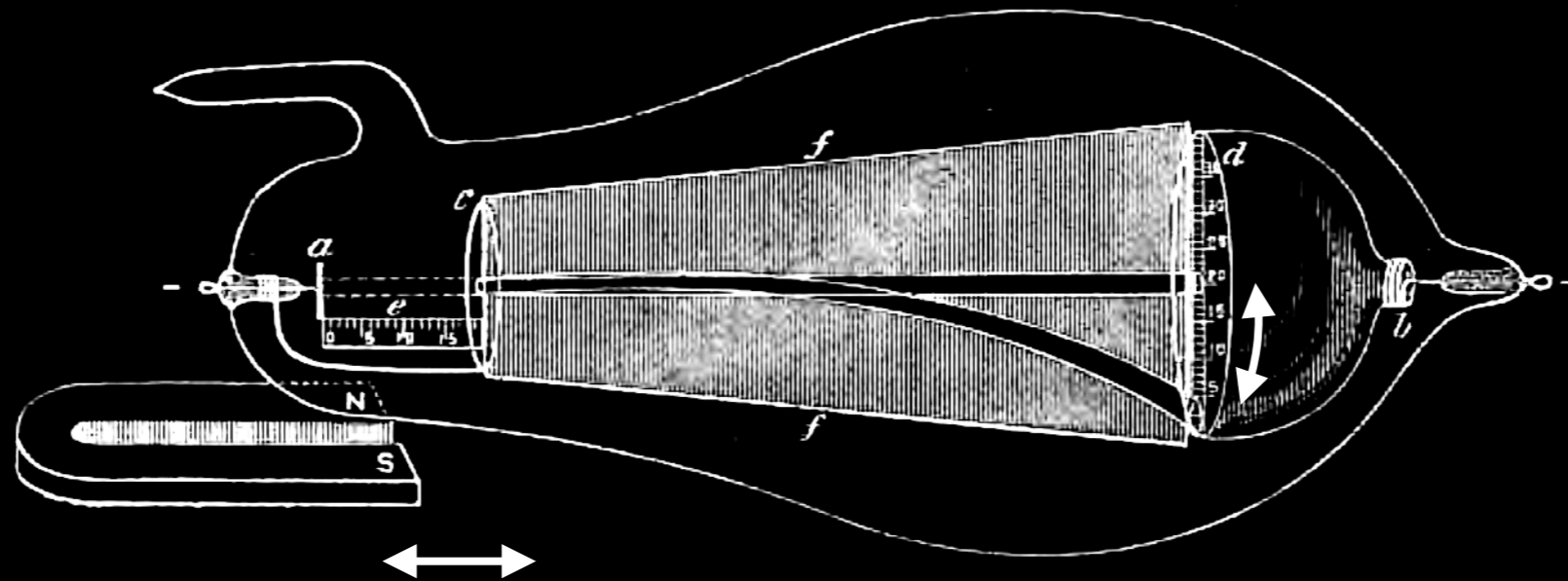


Magnetic deflection (1878)

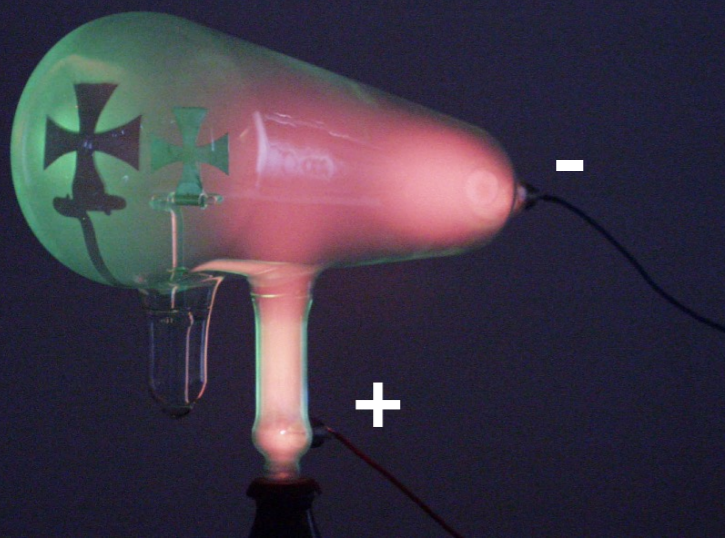


“The path of the ray traces itself in a straight line when the magnet is absent, and curved when the magnet is present.”

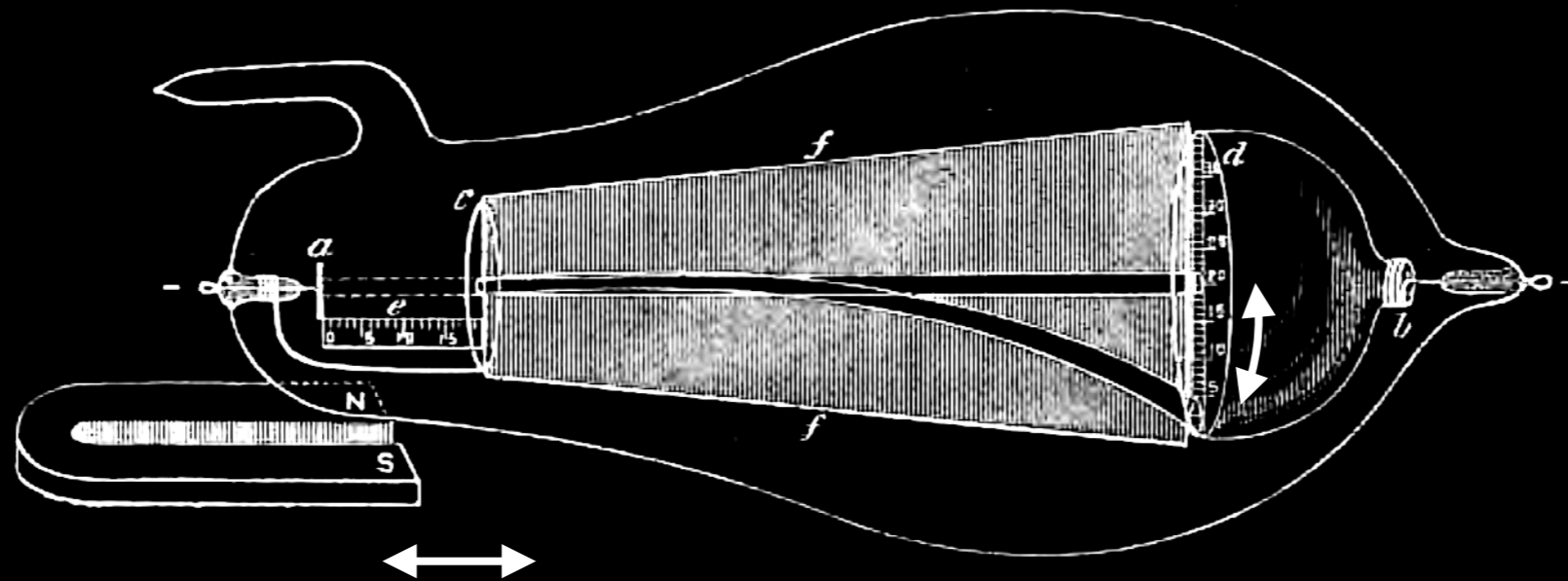
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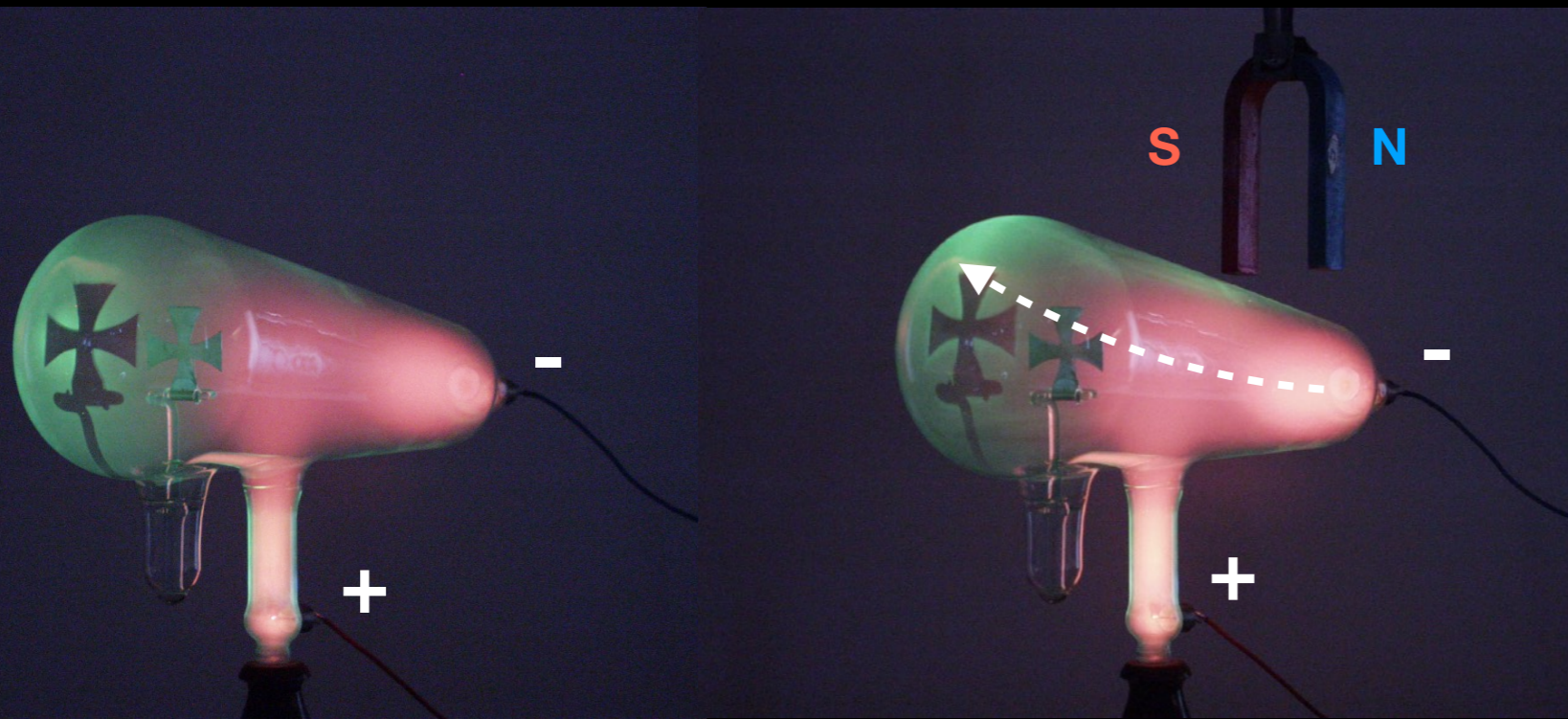
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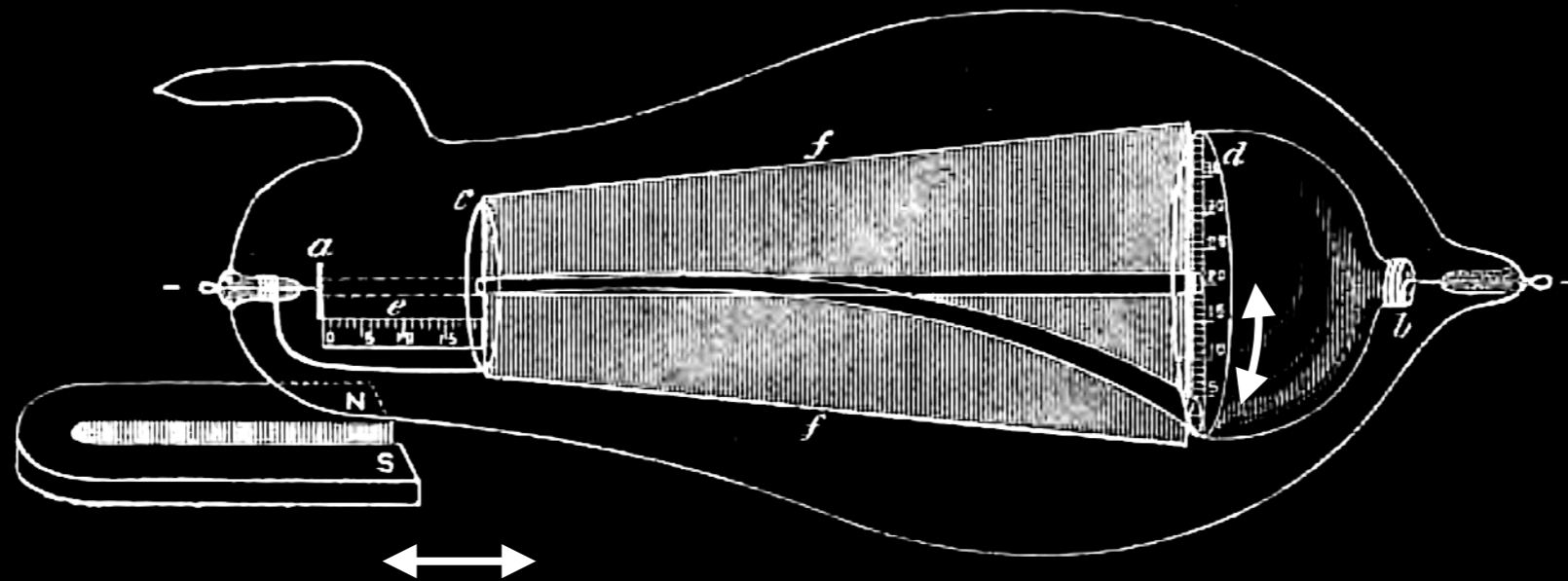
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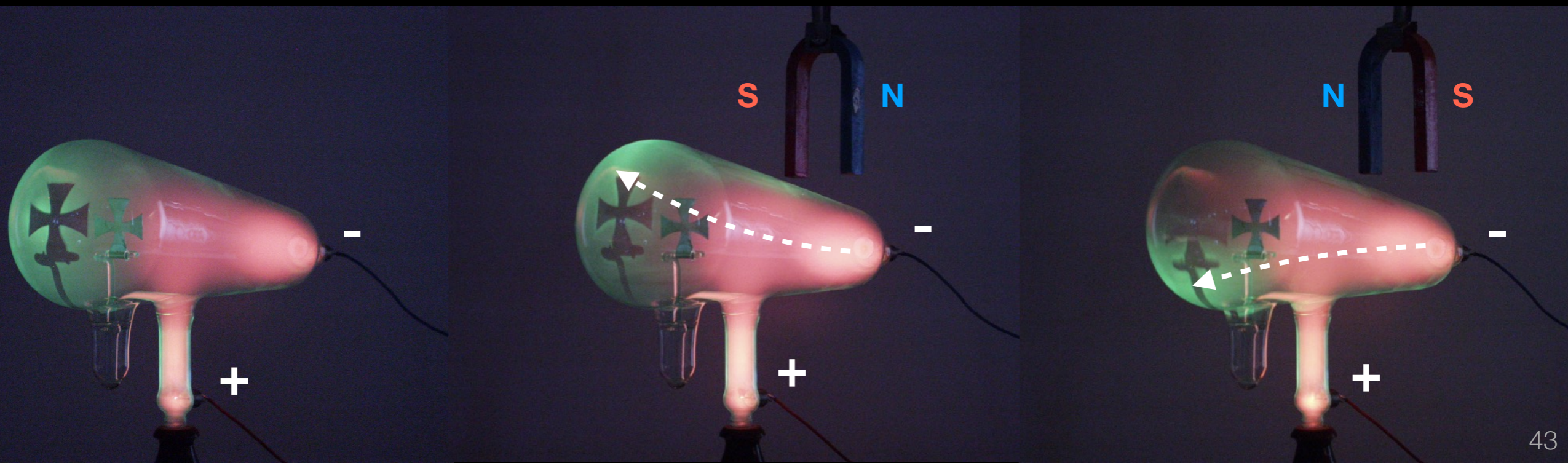
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The kinetic theory of heat ...

Kinetic theory (early 1800s)

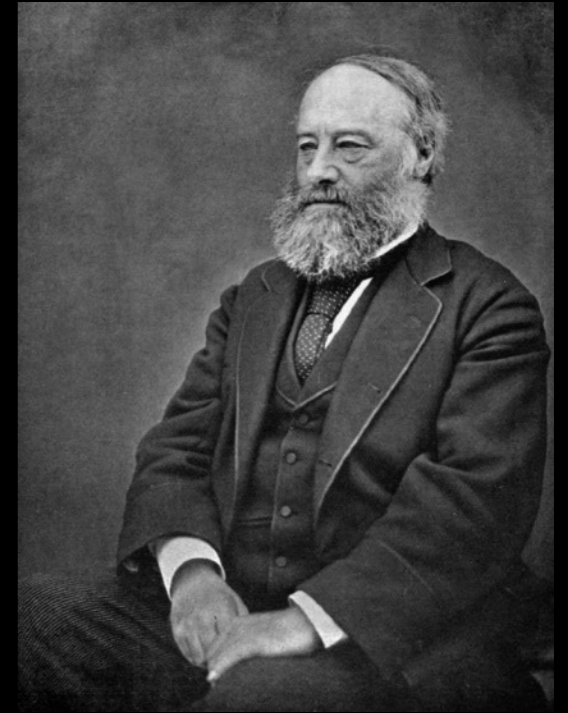
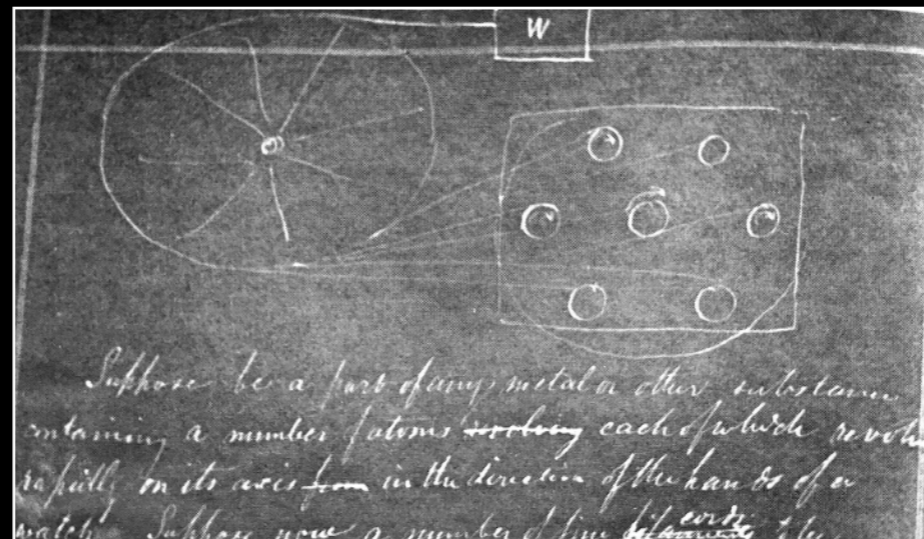
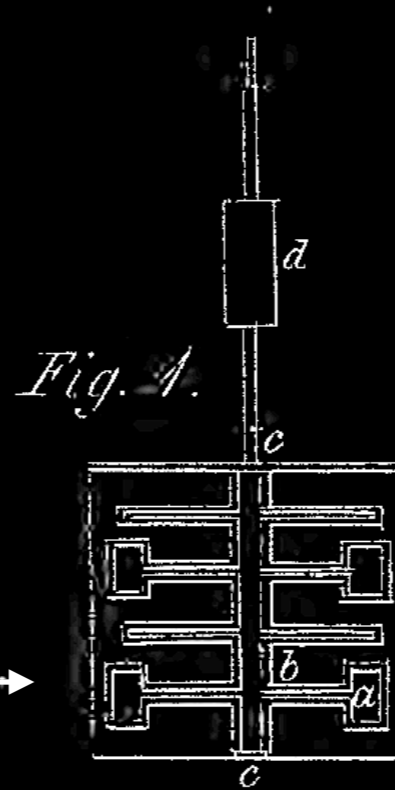
“Heat is a rapid internal tremor of the small particles of the heated bodies.”



Heat from electricity



Heat from friction



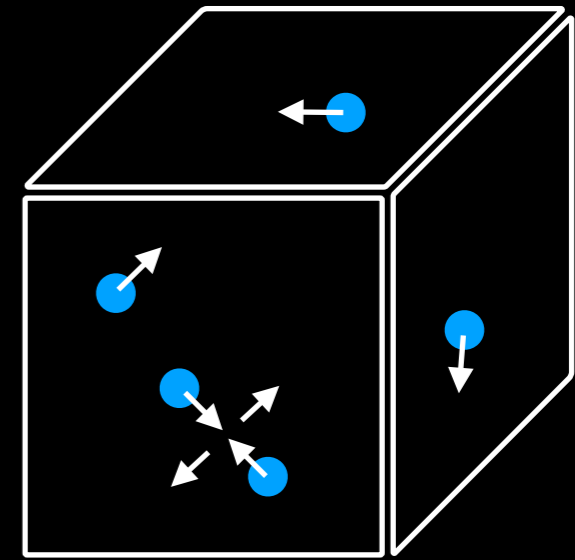
James Joule, 1849:

“Heat is simply a mechanical effect, not a substance.”

... and molecular rays

William Crookes, 1878:

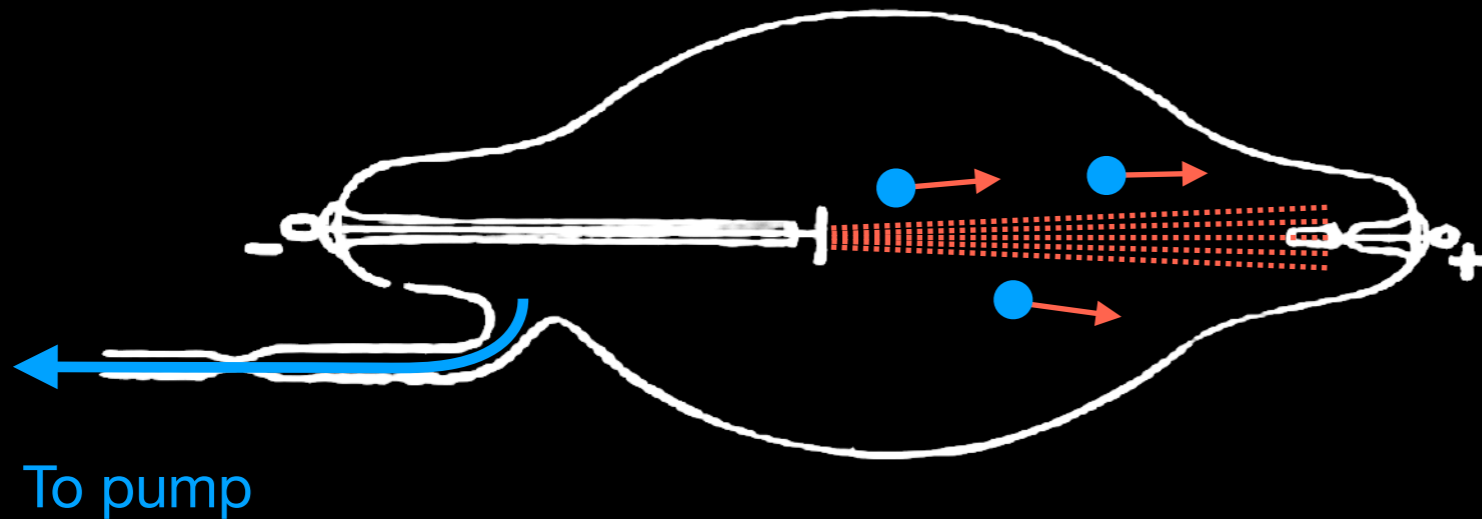
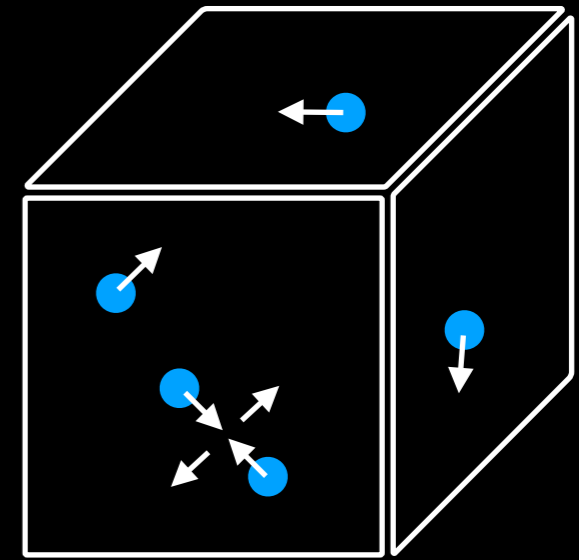
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... and molecular rays

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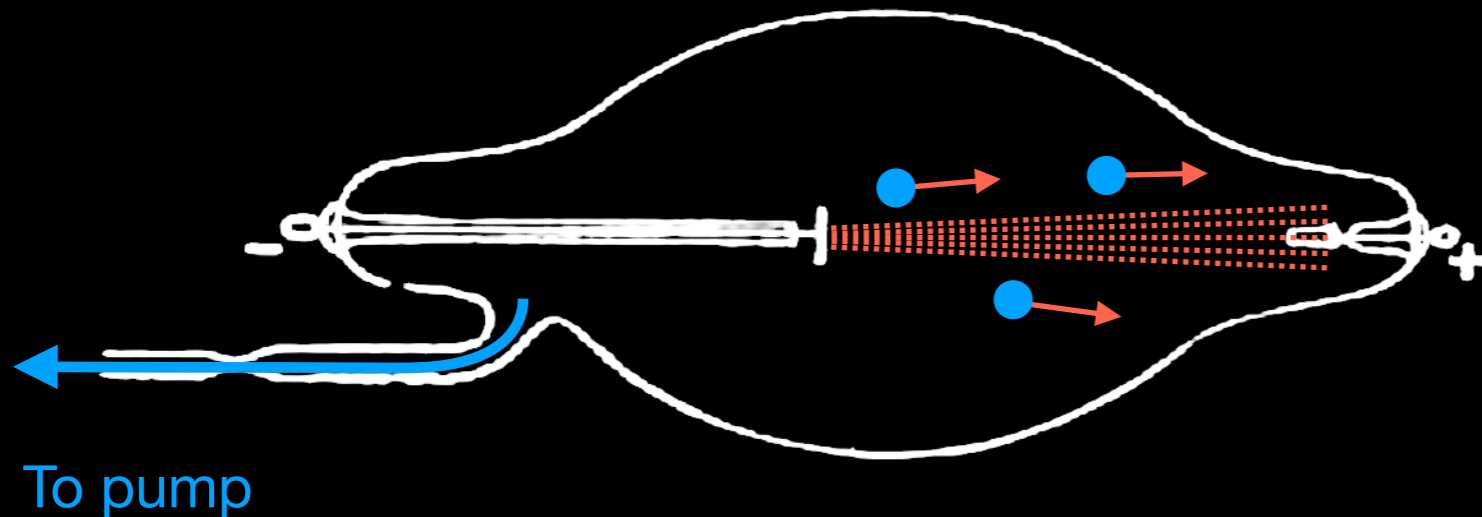
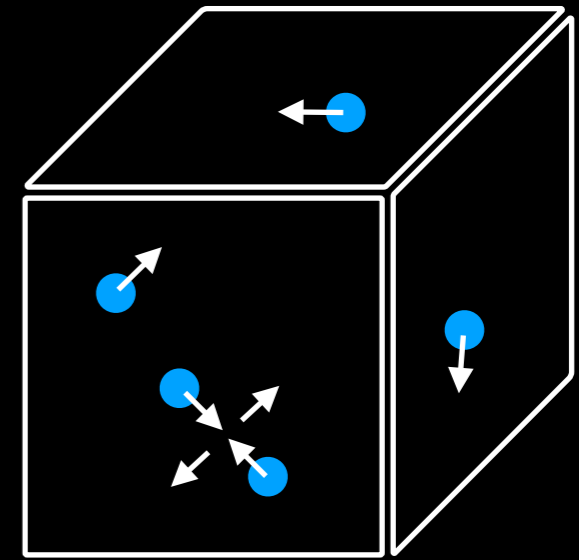
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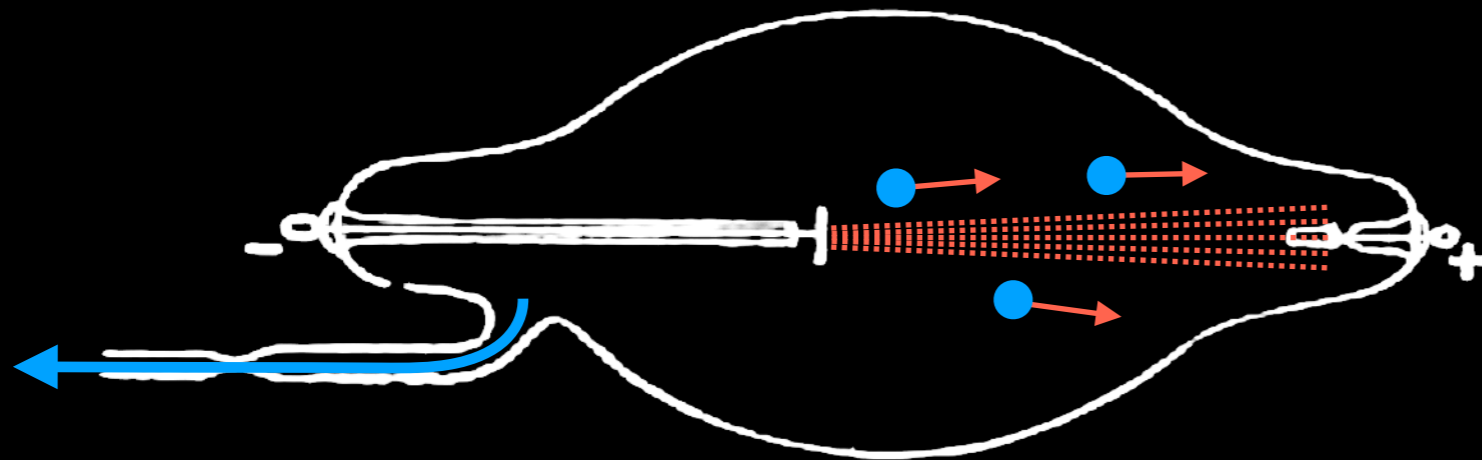
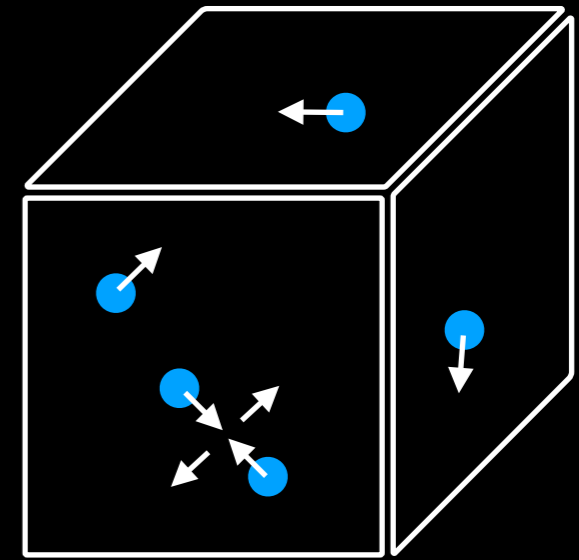


“By great rarefaction the hits become negligible in comparison to the misses.”

... and molecular rays

William Crookes, 1878:

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To pump

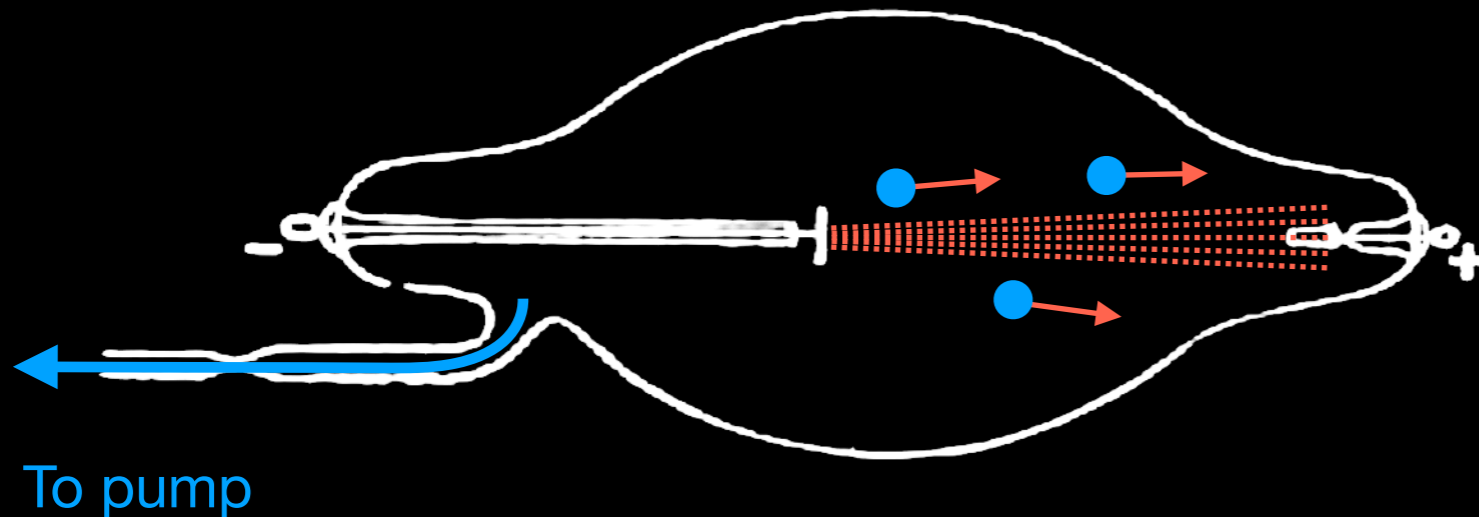
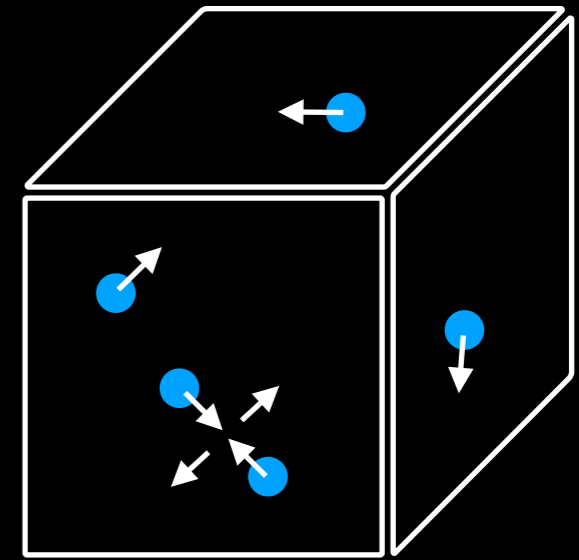
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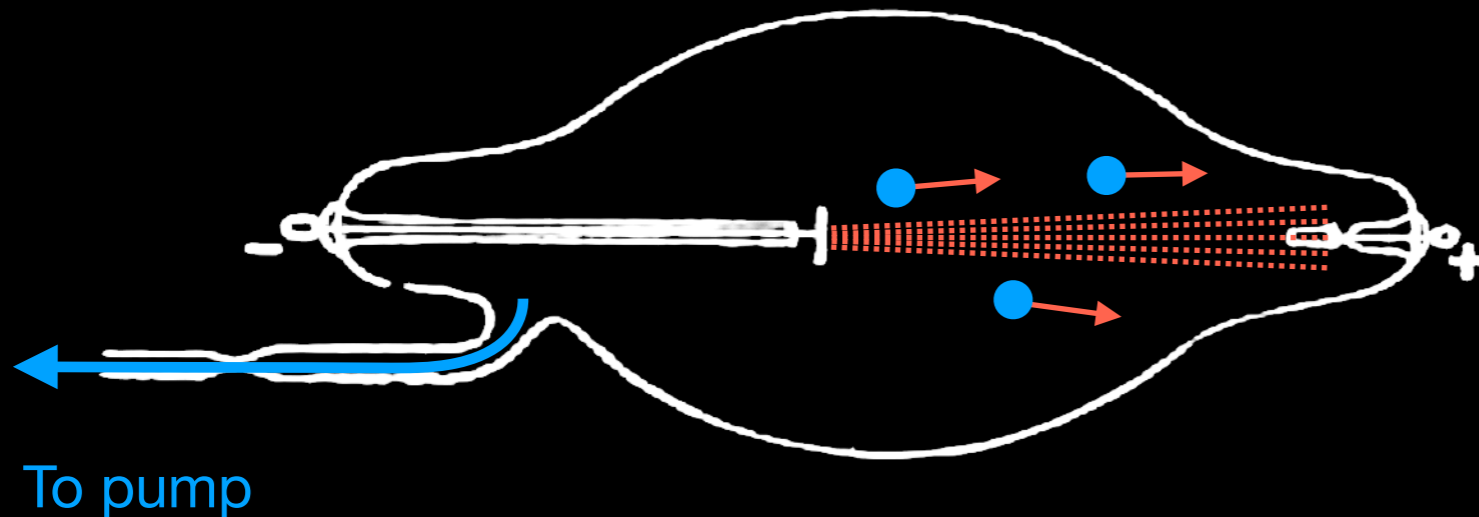
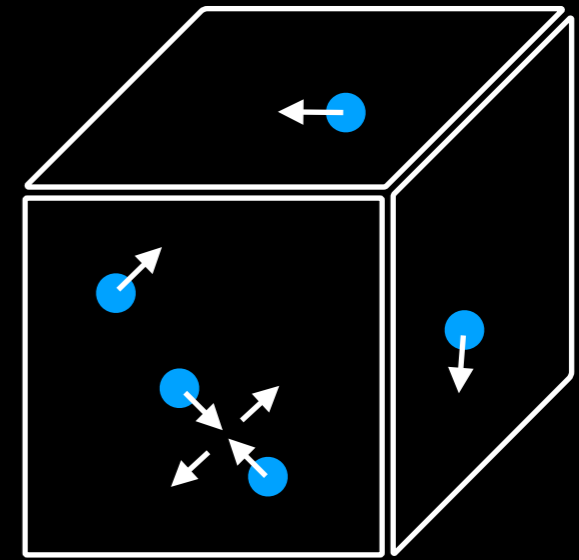
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→ Molecules move in straight lines at low pressures

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Crookes got it wrong!
(What's the connection with electricity?)

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→ Molecules move in straight lines at low pressures

Wilhelm Conrad Röntgen



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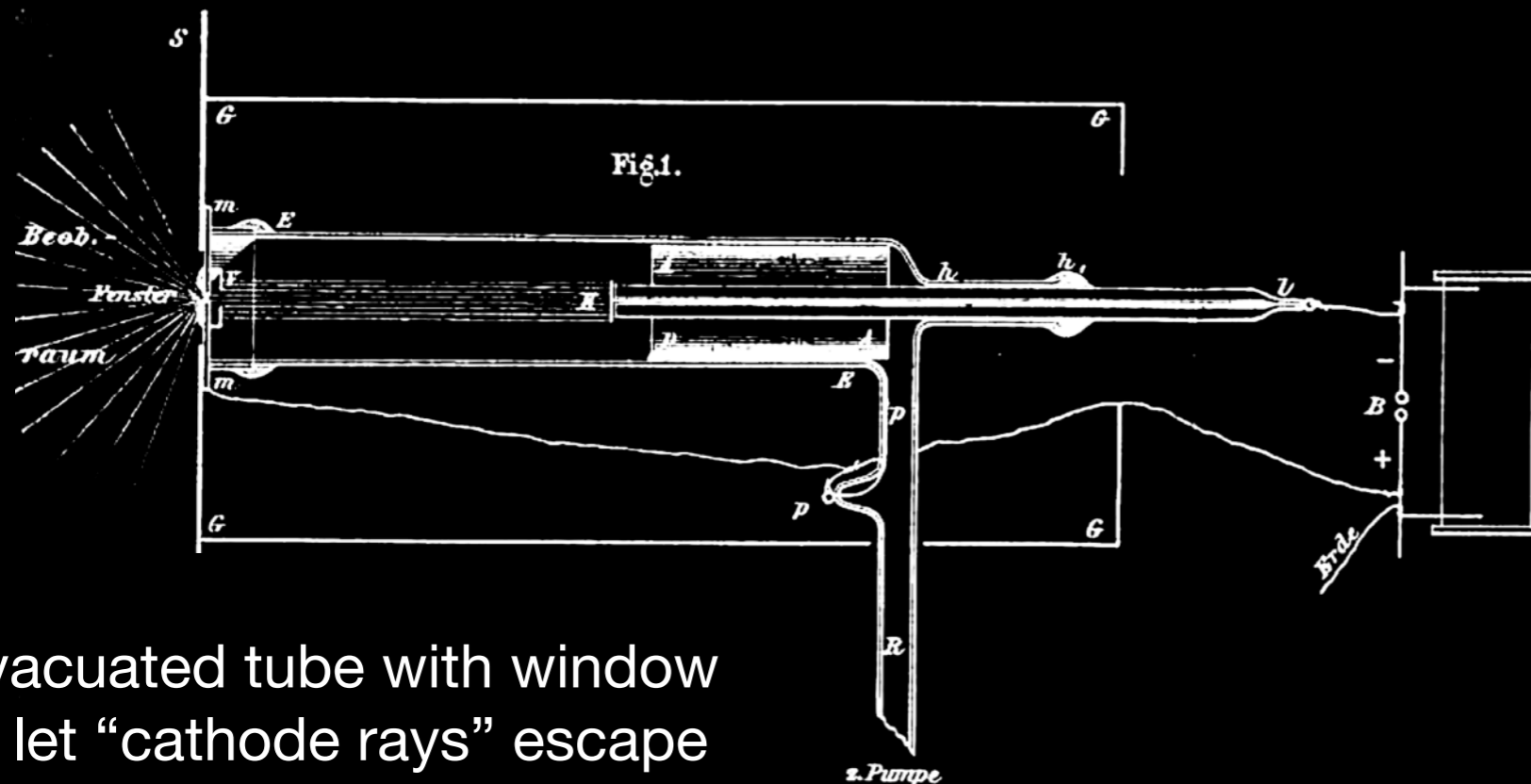
Professor at the
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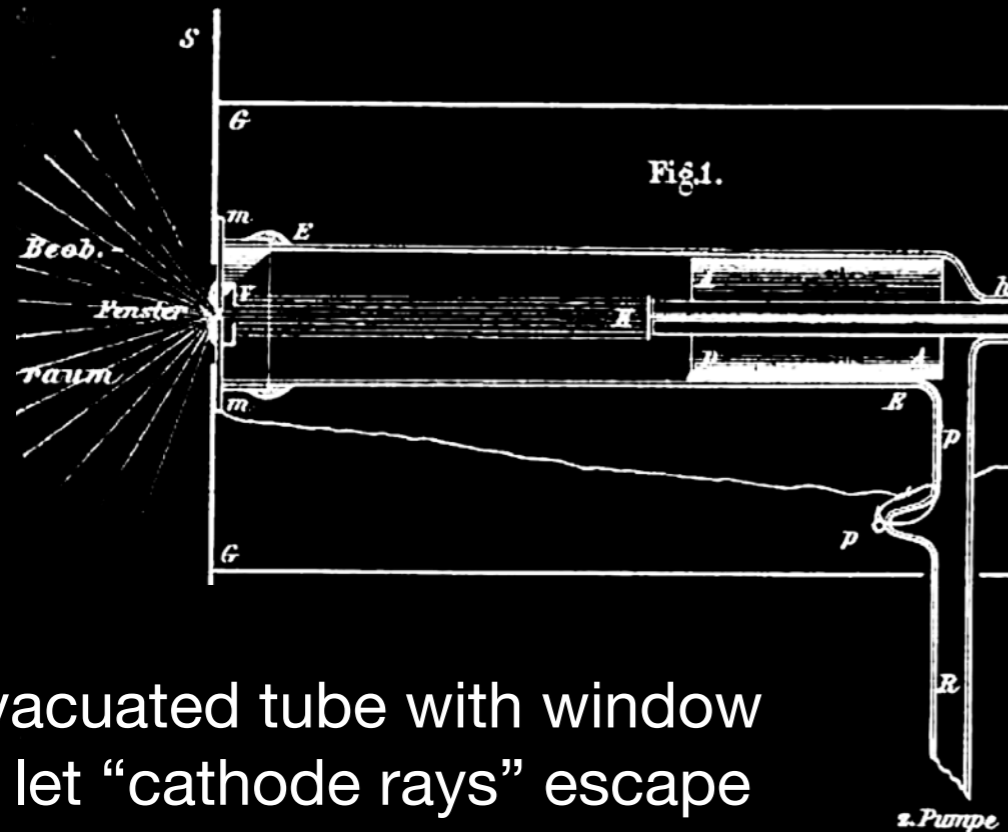
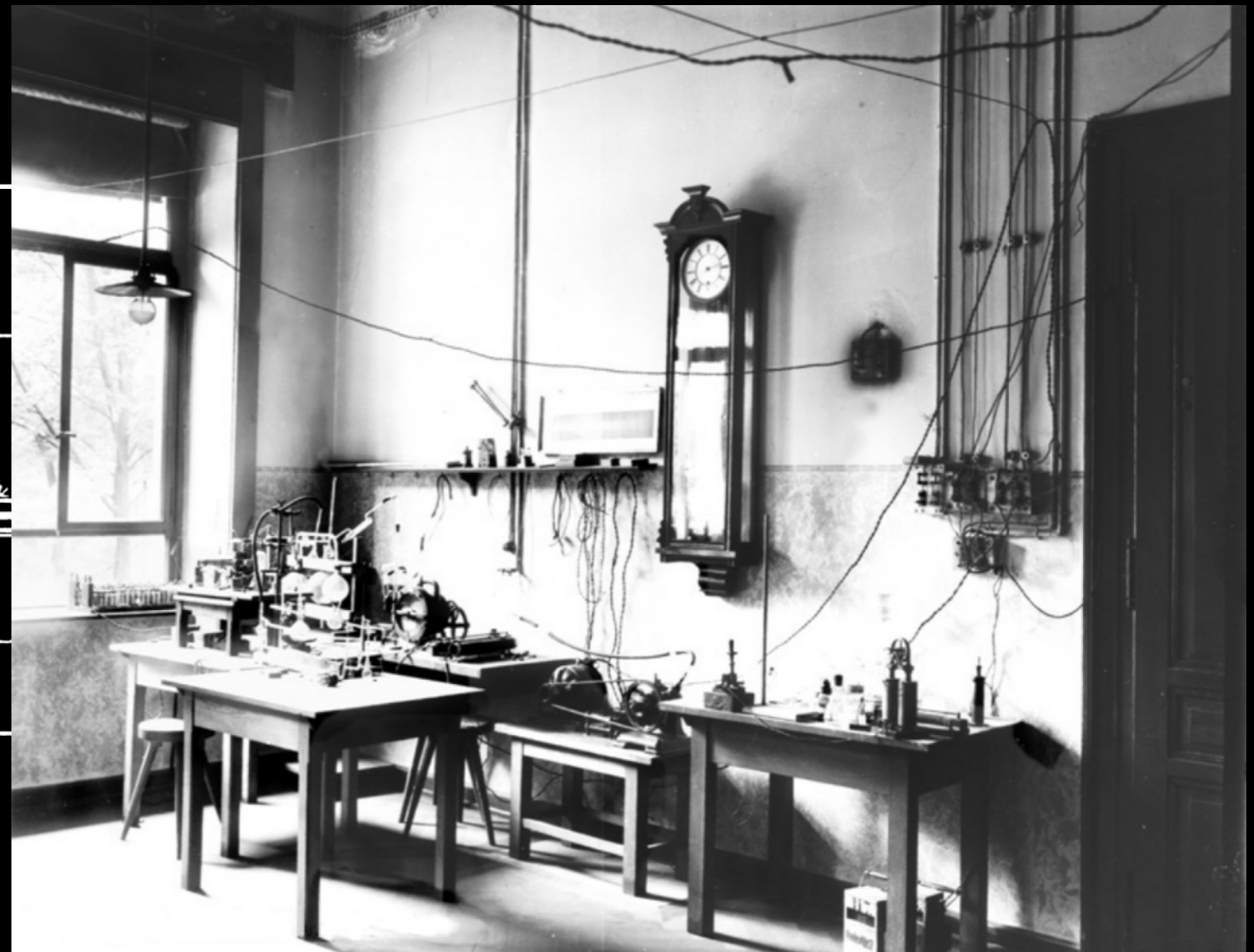


Evacuated tube with window to let "cathode rays" escape

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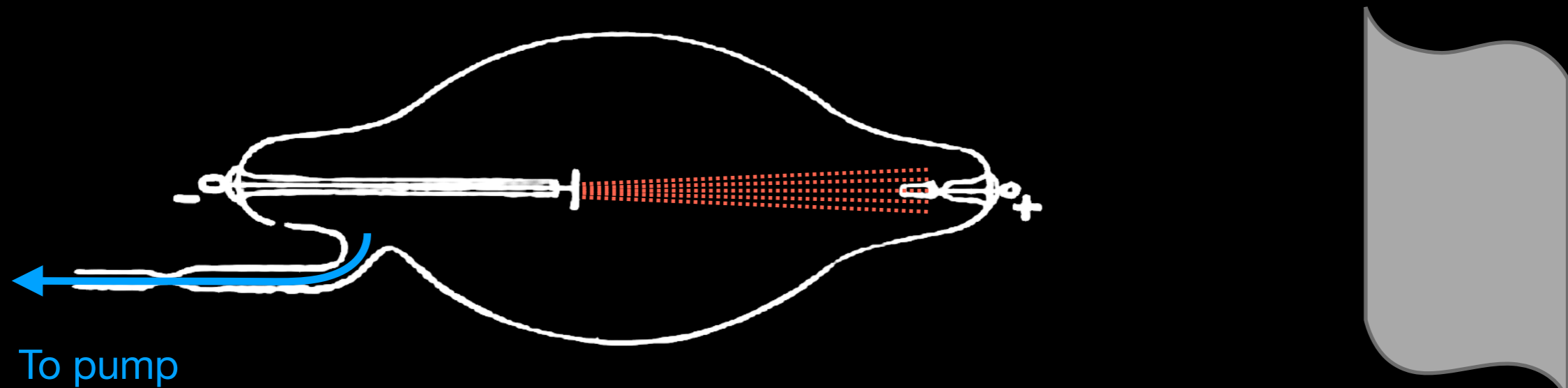
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Röntgen's experiments

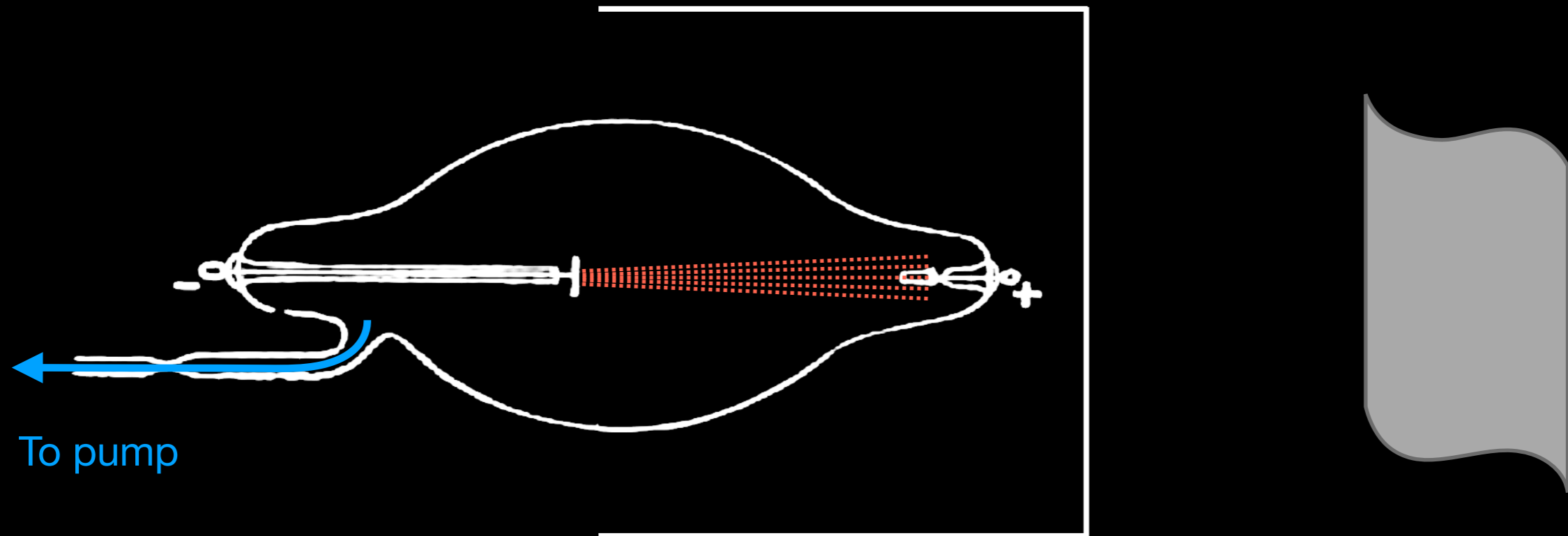
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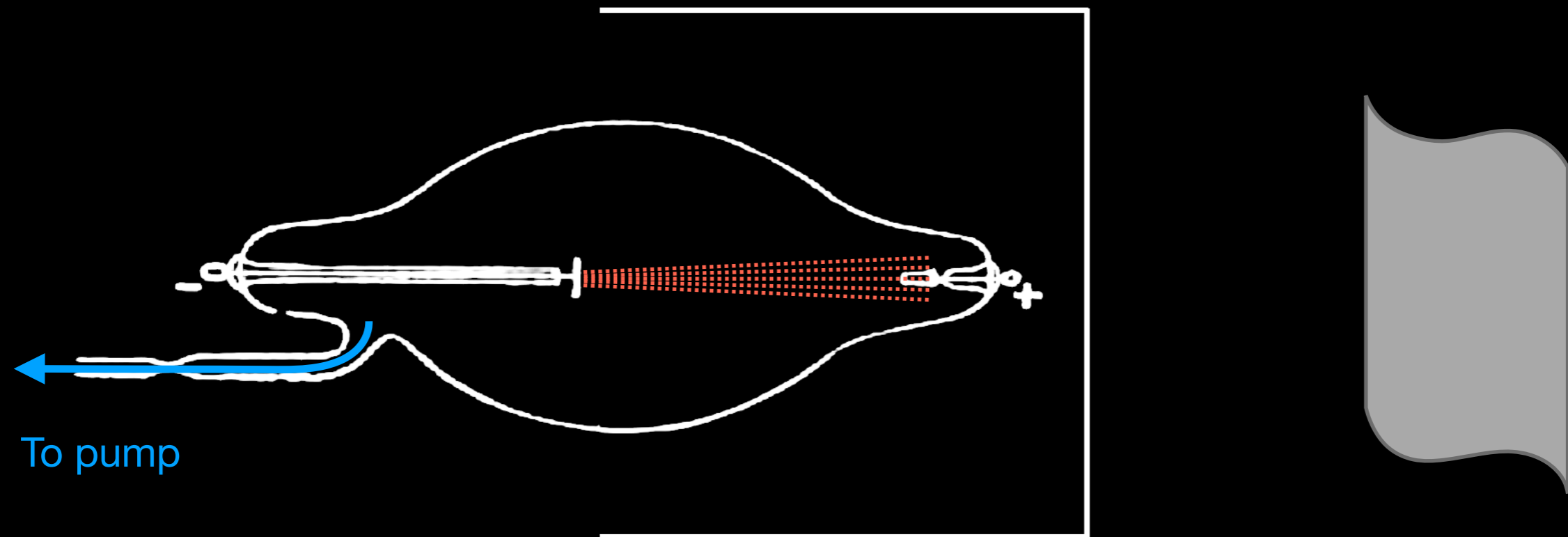
“The tube is surrounded by a fairly close-fitting shield of black paper.”



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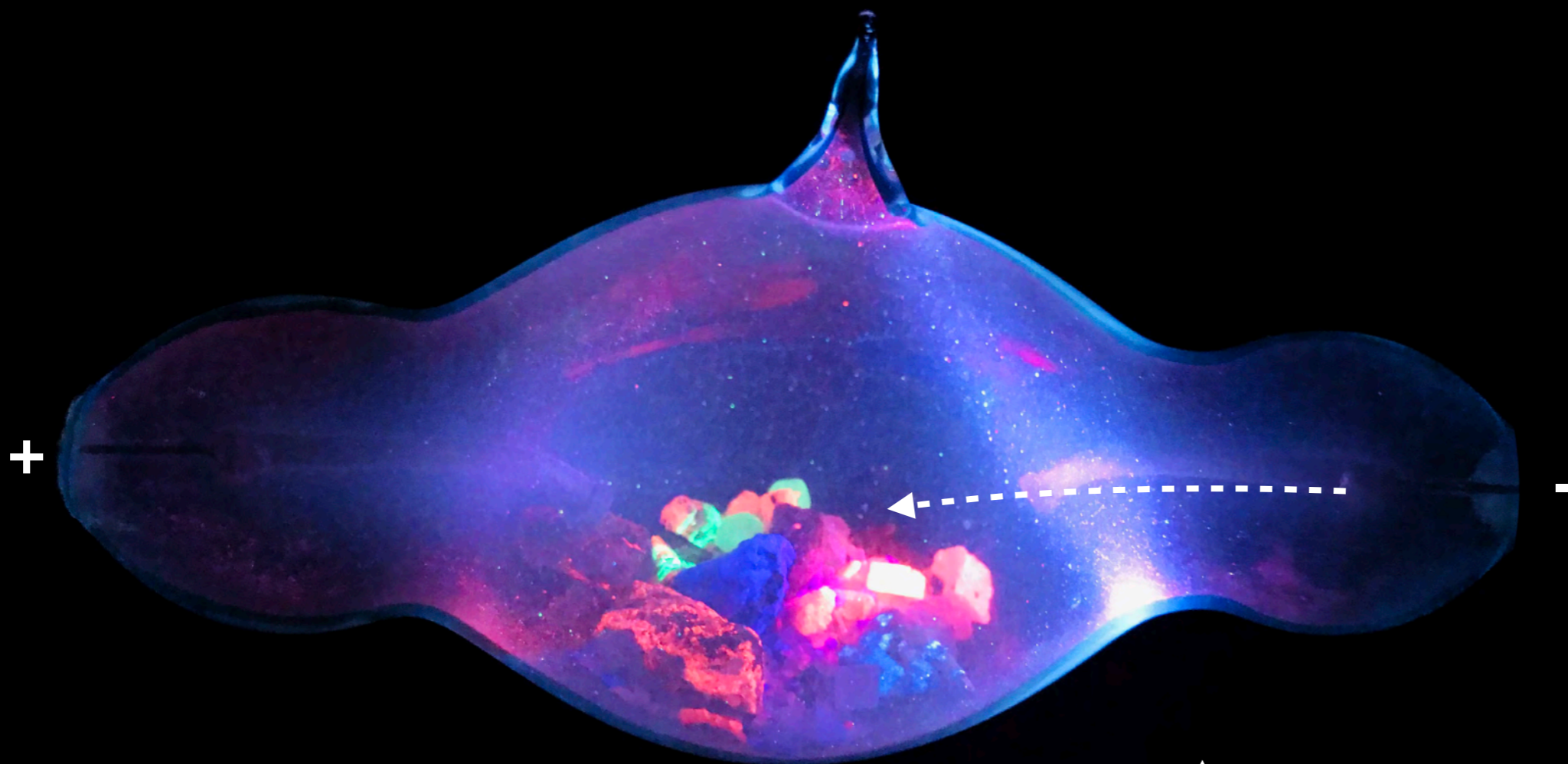
“The tube is surrounded by a fairly close-fitting shield of black paper.”



“Paper covered on one side with barium platinocyanide was brought near the tube.”

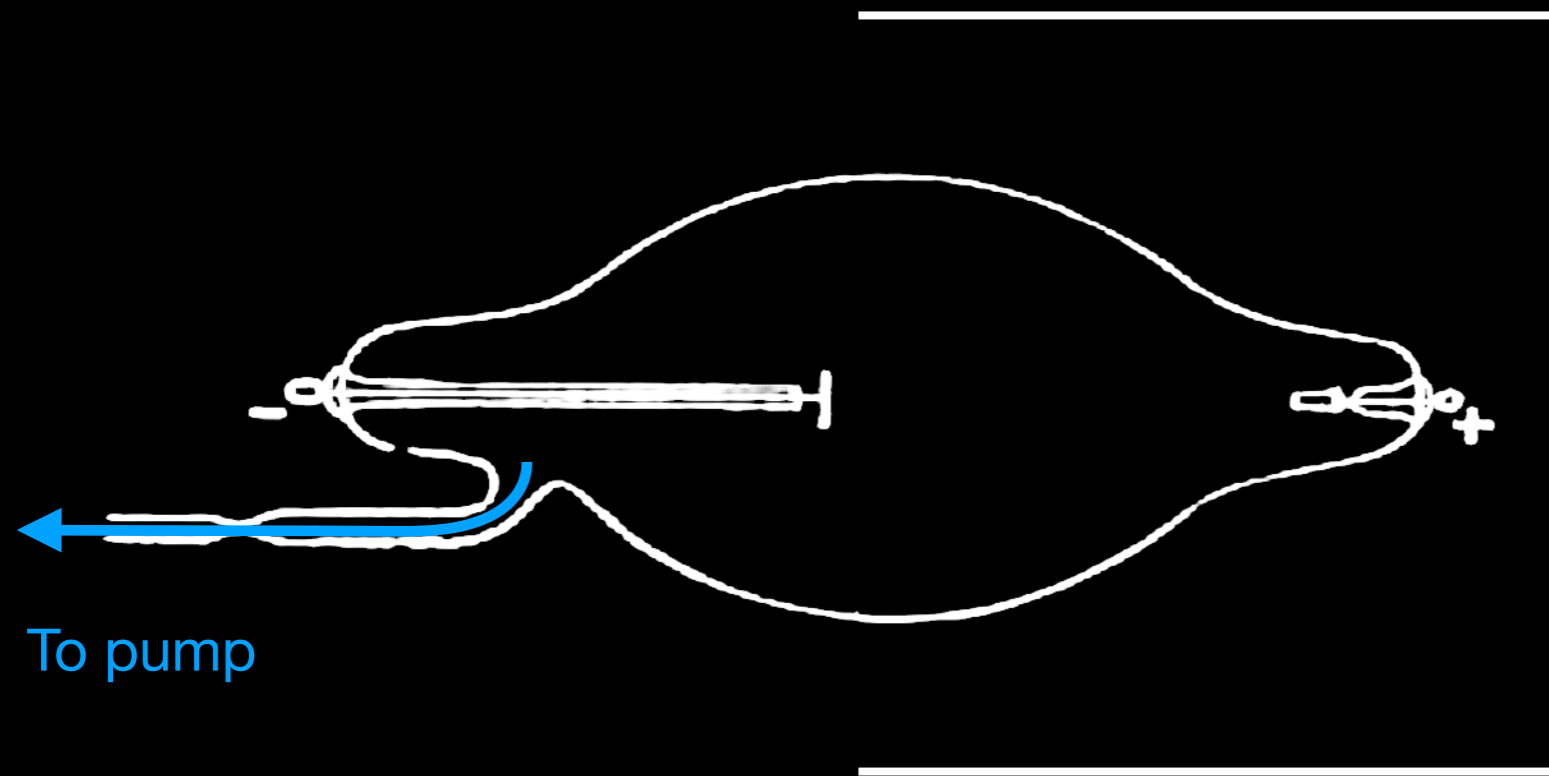
Barium platinocyanide?!

Very common material, used by Crookes and others in lecture demonstrations



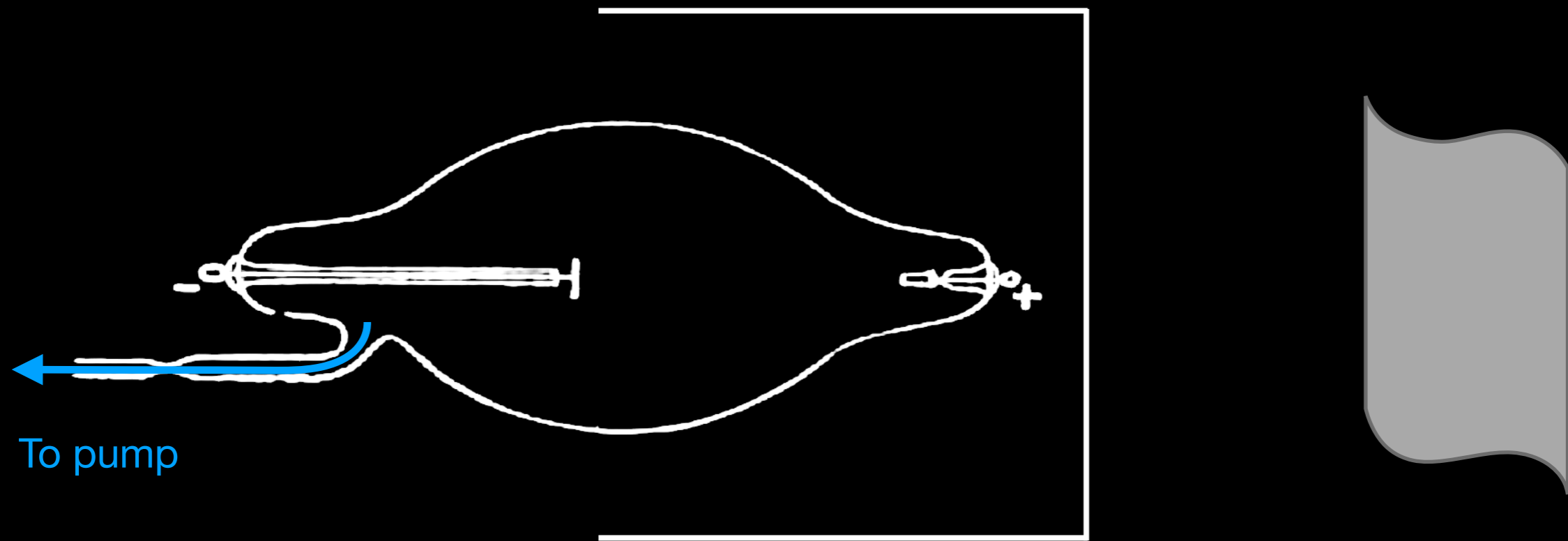
Crookes' tube containing fluorescent materials

“A new kind of rays” (1895)



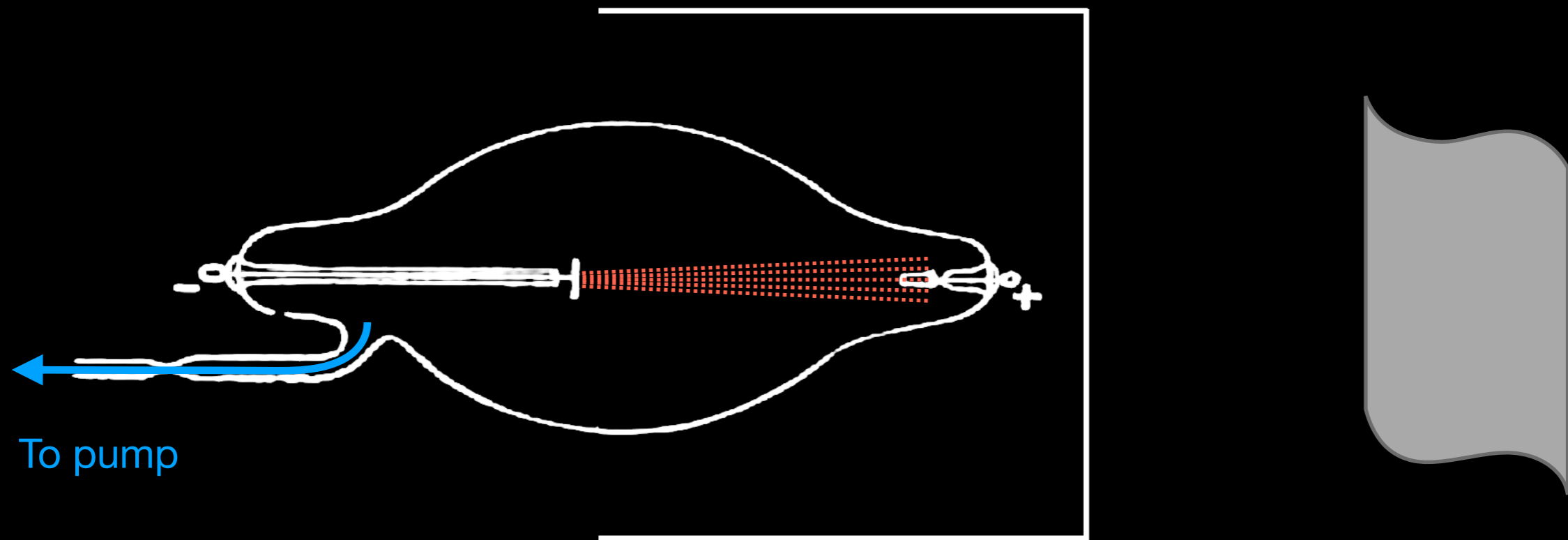
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“The moment the current passed, the paper began to glow.”



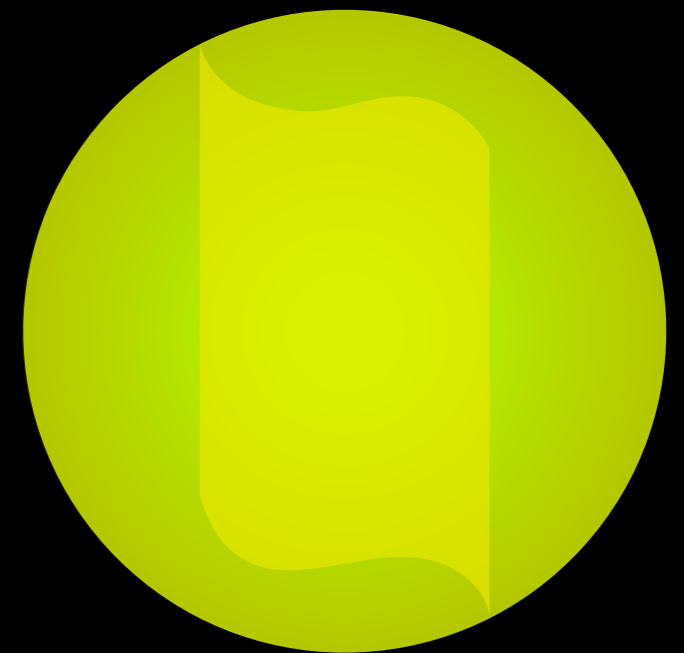
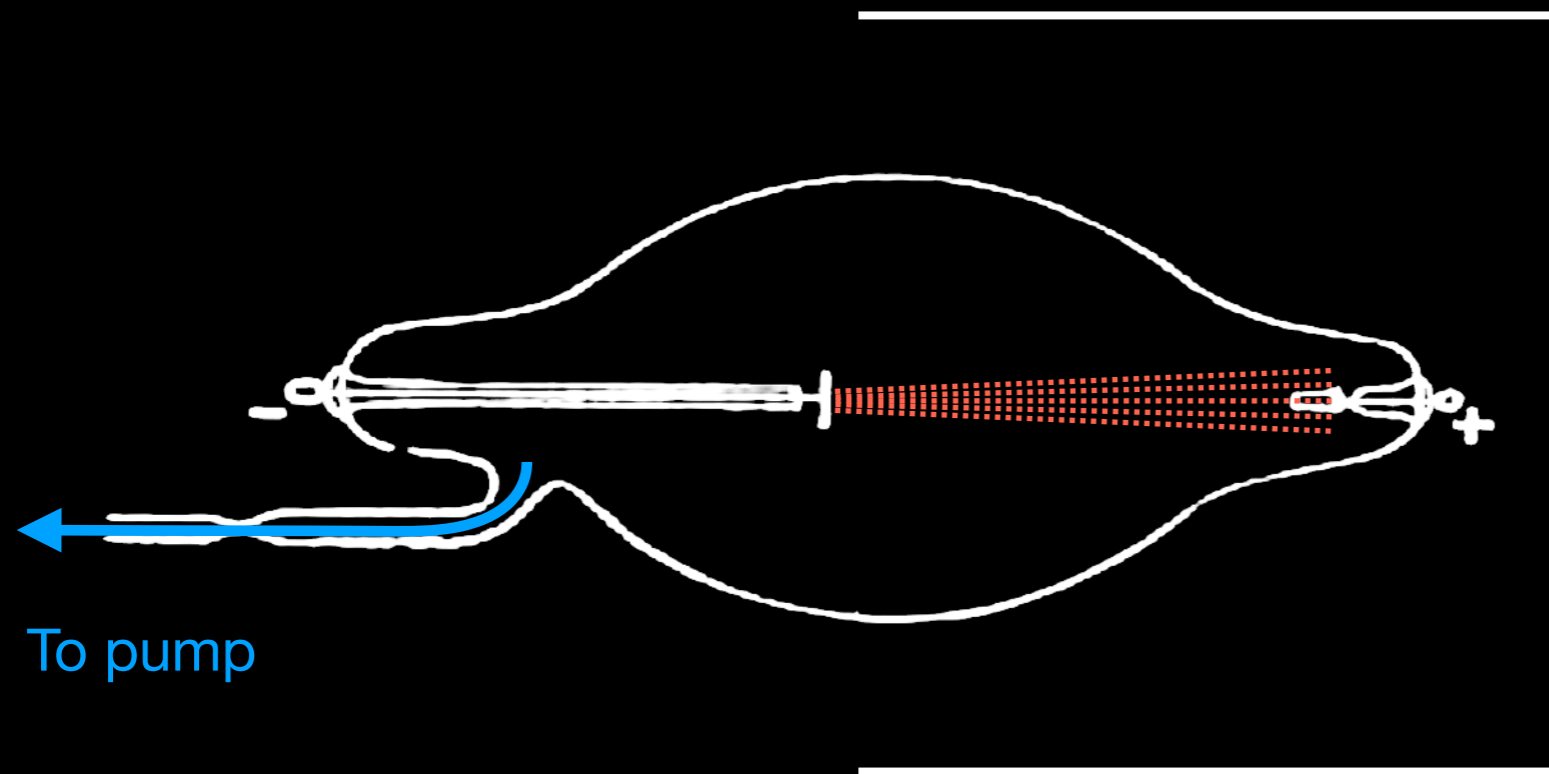
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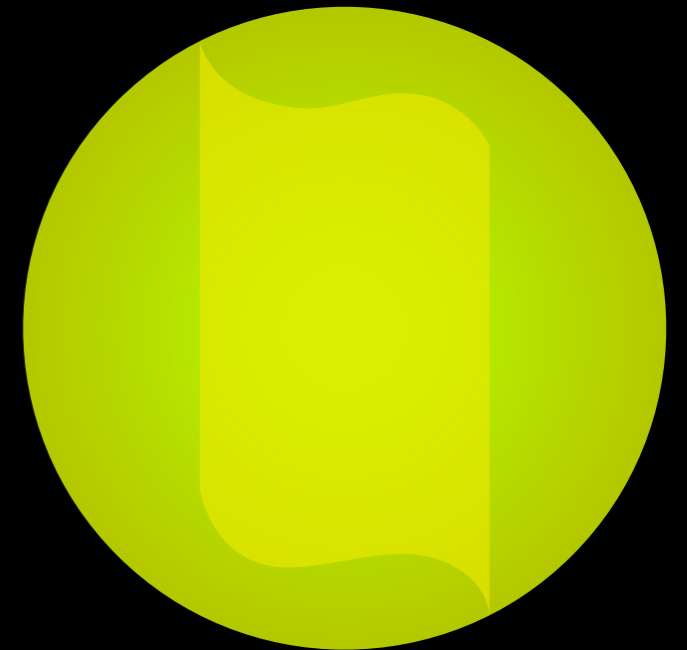
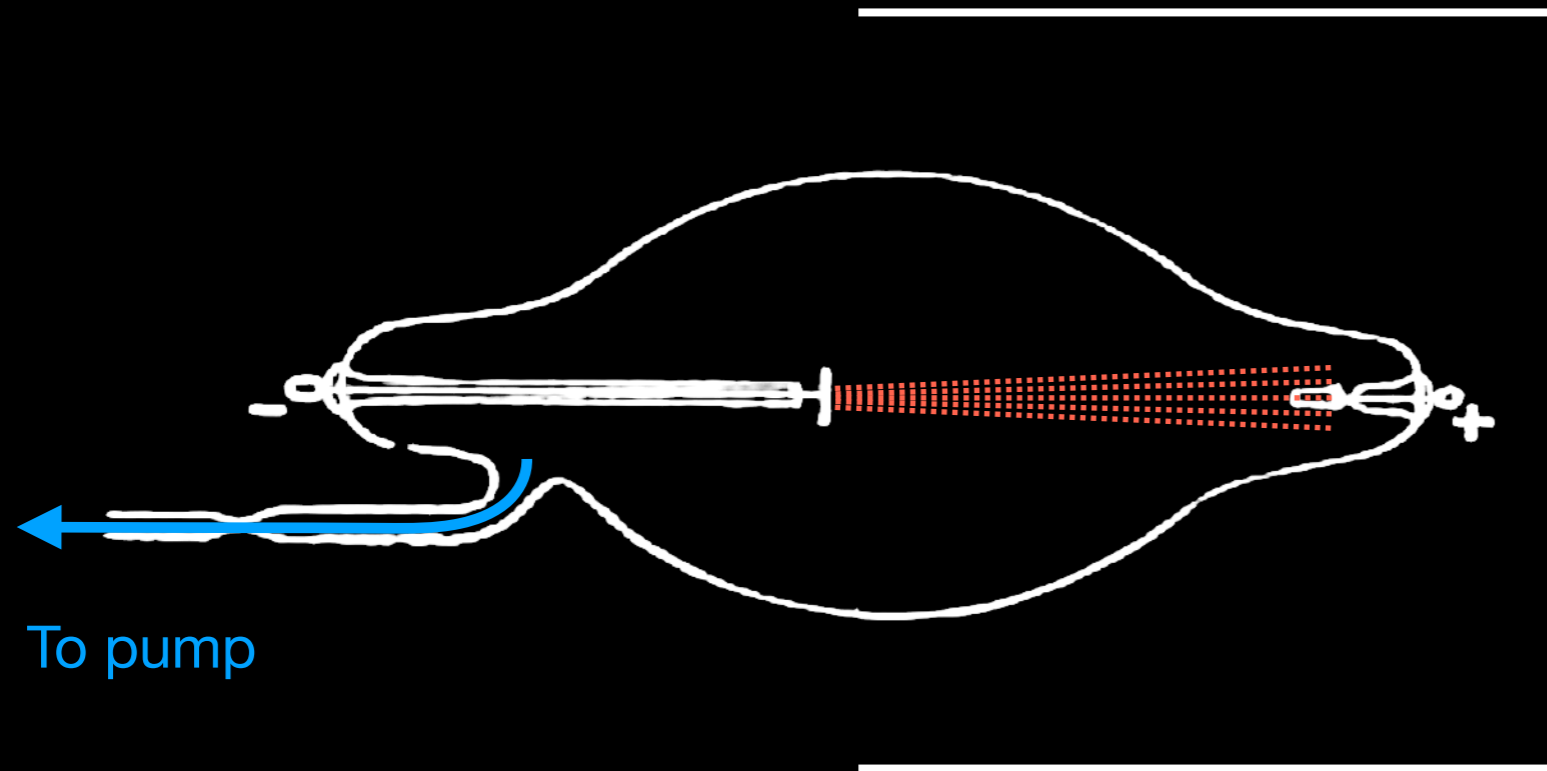
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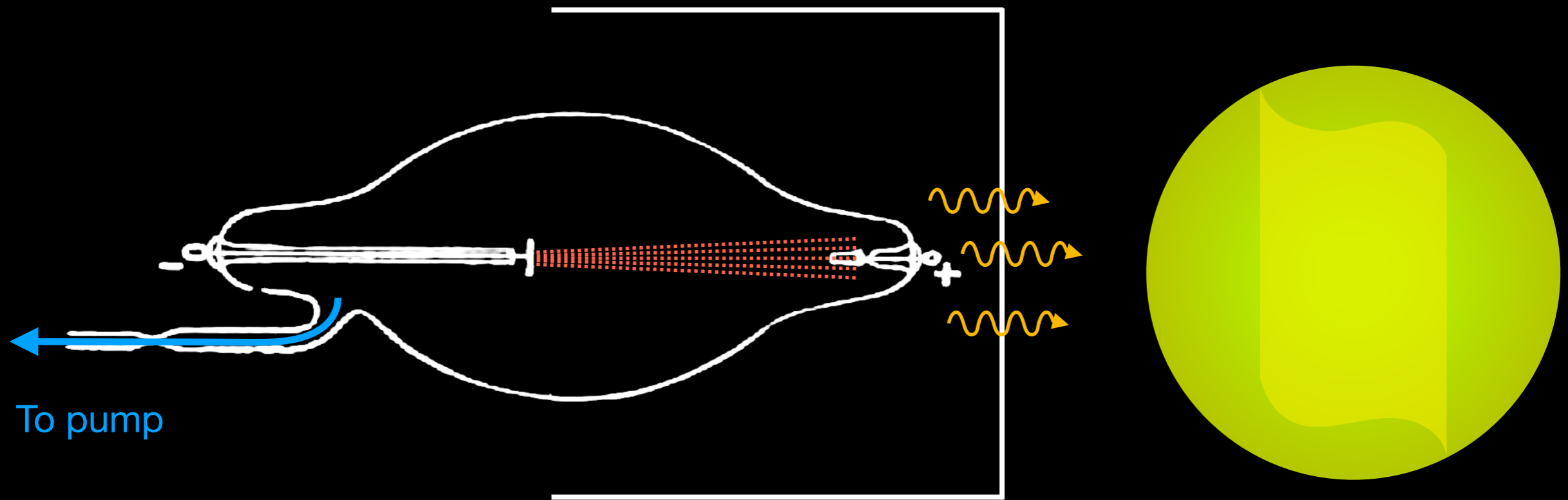
*“A yellowish-green light spread all over its surface in clouds, waves, and flashes.
The luminescence trembled, wavered, and floated over the paper,
in rhythm with the snapping of the discharge.”*



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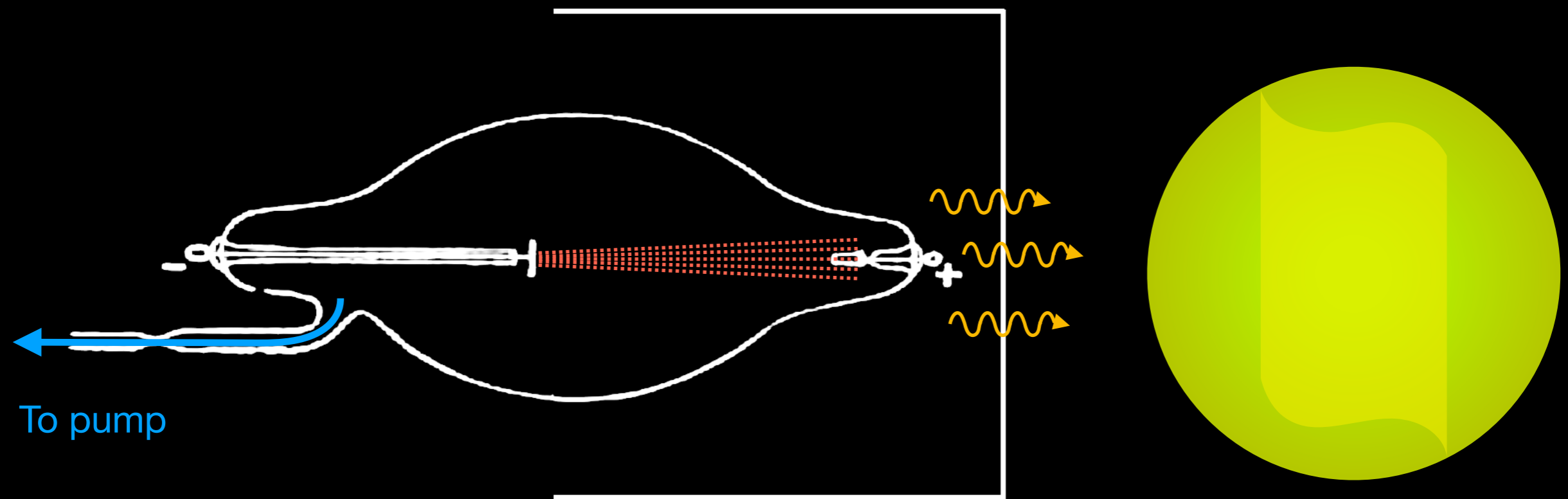


“It is seen that some agent is capable of penetrating black cardboard which is quite opaque to ultra-violet light, sunlight, or arc light.”

“A new kind of rays” (1895)

“It is therefore of interest to investigate how far other bodies can be penetrated by the same agent.”

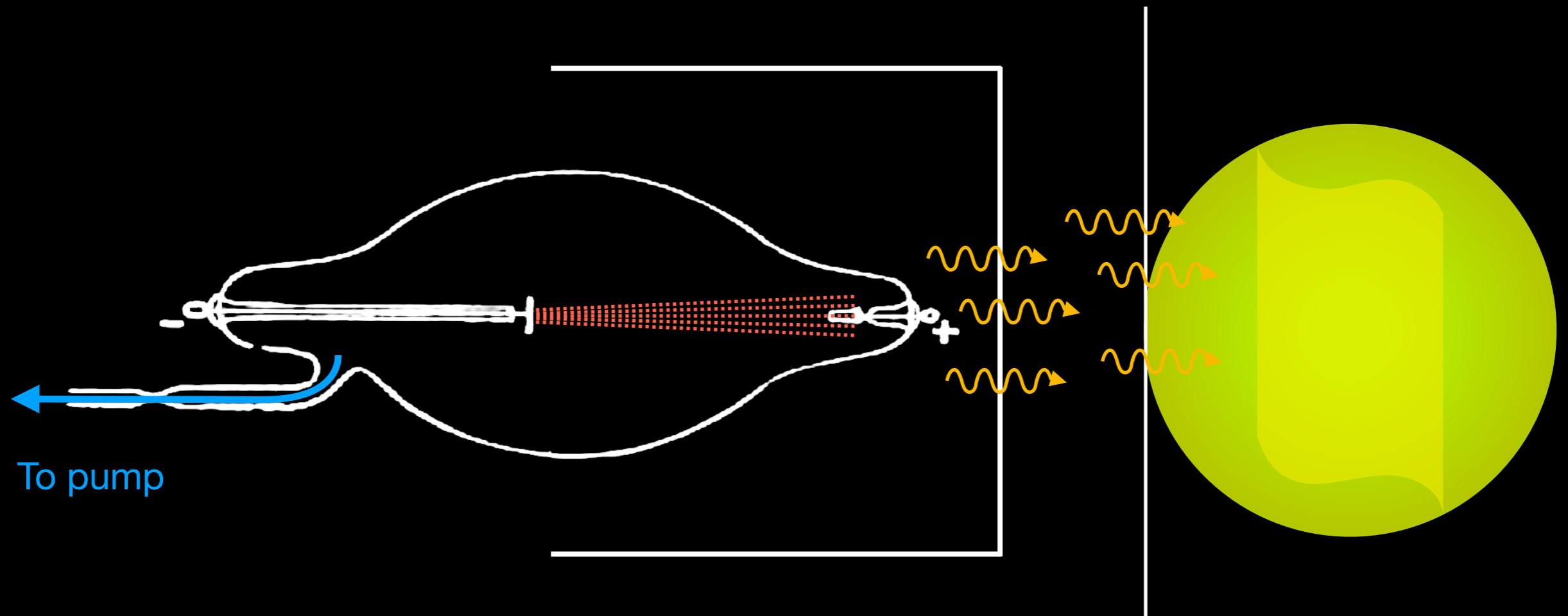
“For example, paper is very transparent.”



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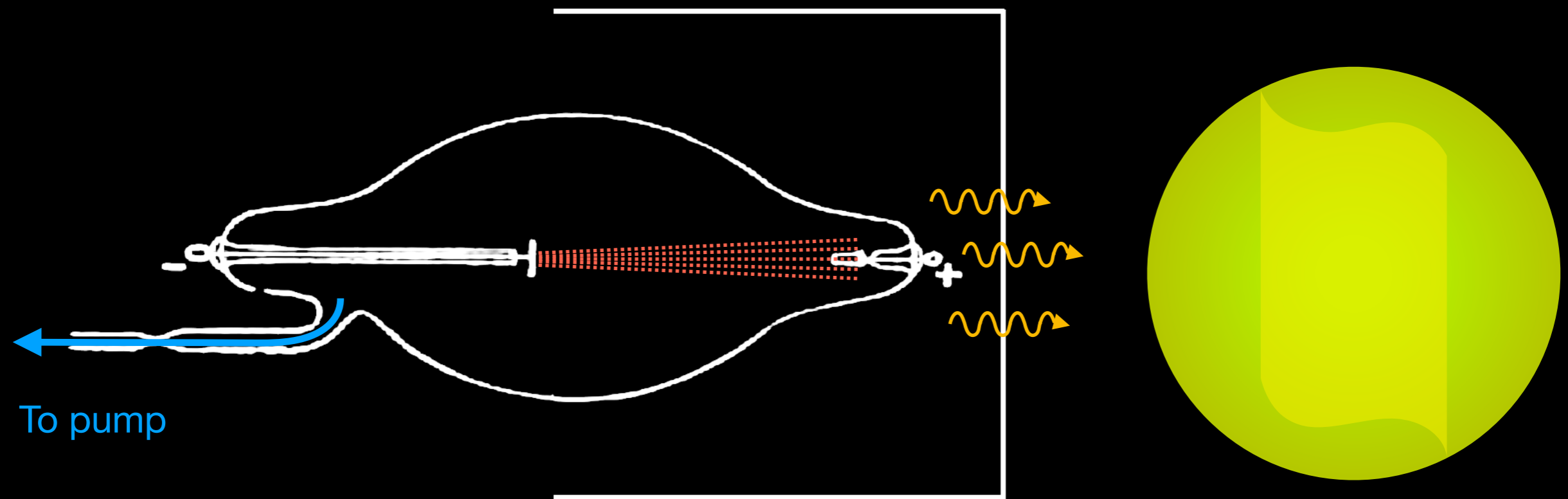
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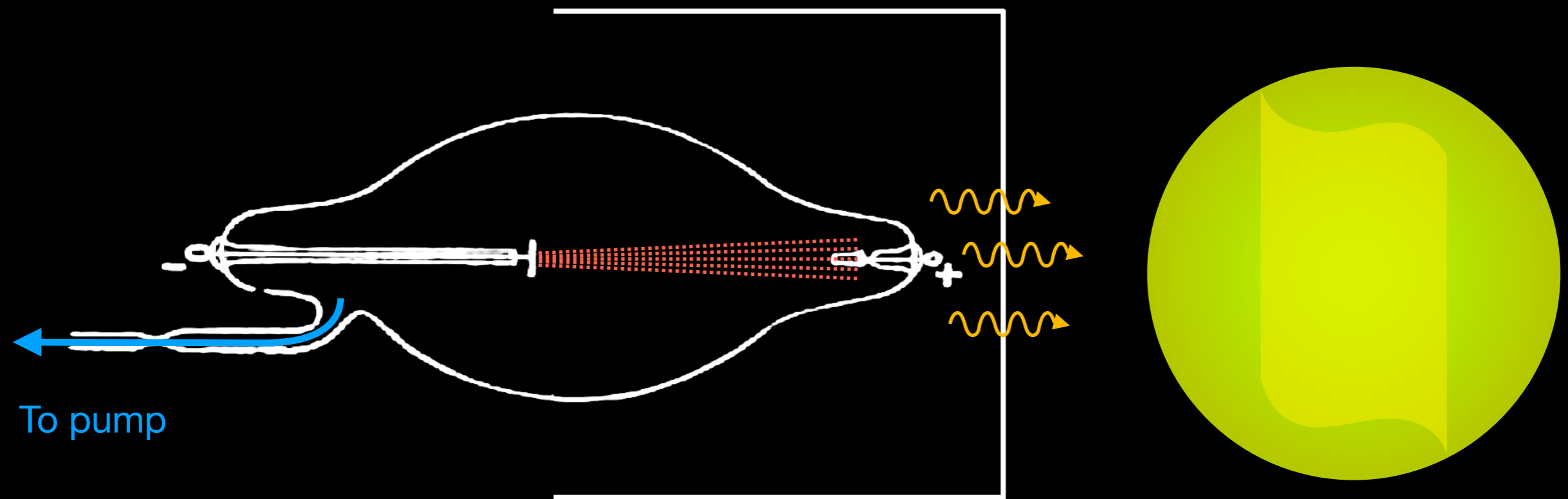
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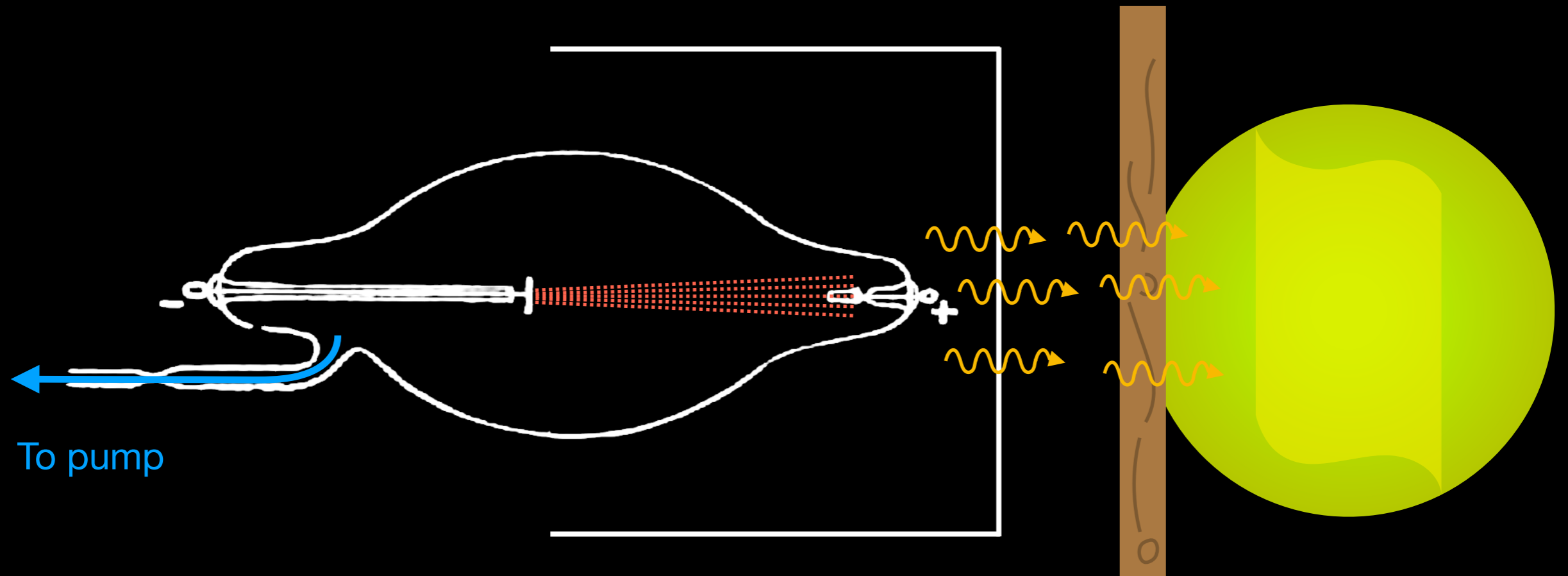


“Thick blocks of wood are still transparent.”

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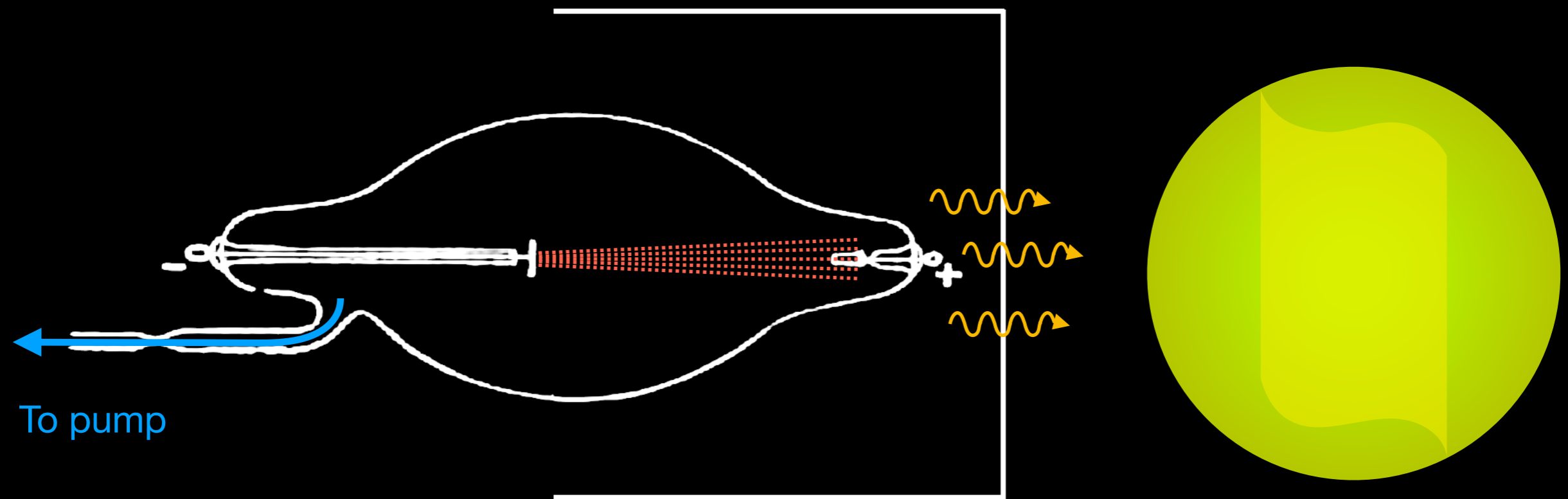
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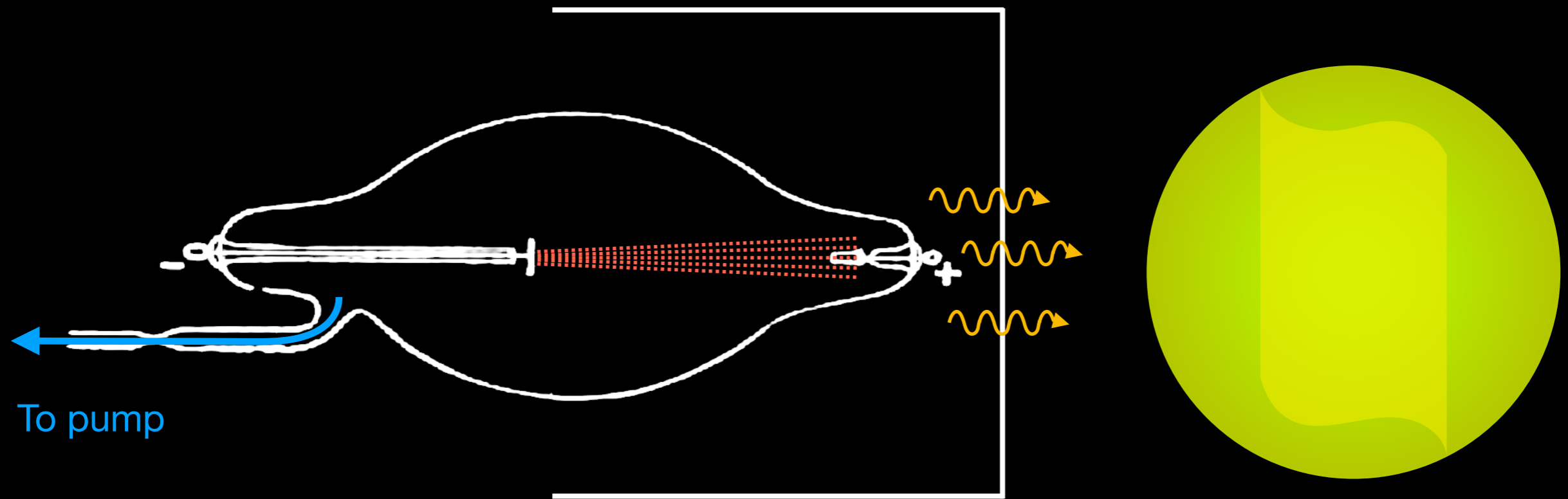
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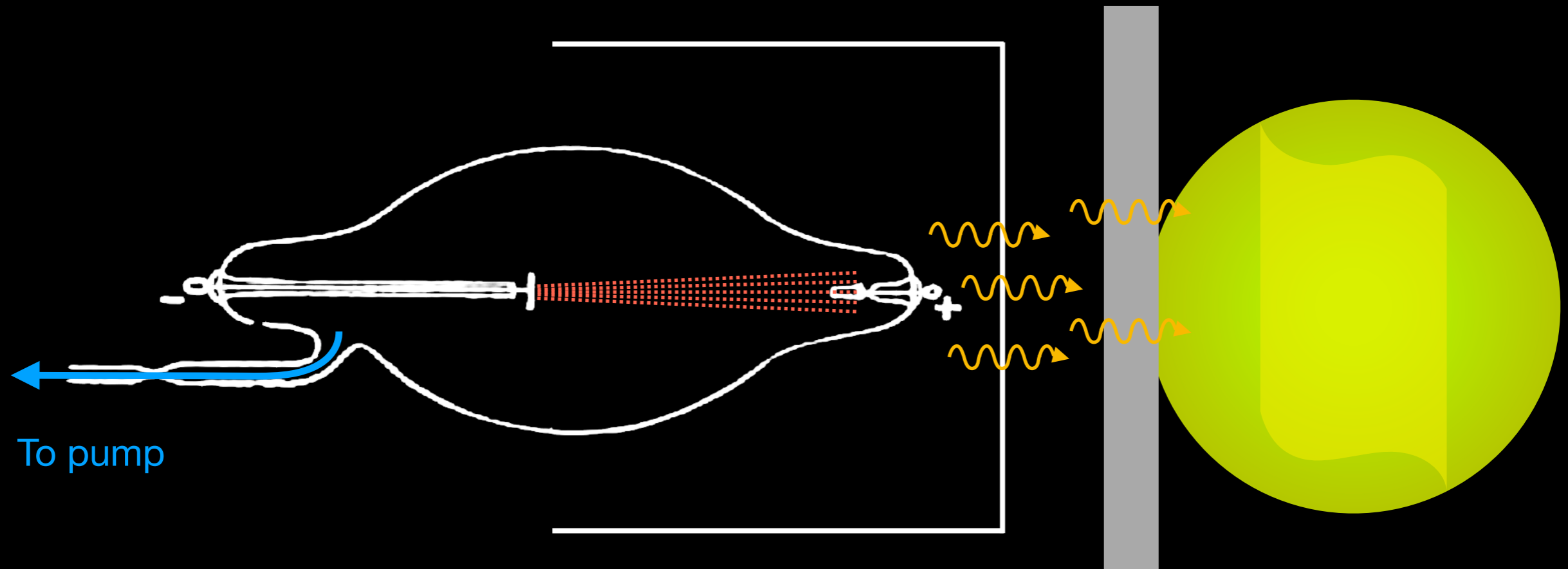
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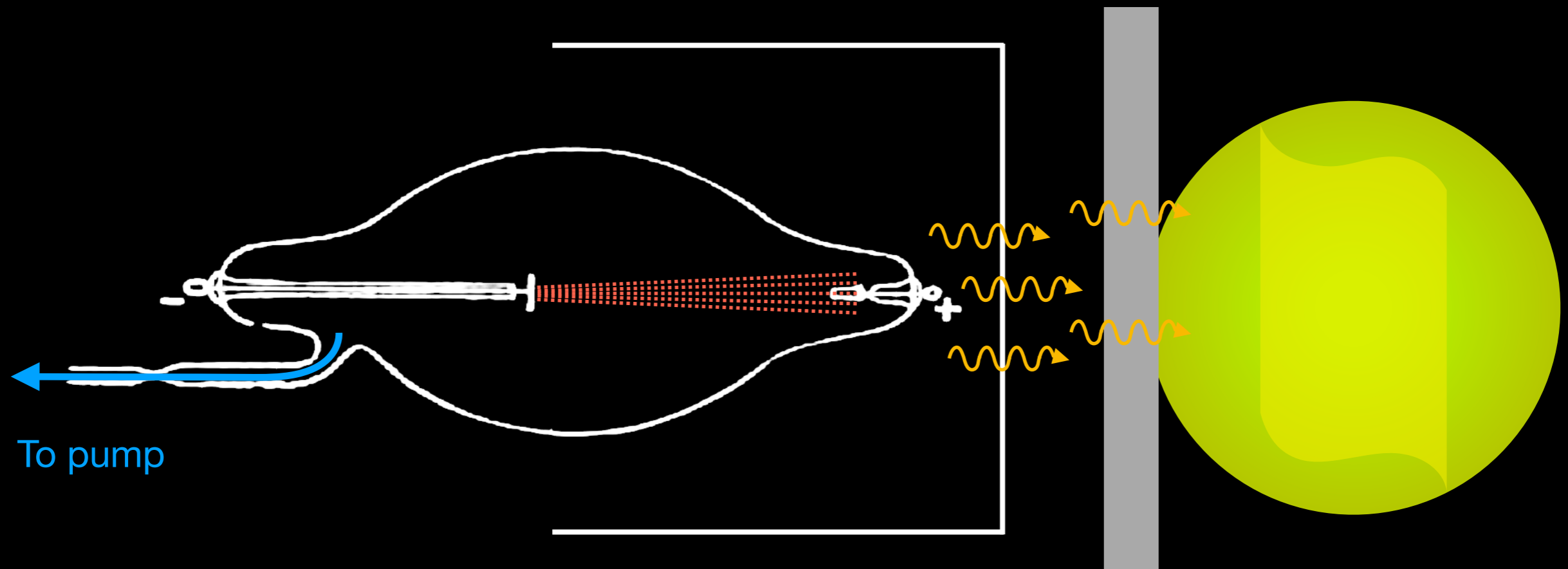
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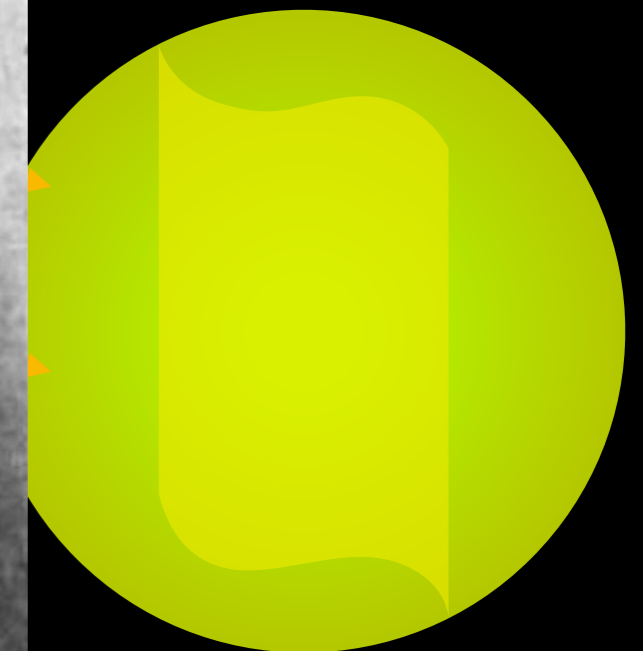
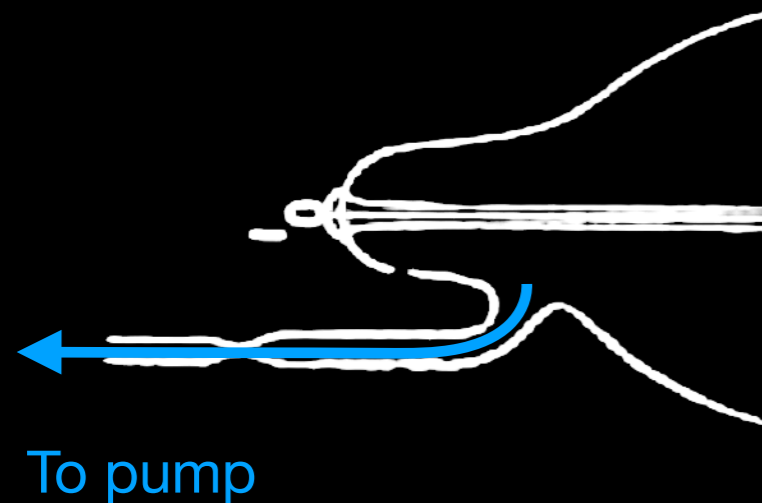
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of the X-rays
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The first x-ray in history!



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A world-changing discovery

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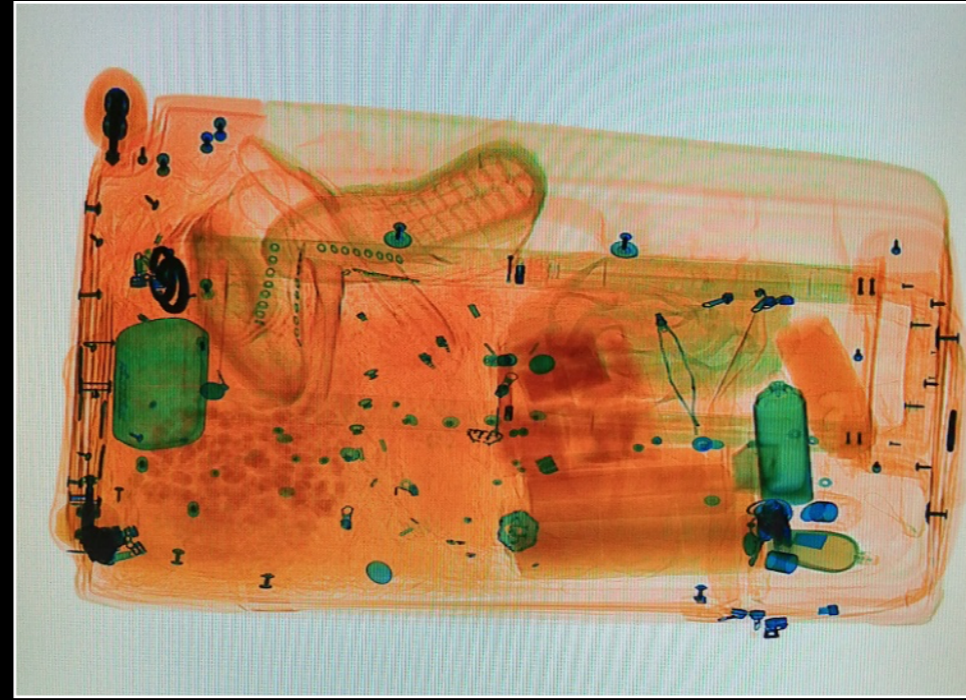
Medicine

A world-changing discovery



R

Medicine



(Airport) security

A world-changing discovery



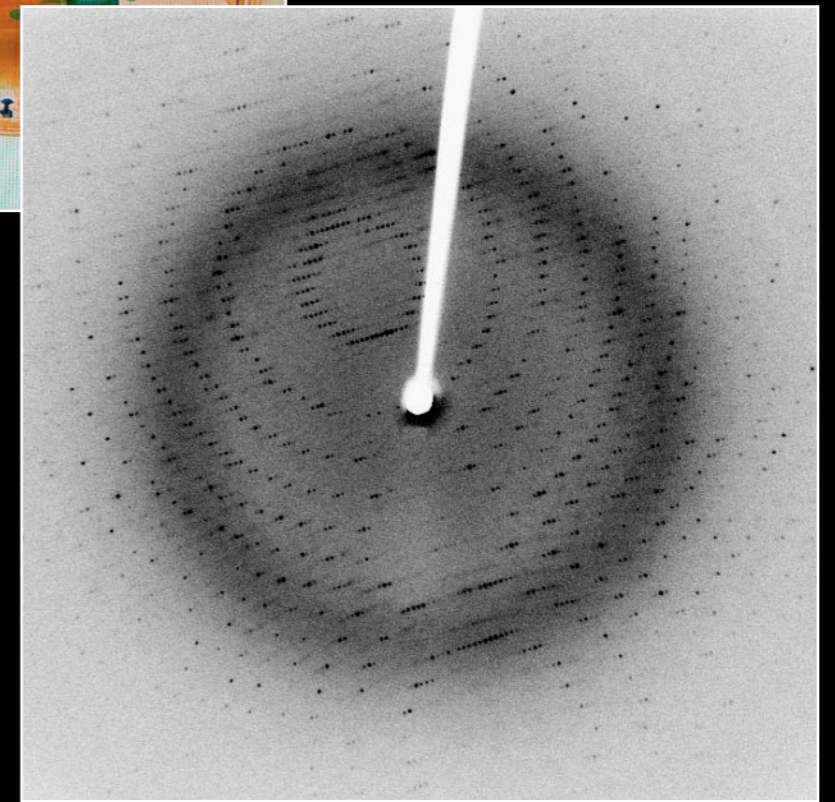
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(Airport) security

Materials science,
crystallography



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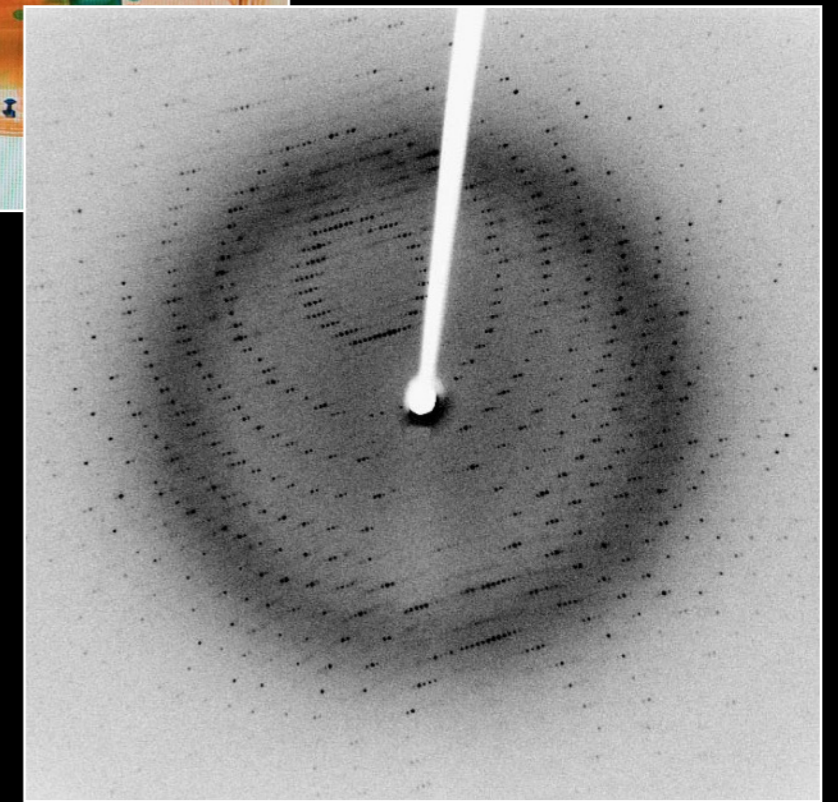


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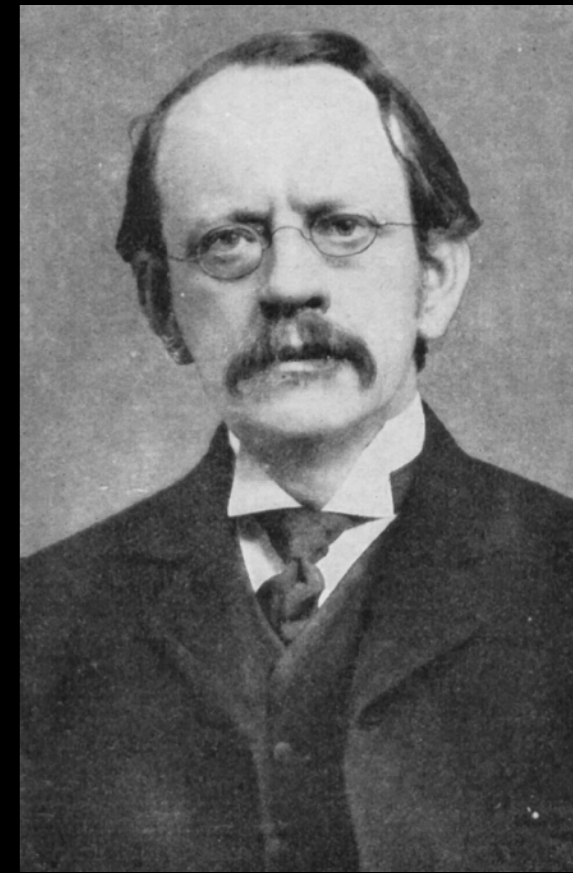
But what about the nature of electricity!?!

People still didn't know what the "molecular rays" or "cathode rays" consist of!

Joseph John Thomson



Joseph John Thomson



ON THE MOTION OF VORTEX RINGS.

1882: Prize-winning
Master's thesis

§ 1. THE theory that the properties of bodies may be explained by supposing matter to be collections of vortex lines in a perfect fluid filling the universe has made the subject of vortex

Joseph John Thomson



1884: Professor at the Cavendish Laboratory in Cambridge

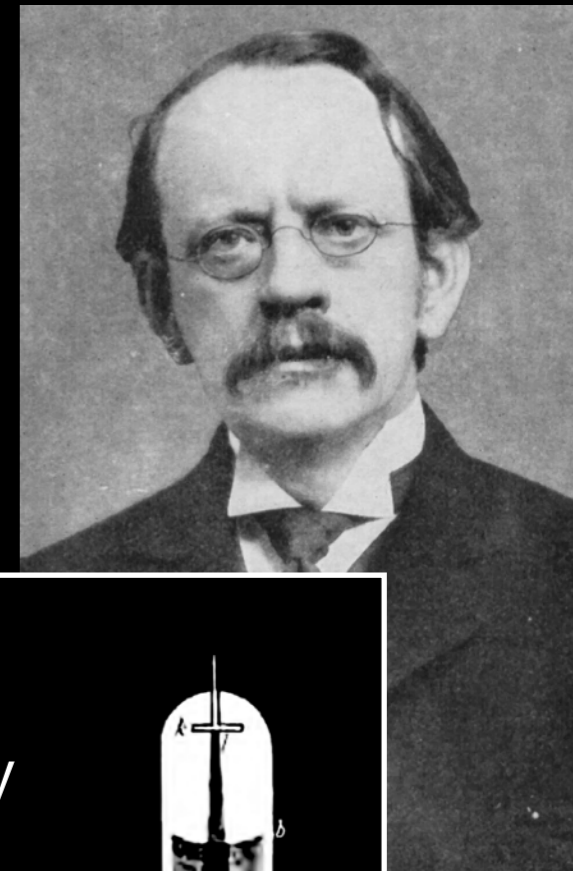


1882: Prize-winning Master's thesis

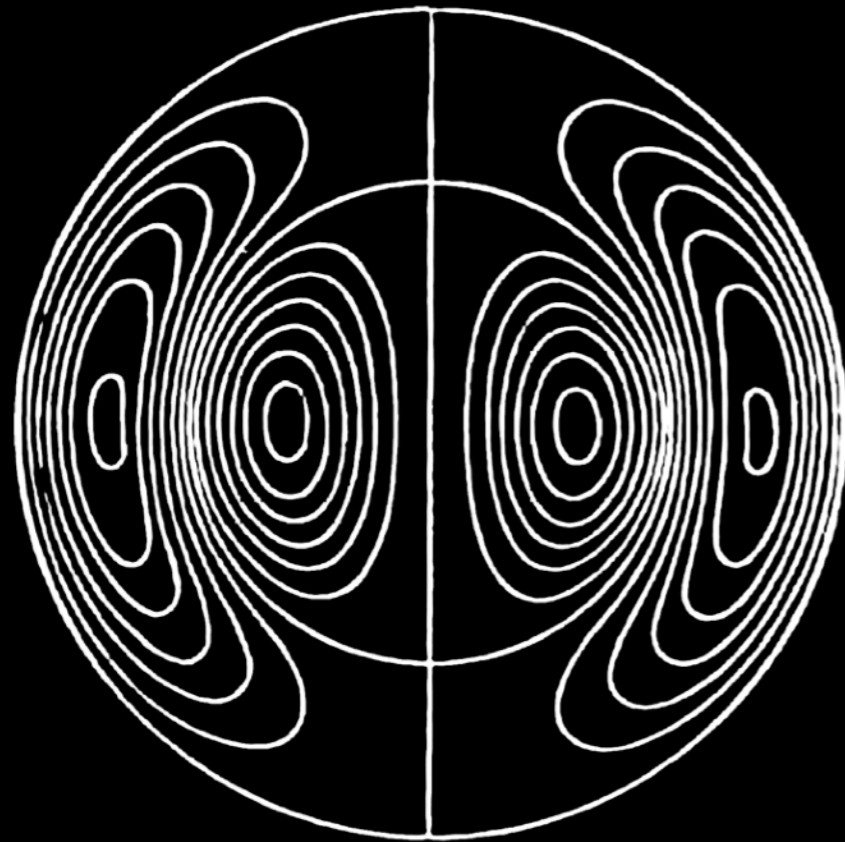
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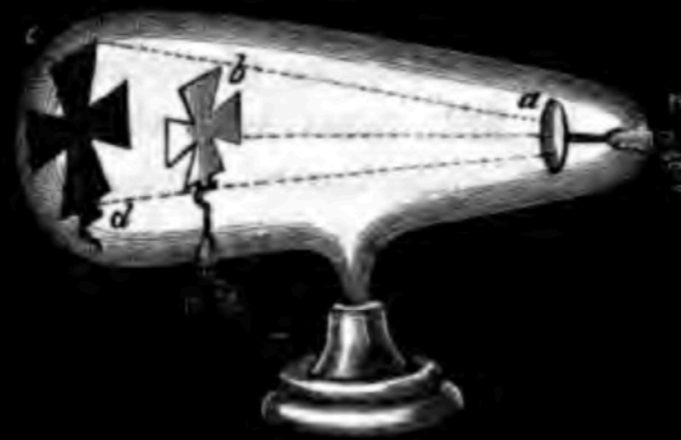
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1897: Textbook "*Notes on recent researches in electricity and magnetism*"

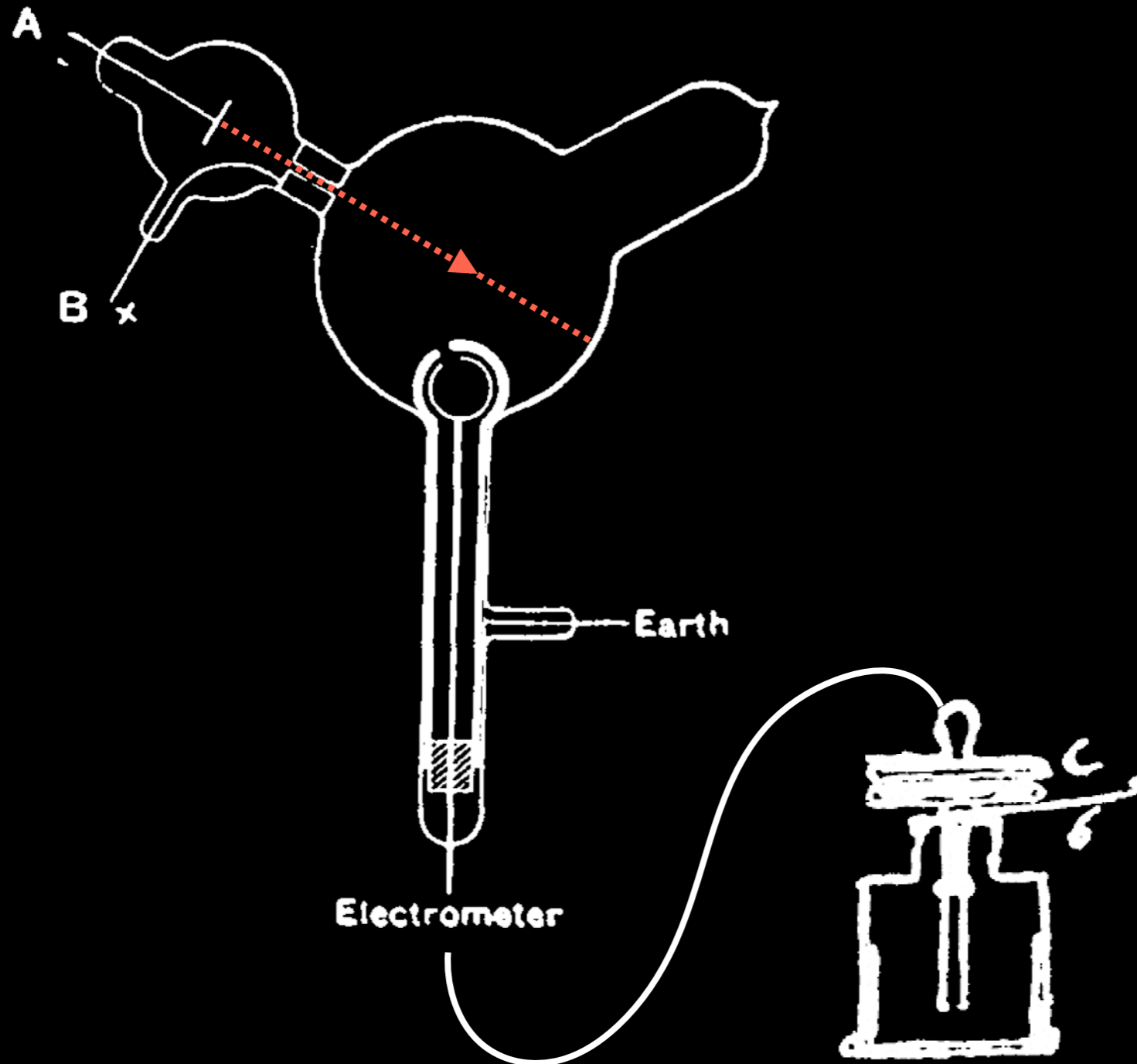


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Magnetic deflection

“Cathode”
(= negative pole)



Measuring electric charge

Measuring electric charge



Alessandro Volta

Measuring electric charge

*"What can be done that's any good if things
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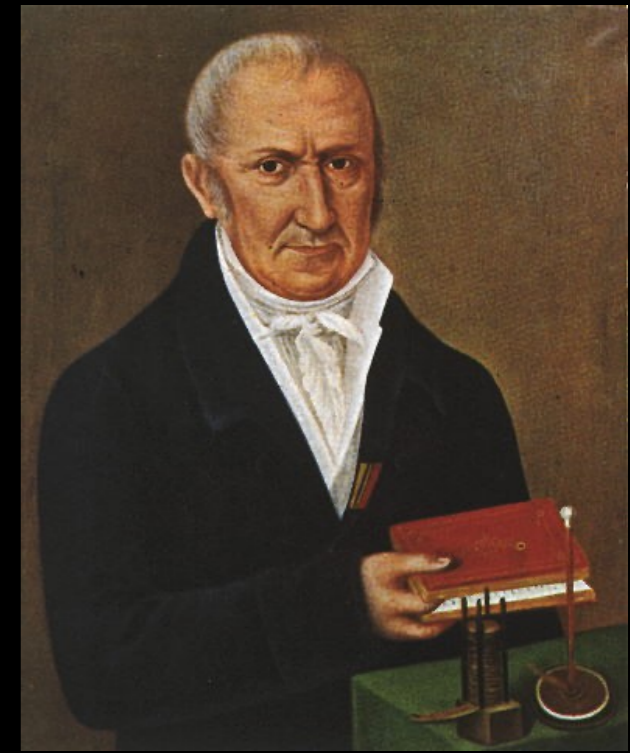
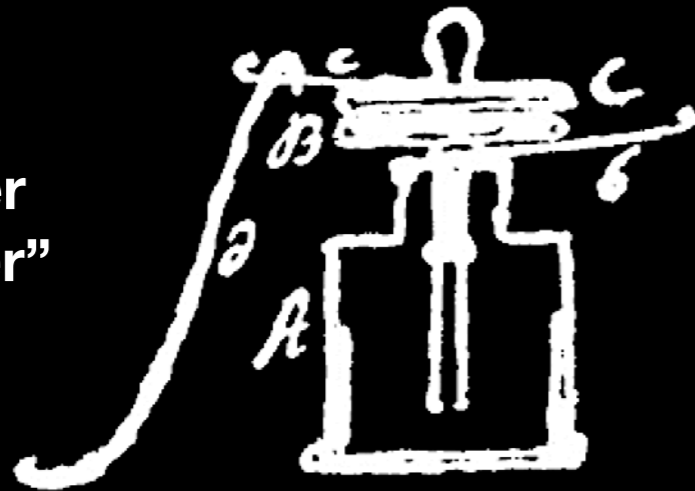


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Measuring electric charge

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"Condenser electrometer"

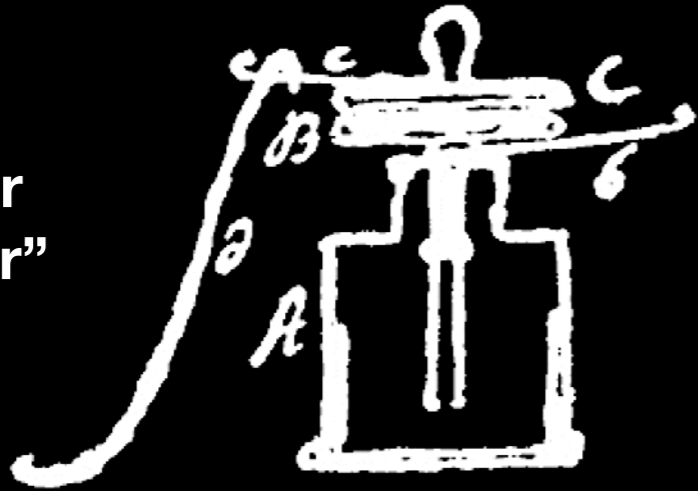


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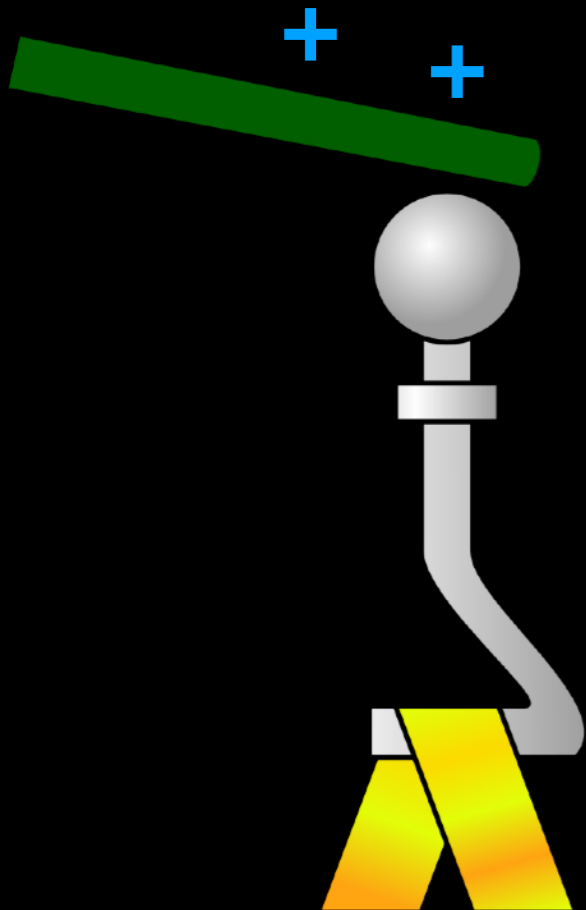
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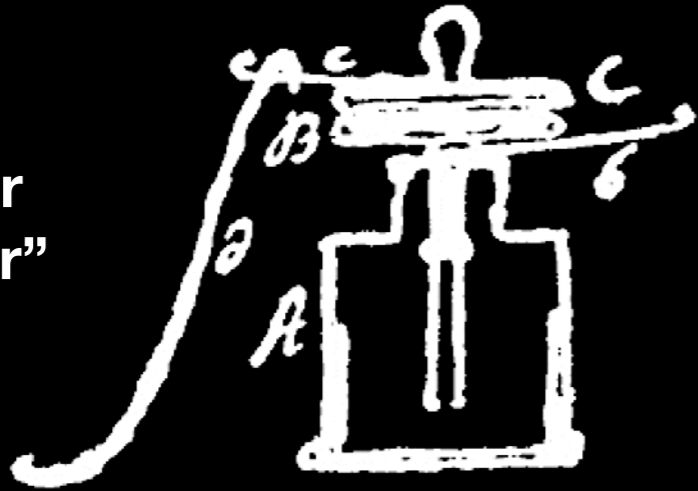
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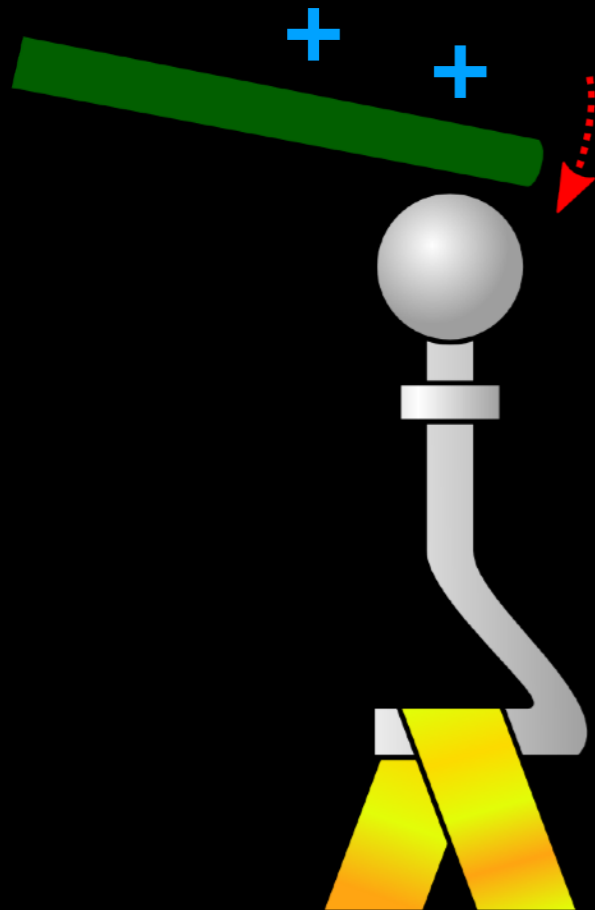
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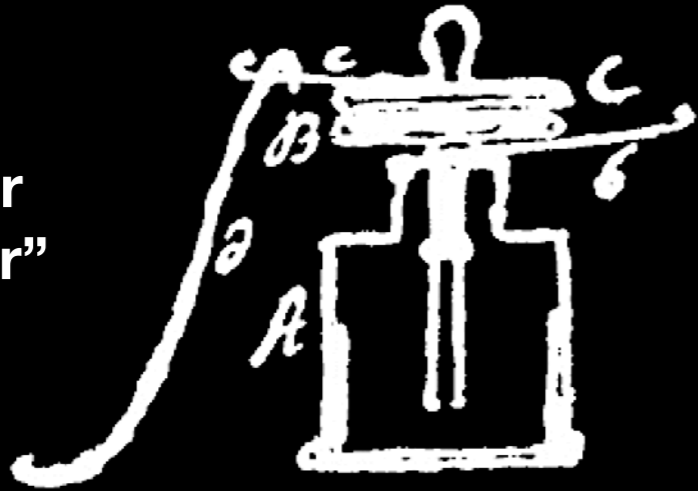
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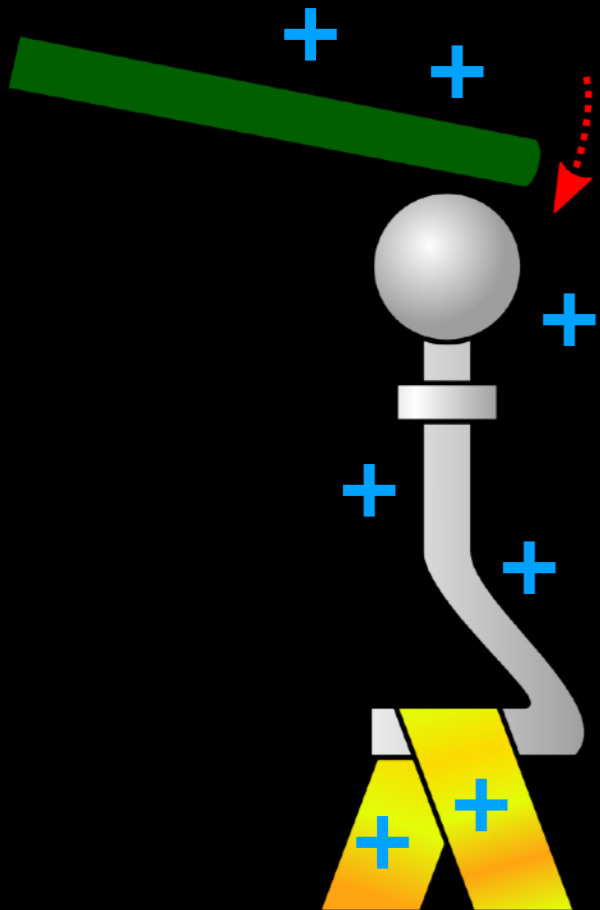
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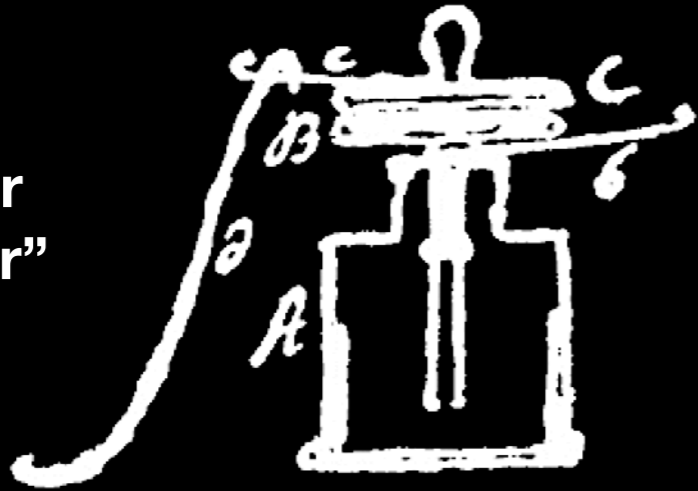
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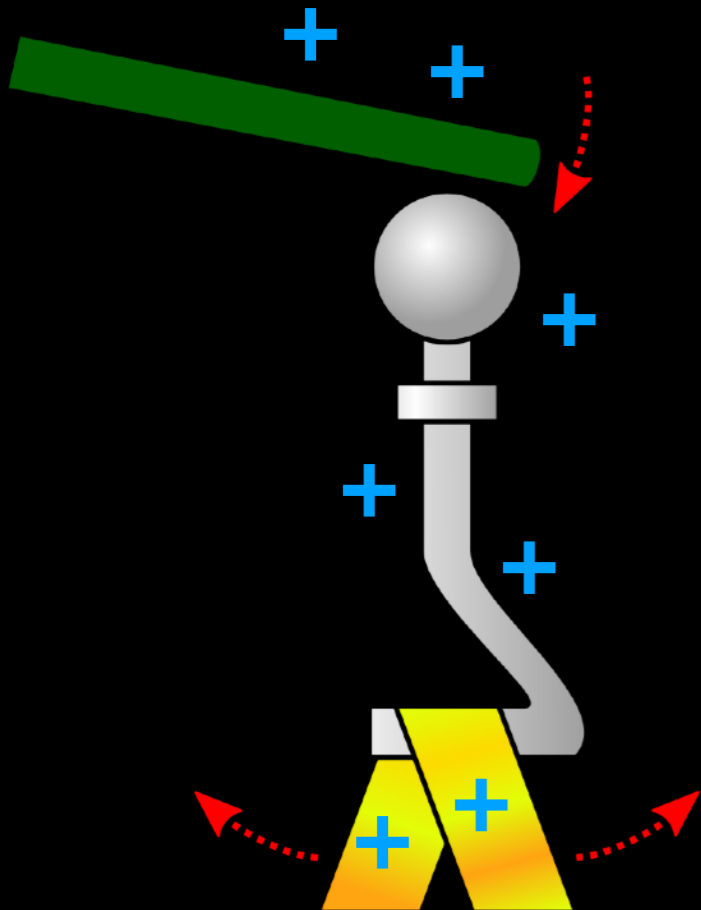
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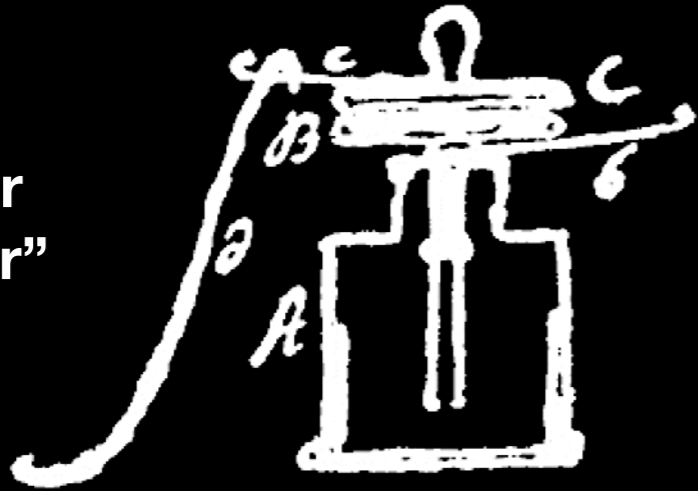
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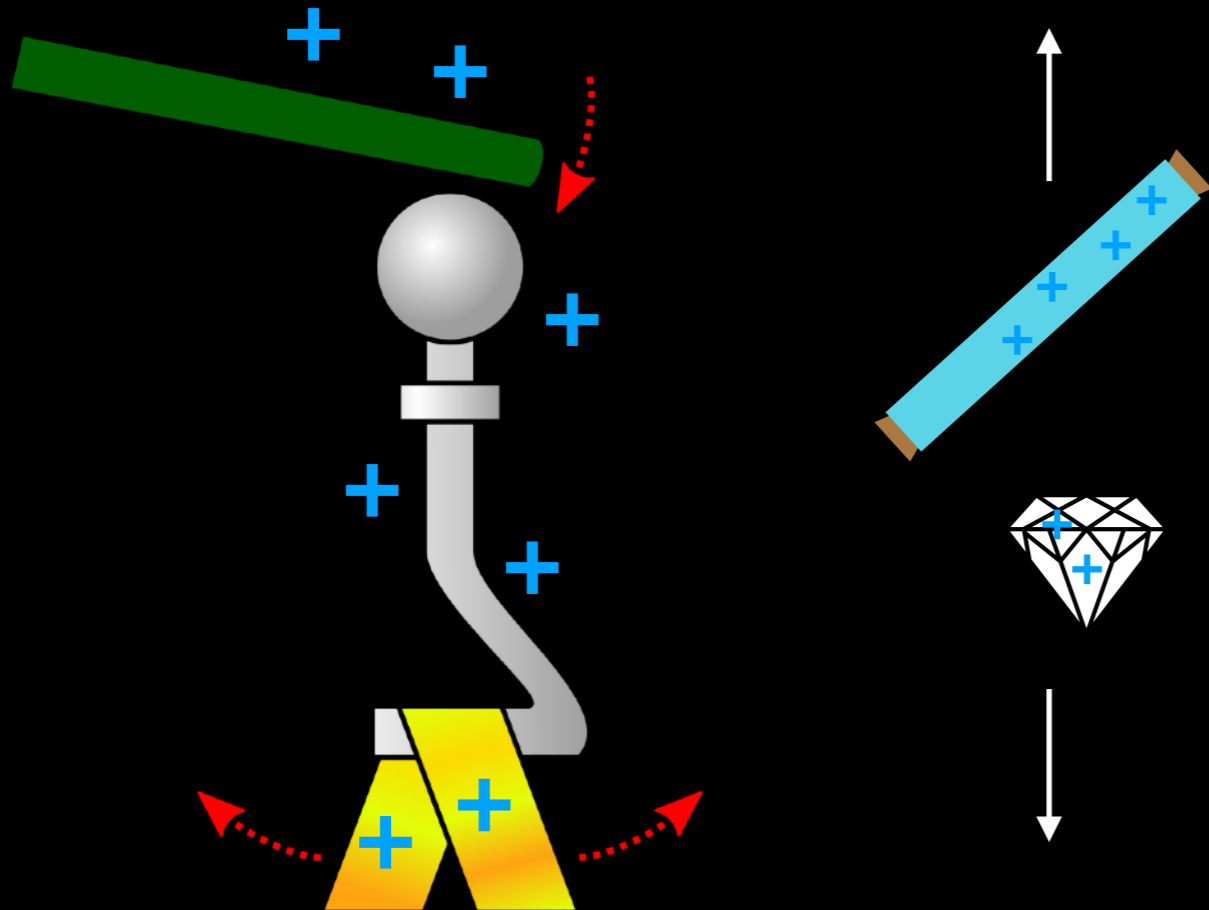
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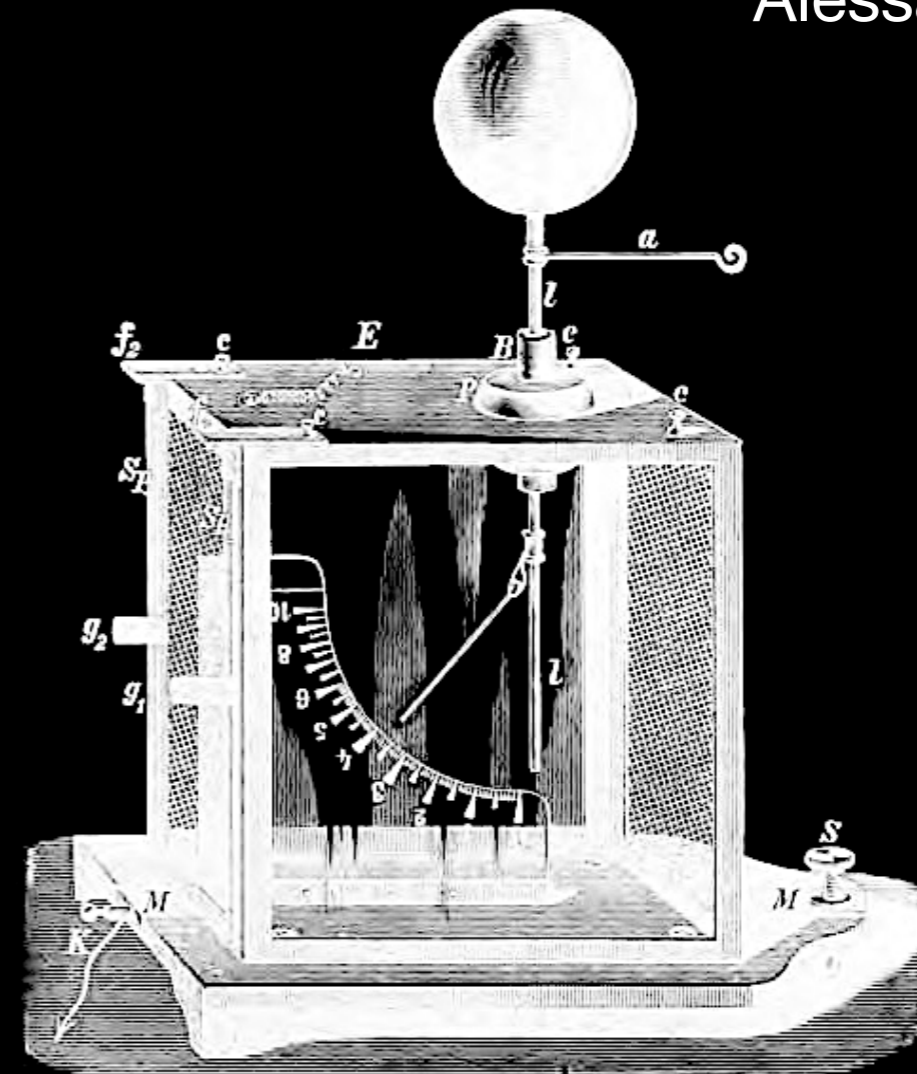
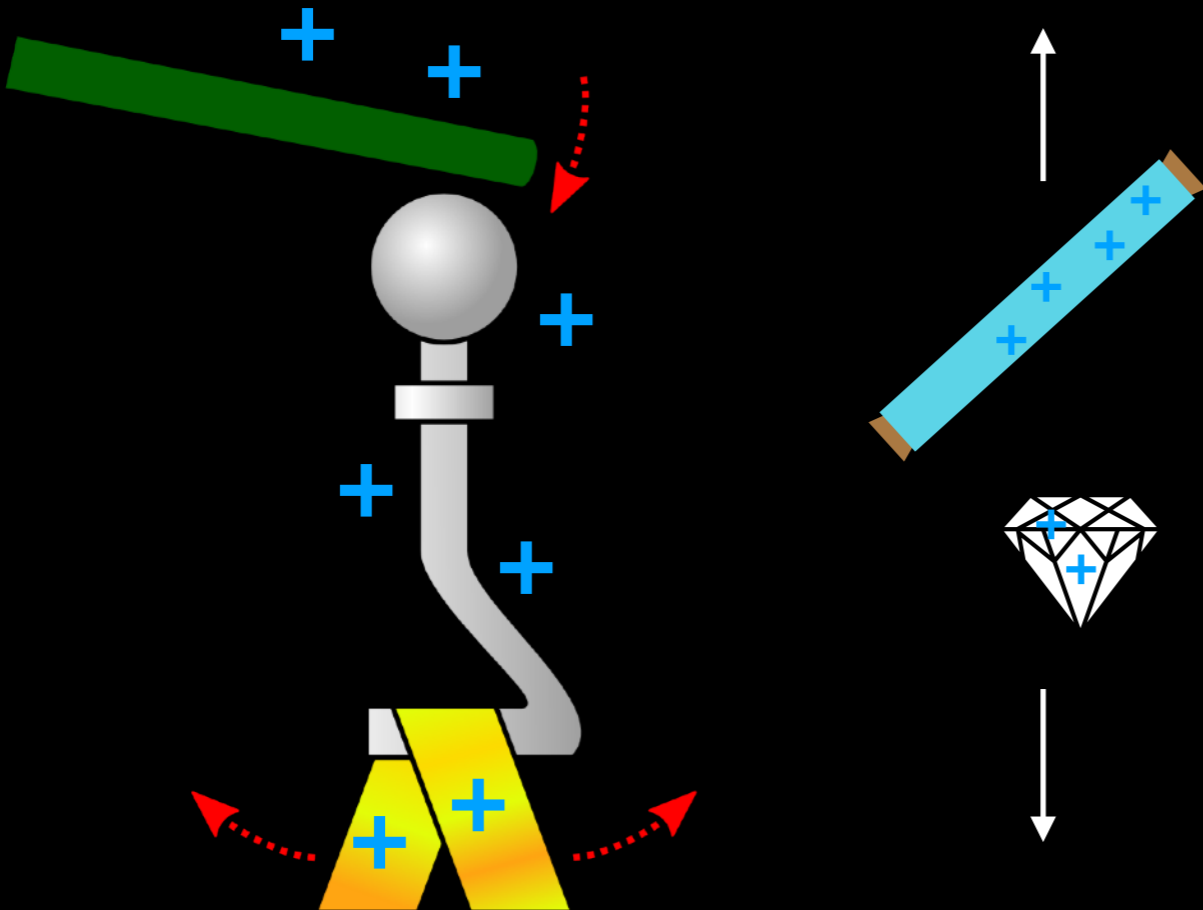
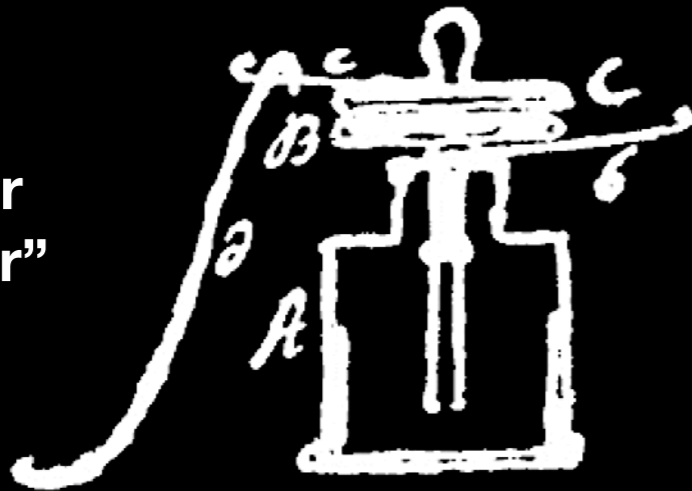
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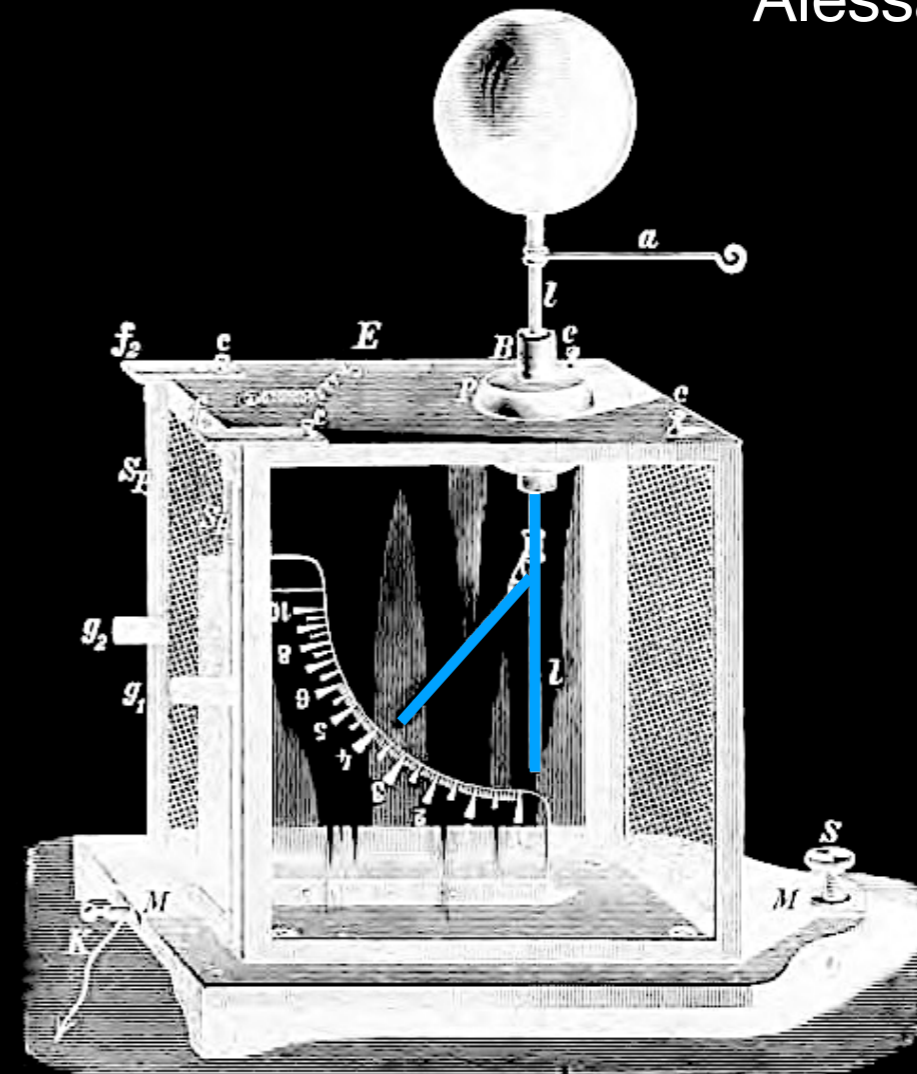
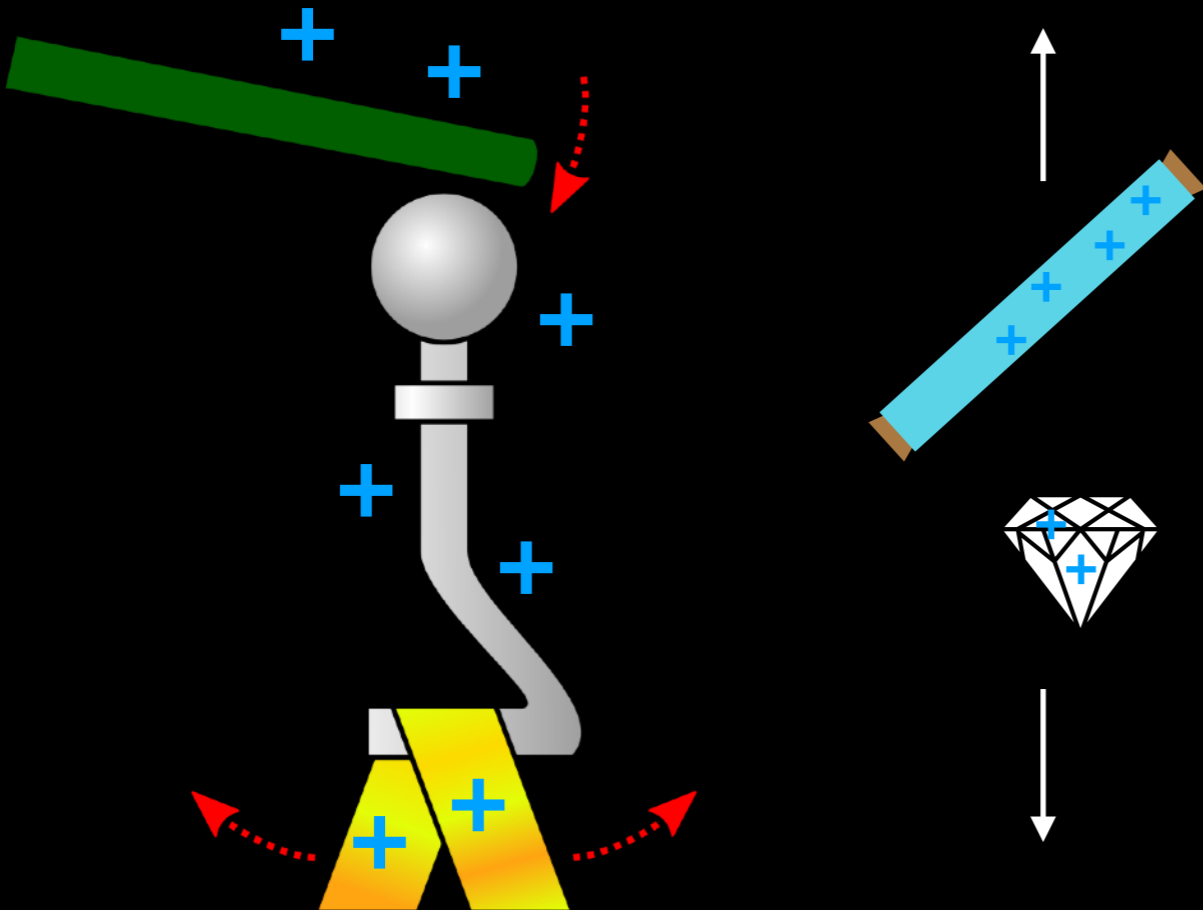
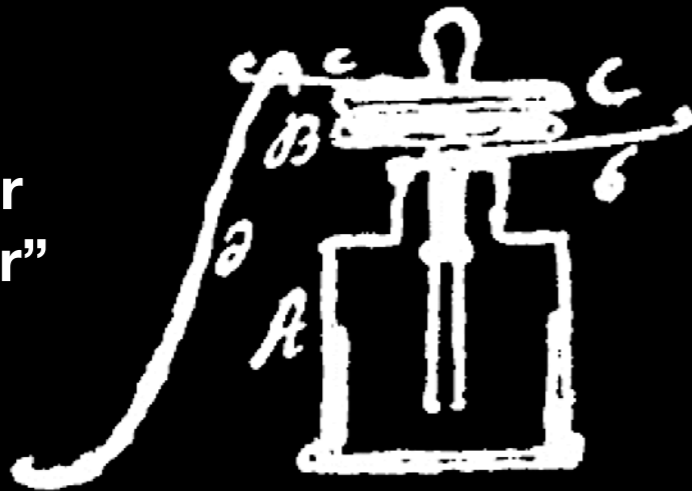
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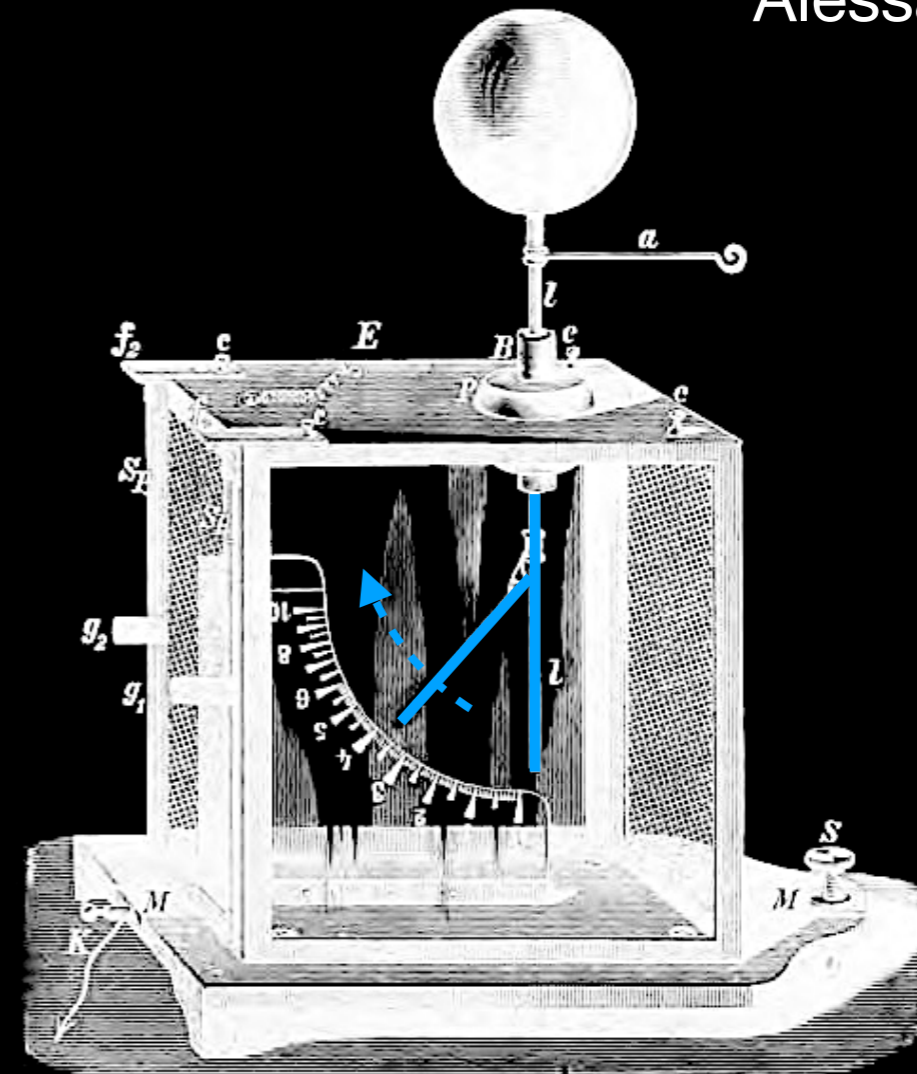
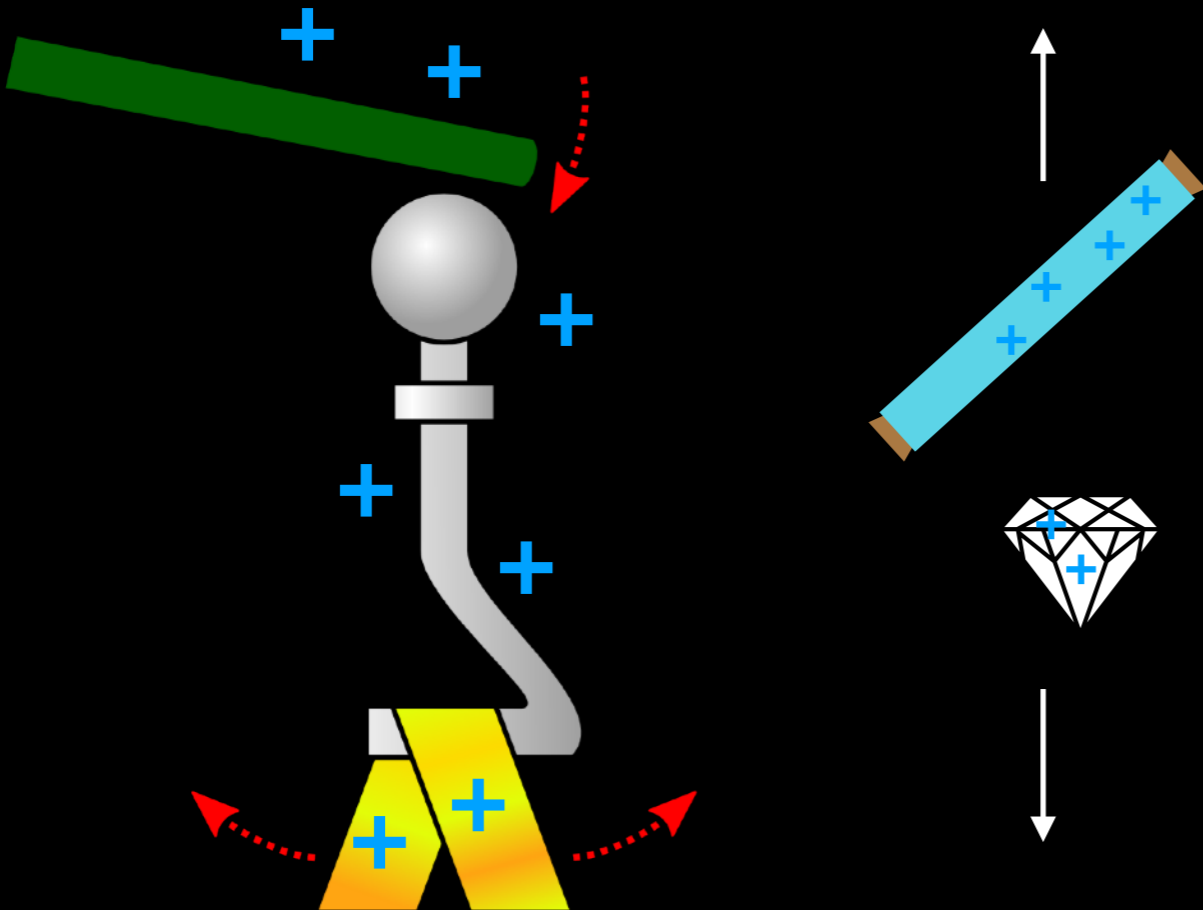
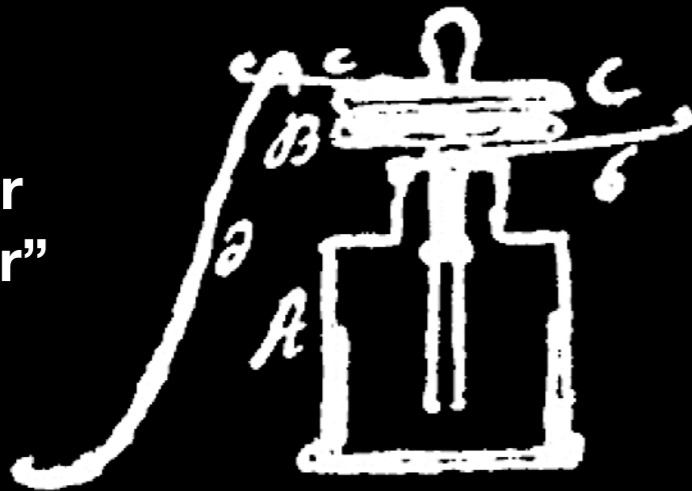
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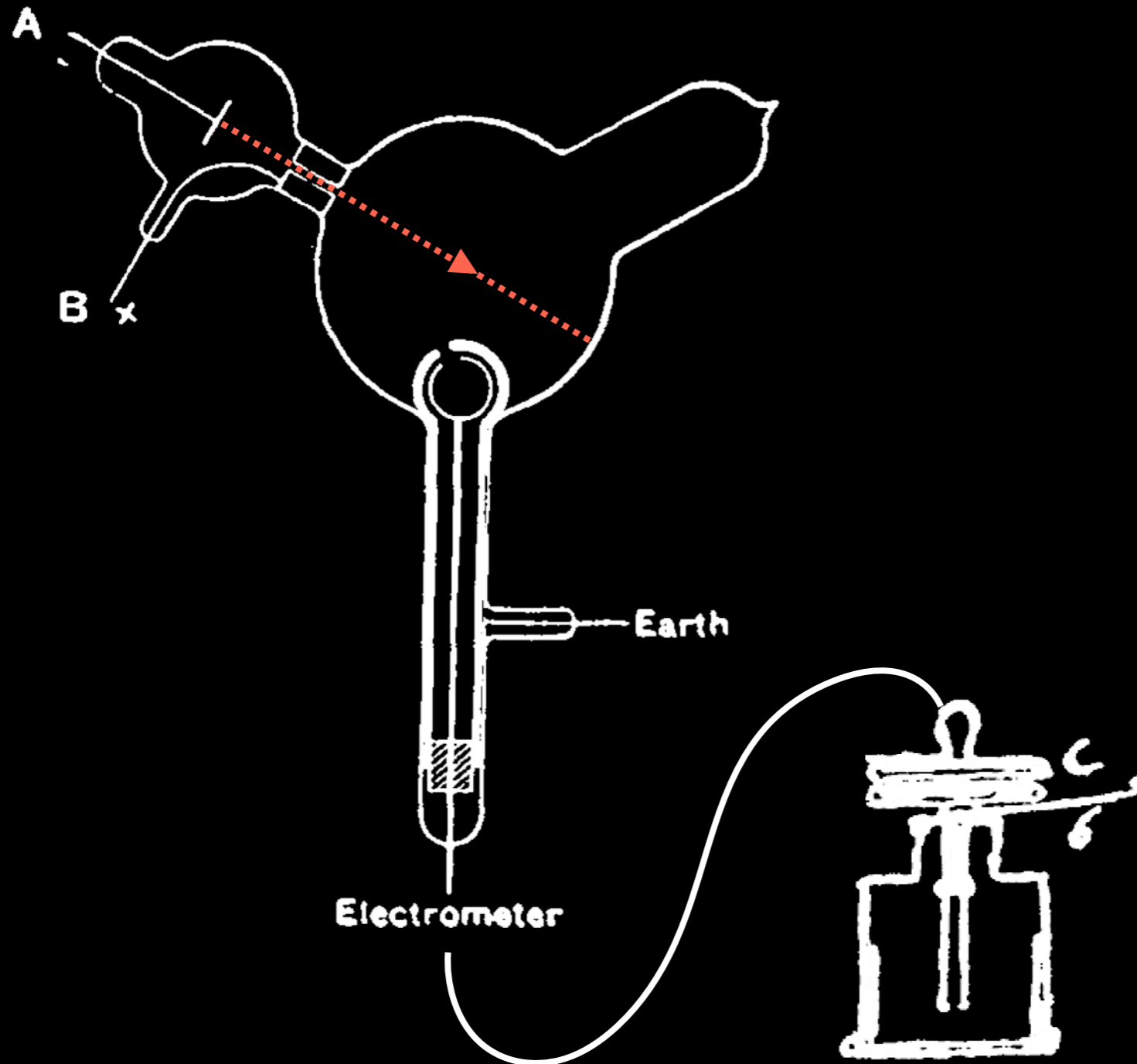
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Magnetic deflection

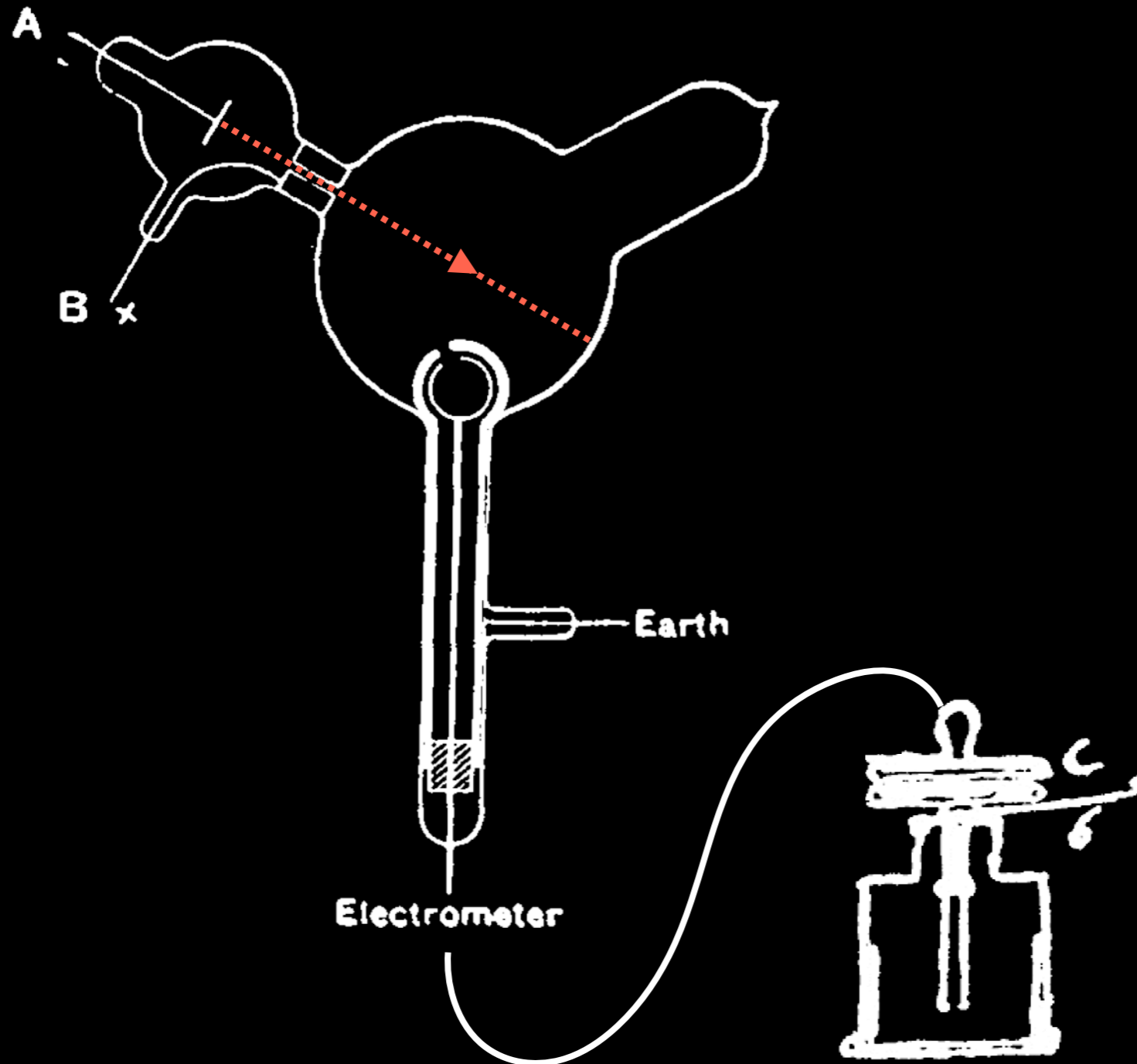
“Cathode”
(= negative pole)



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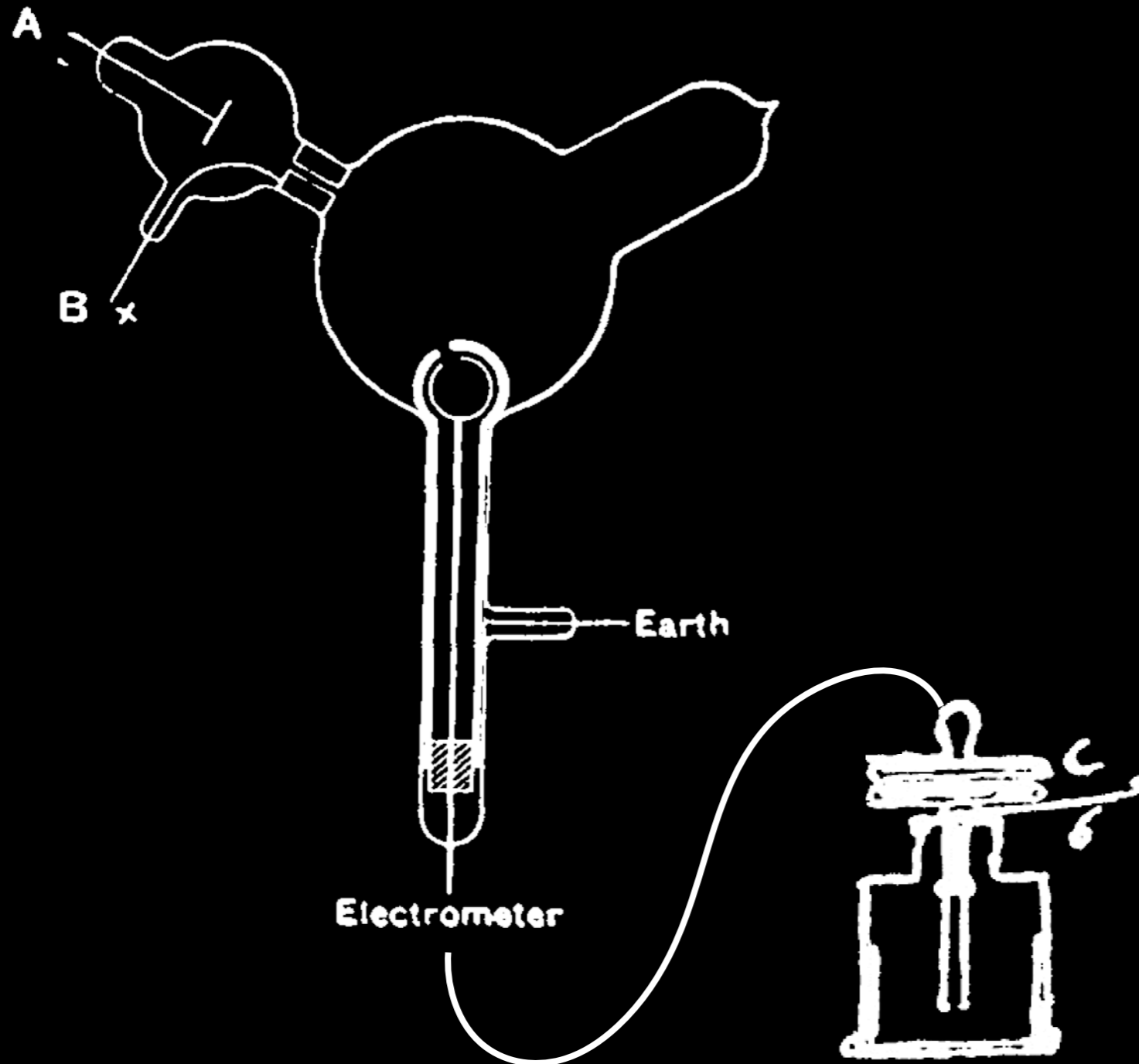
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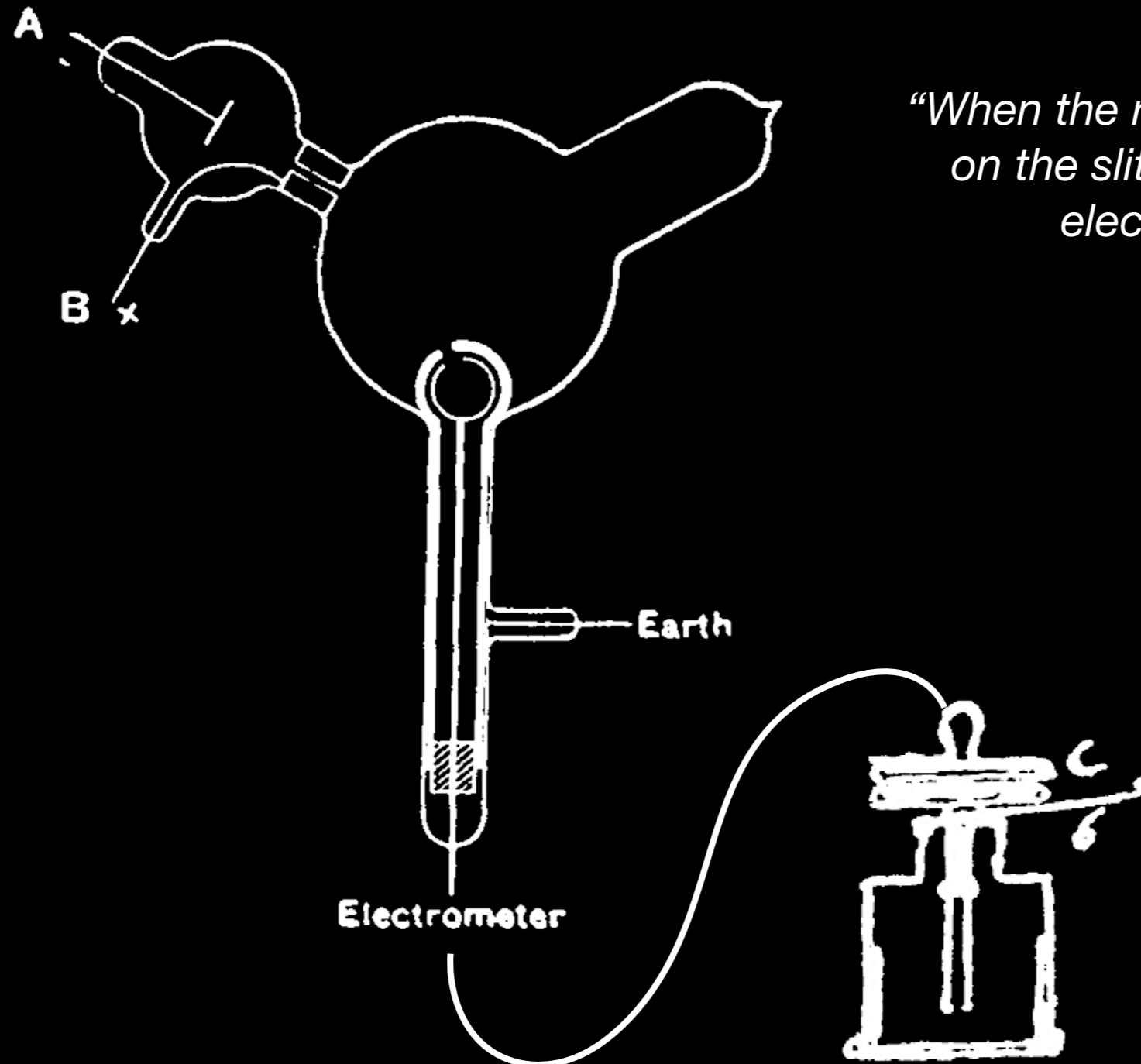
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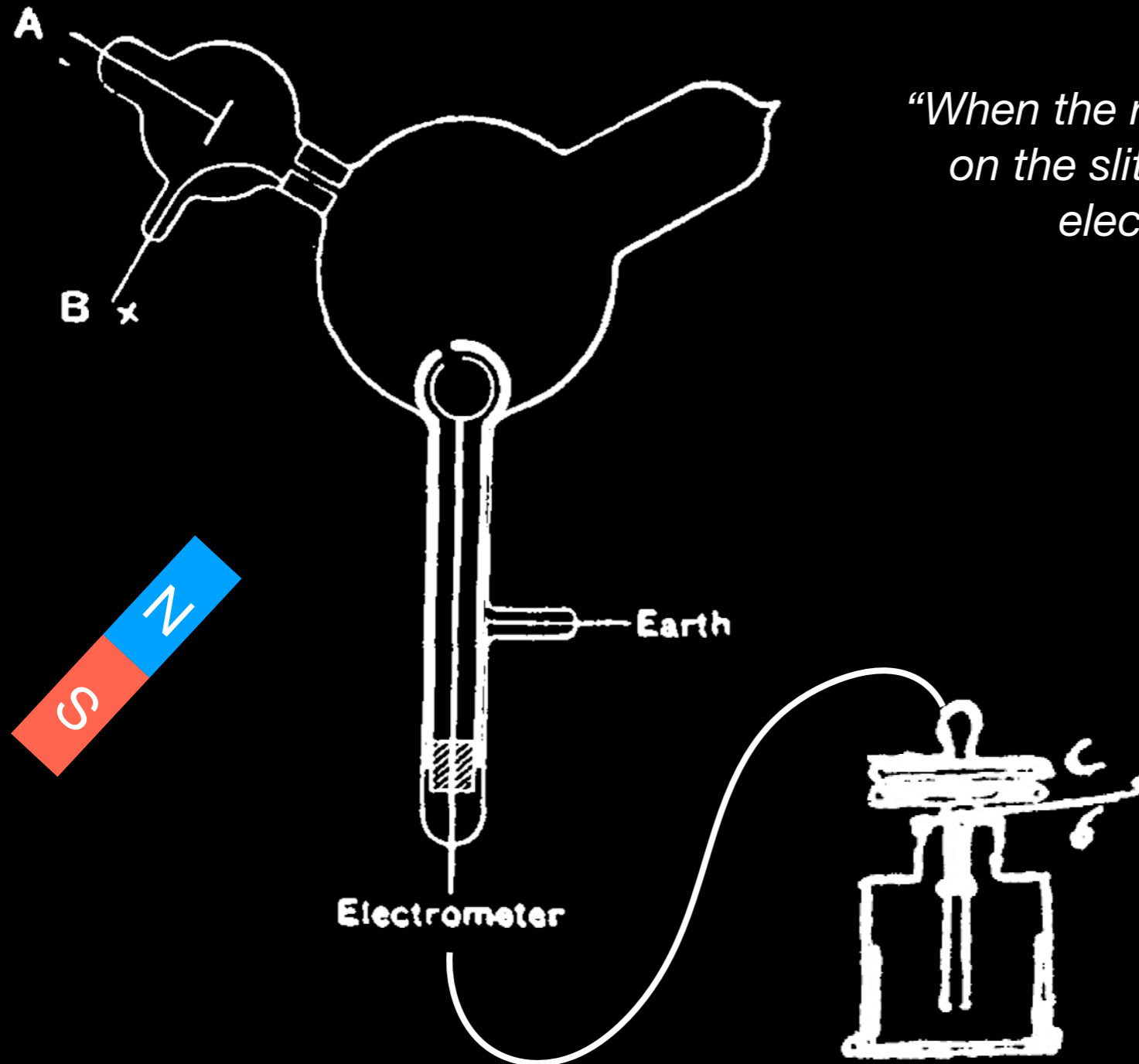


“When the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer.”

Magnetic deflection

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(= negative pole)

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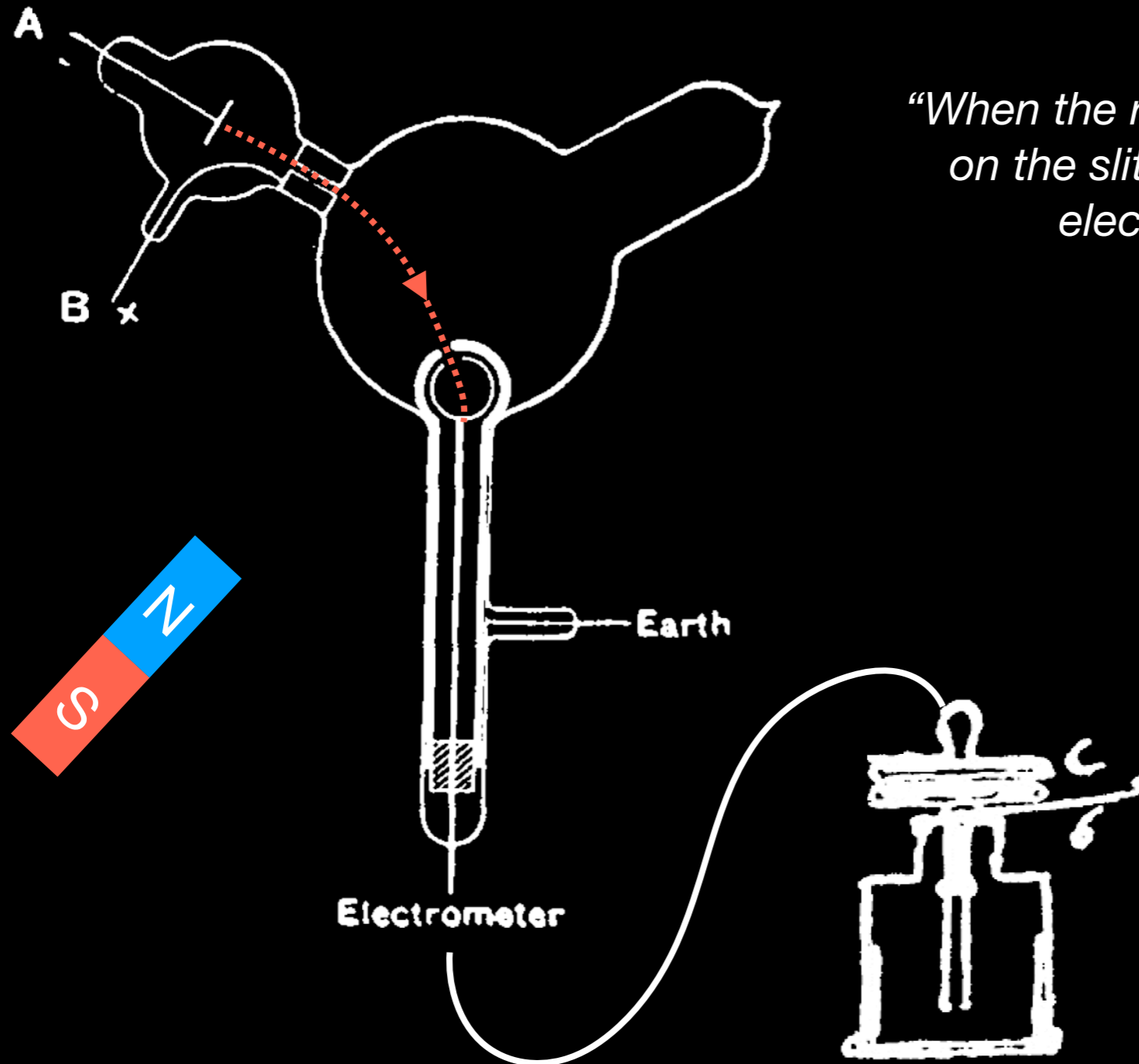


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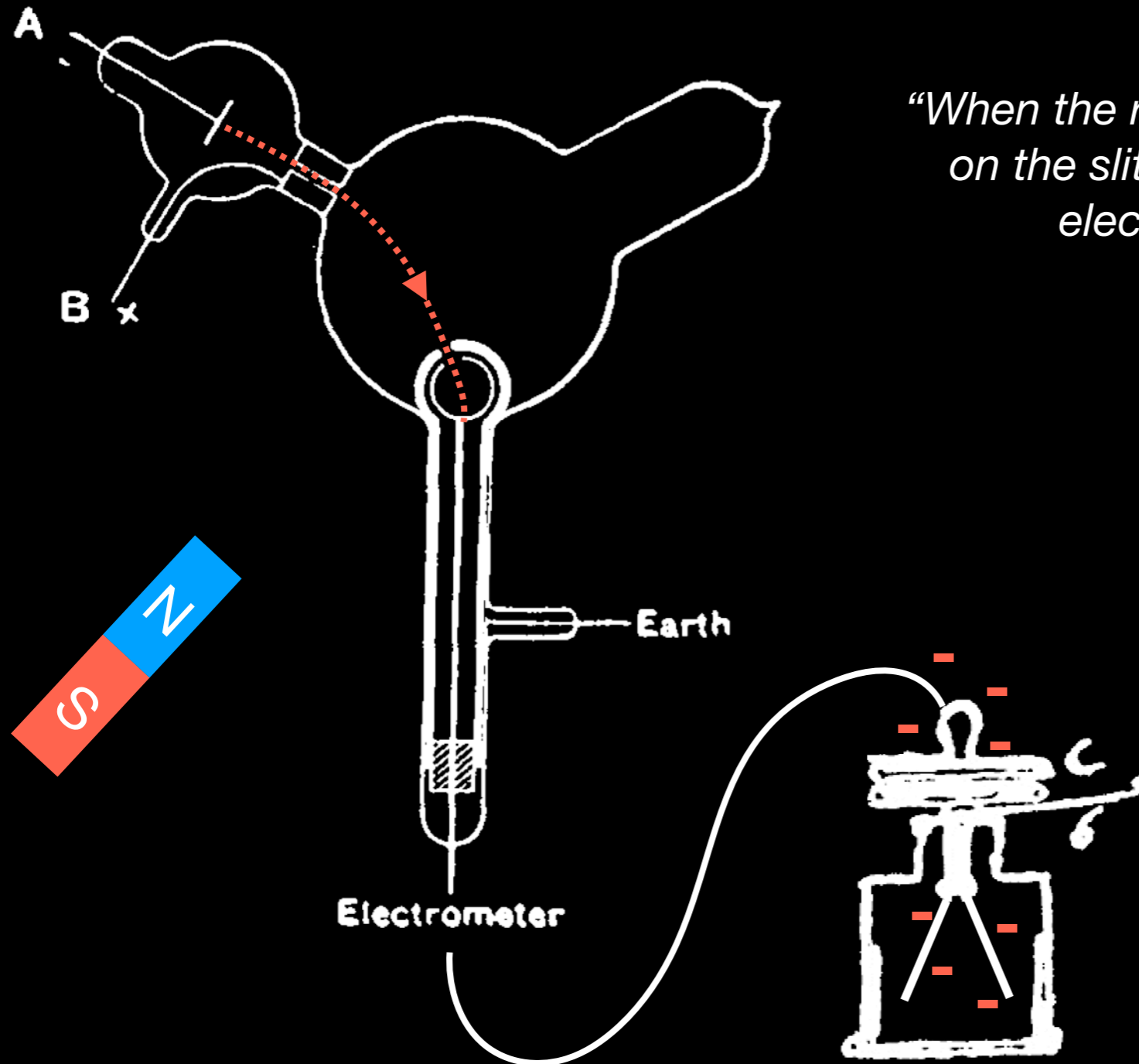


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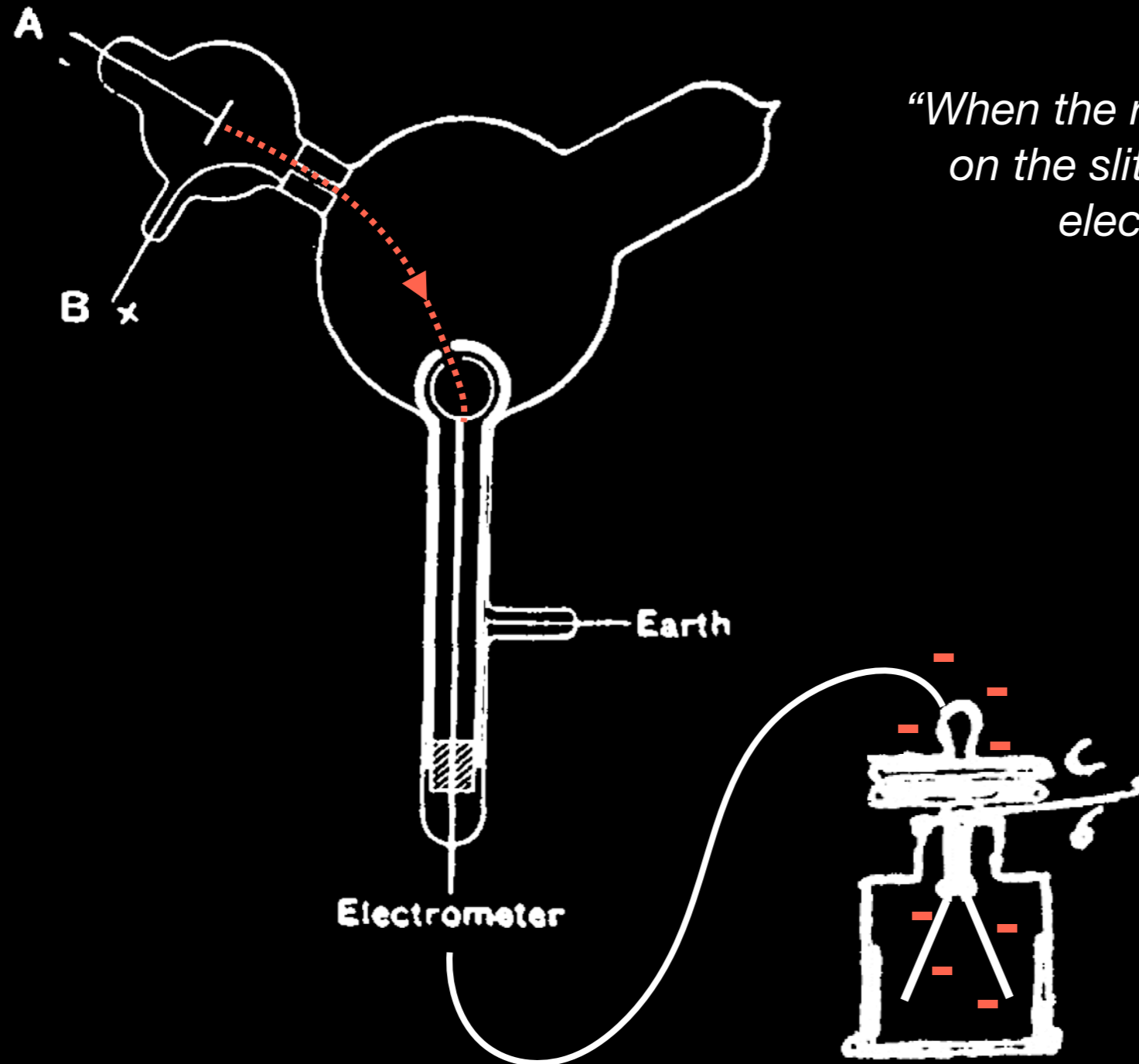


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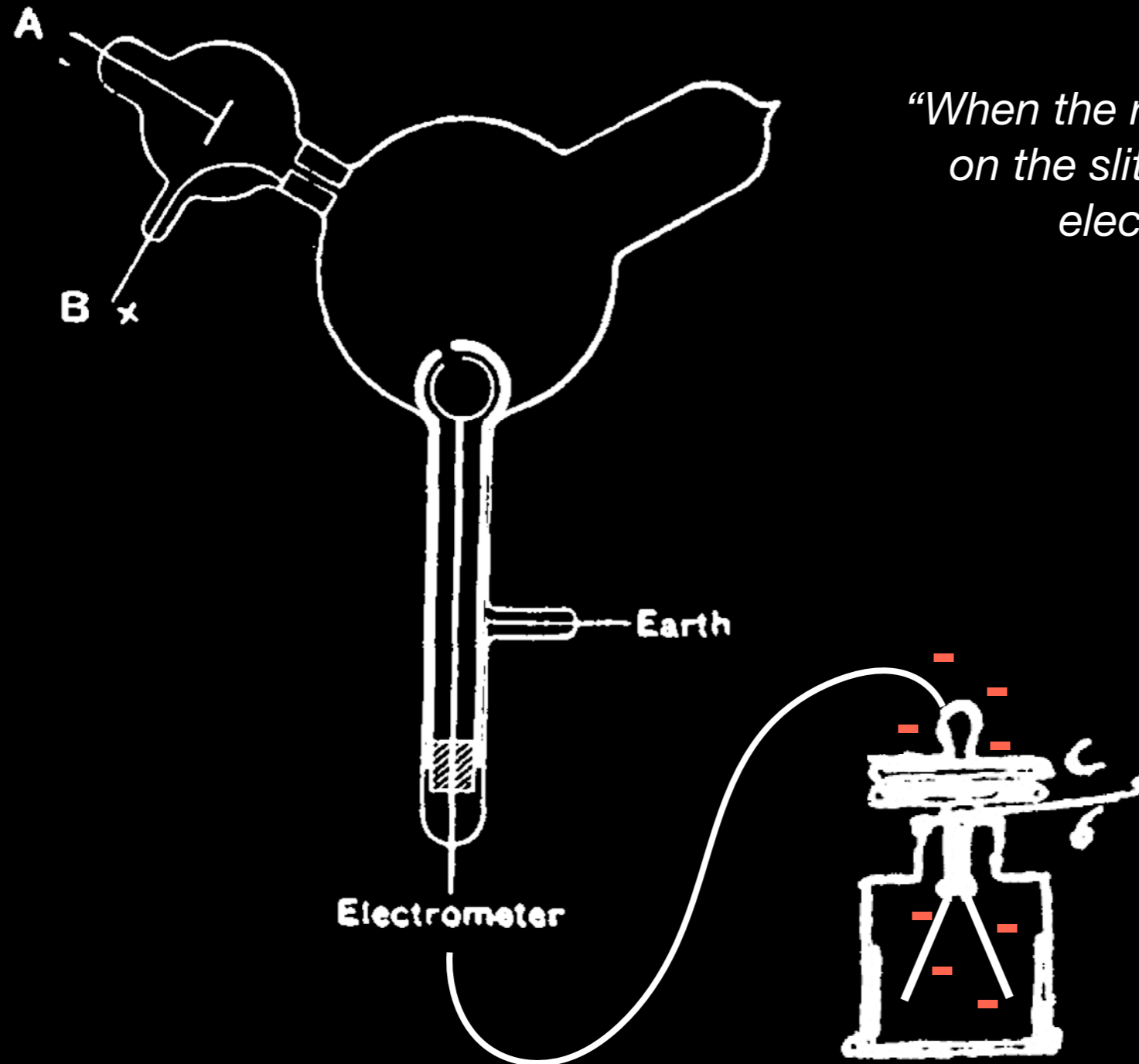


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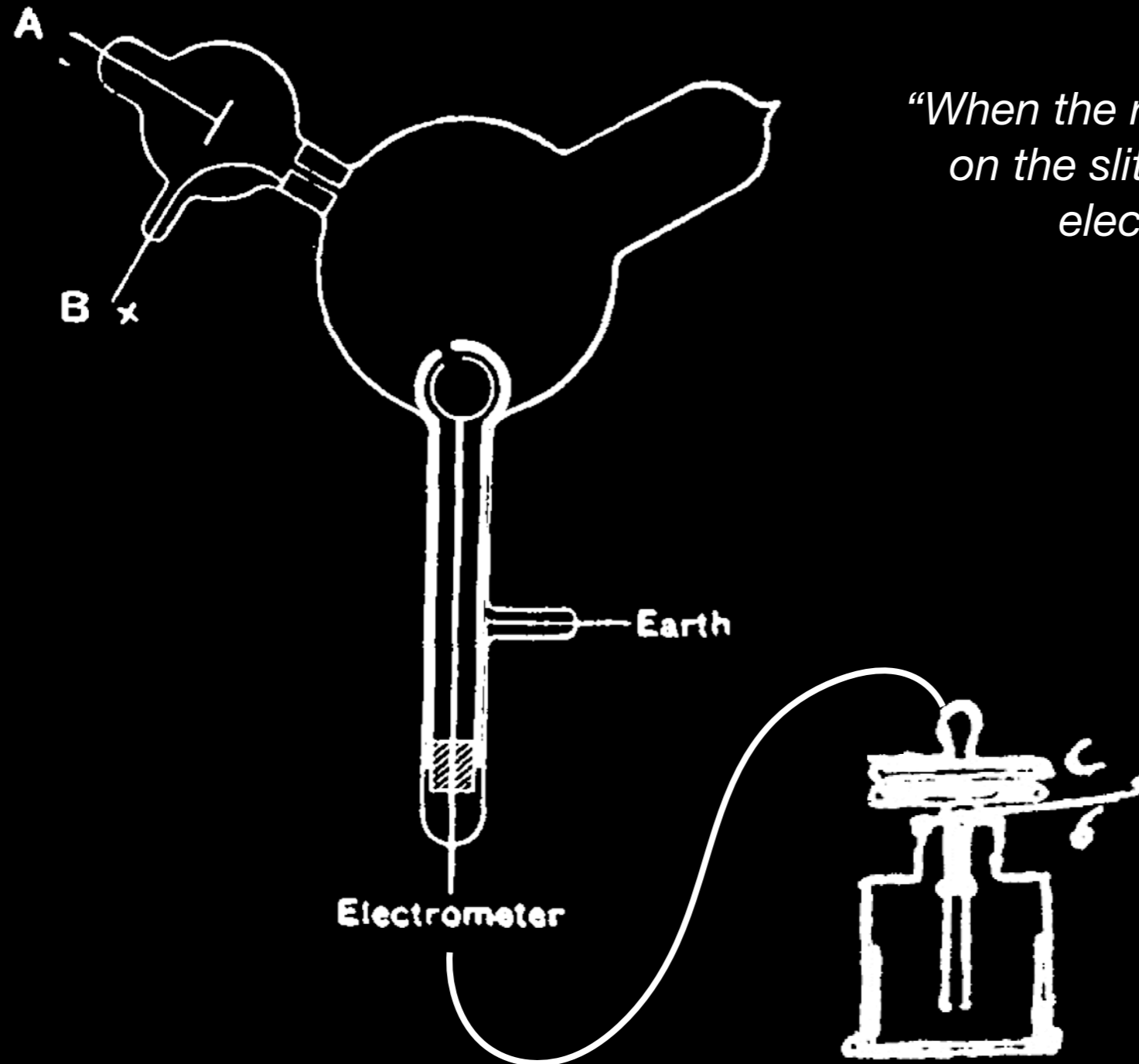


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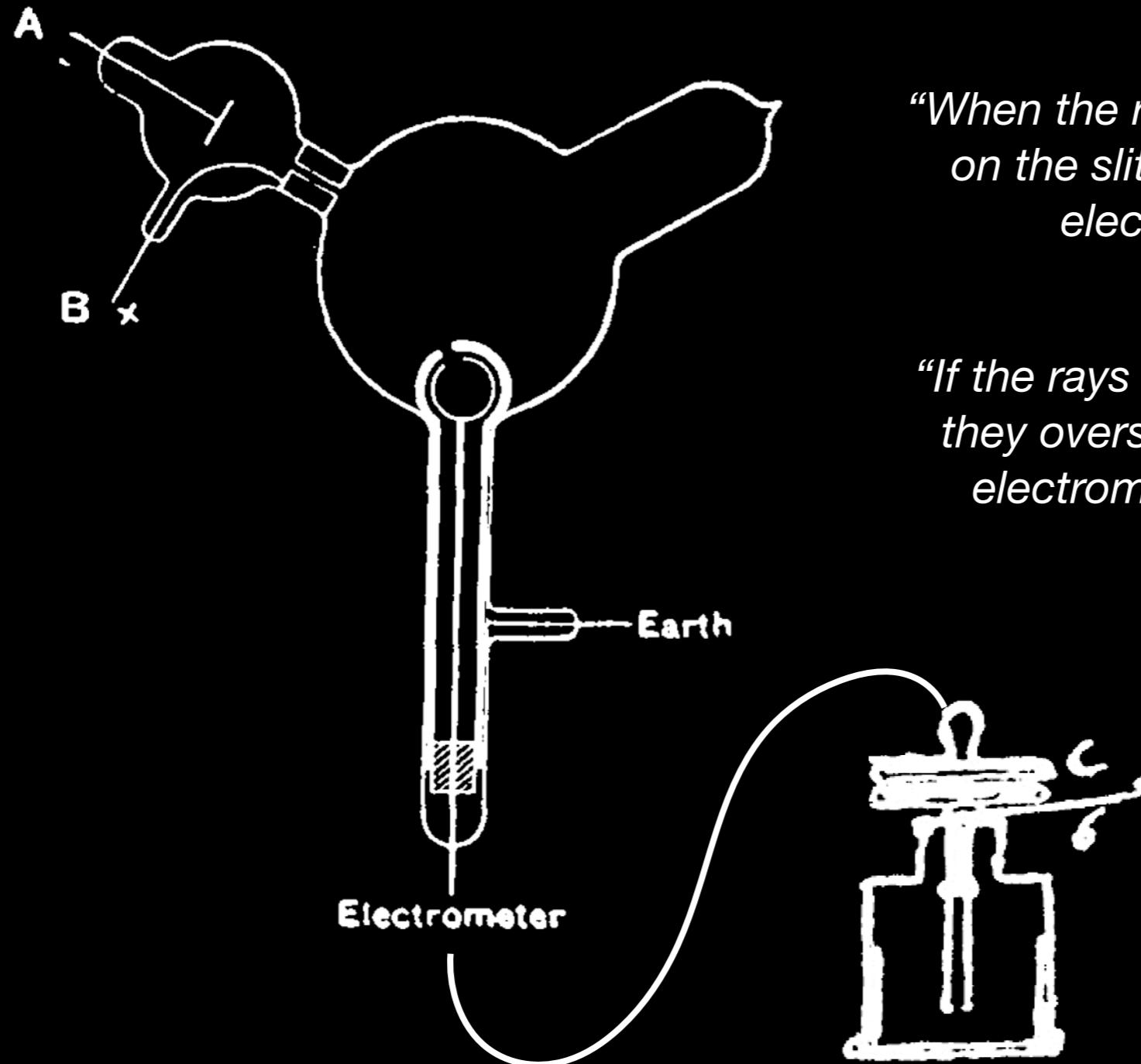


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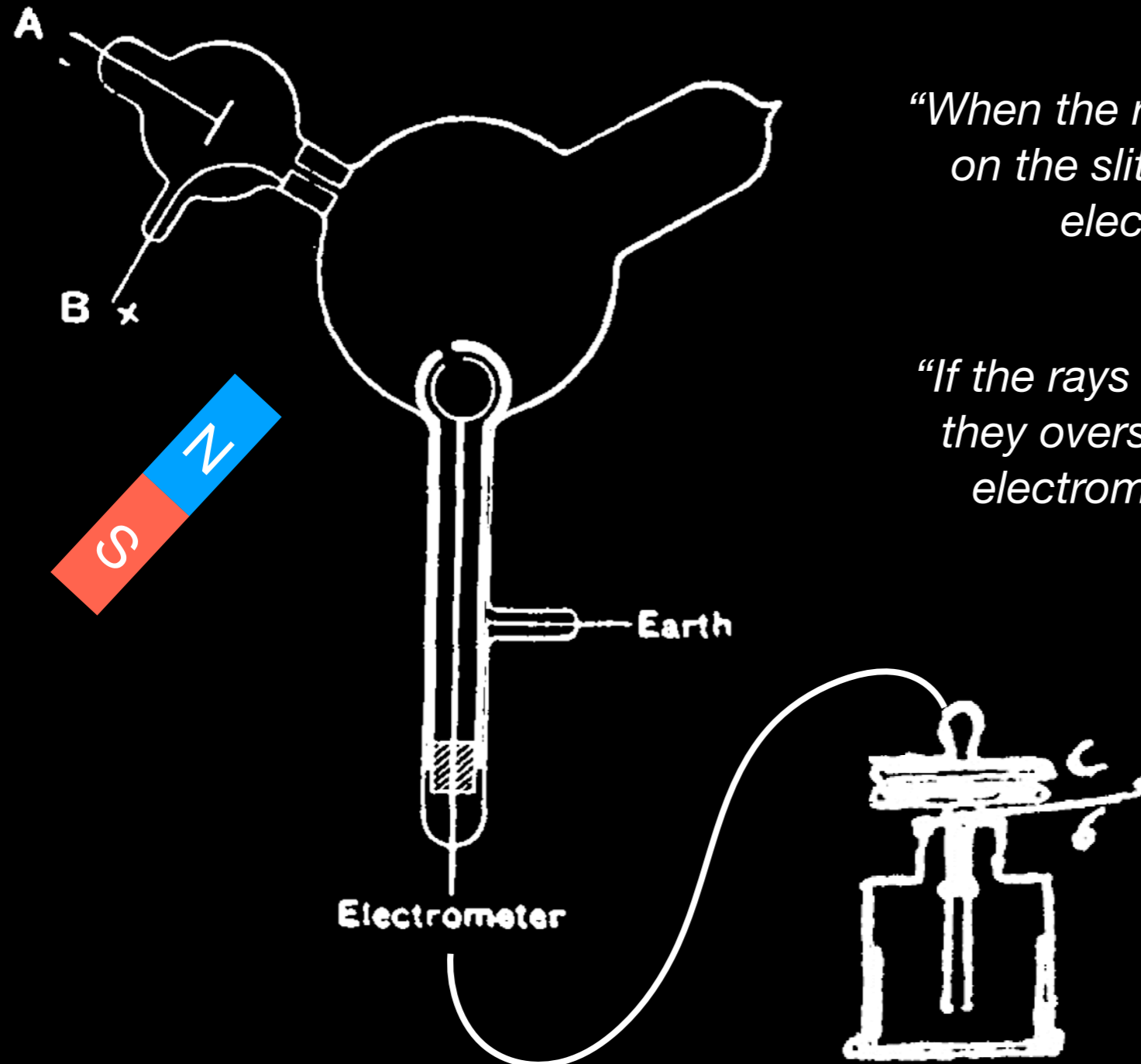
“When the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer.”

“If the rays were so much bent by the magnet that they overshot the slit, the charge passing to the electrometer fell to a very small fraction [...]”

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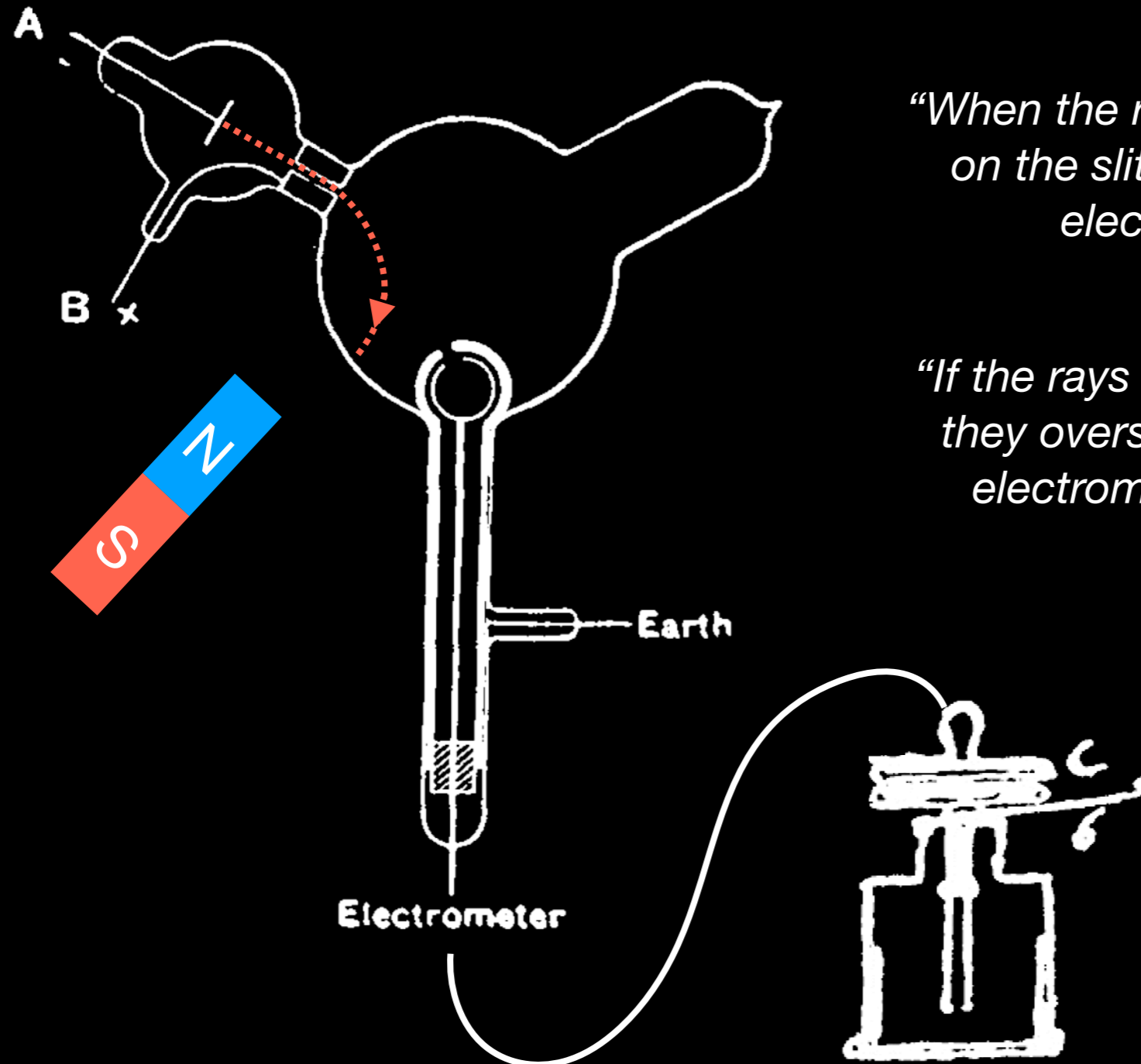
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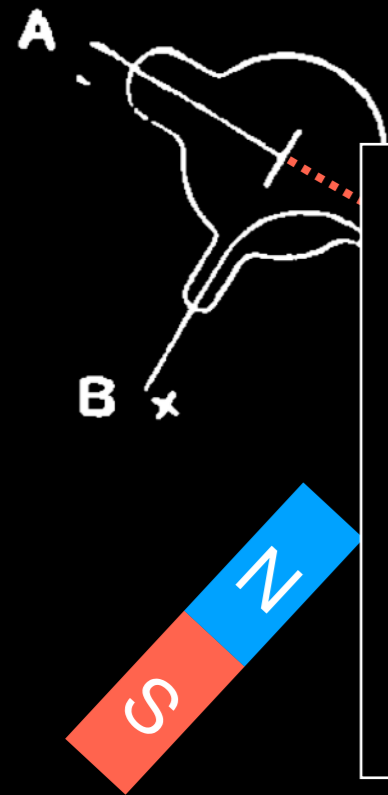
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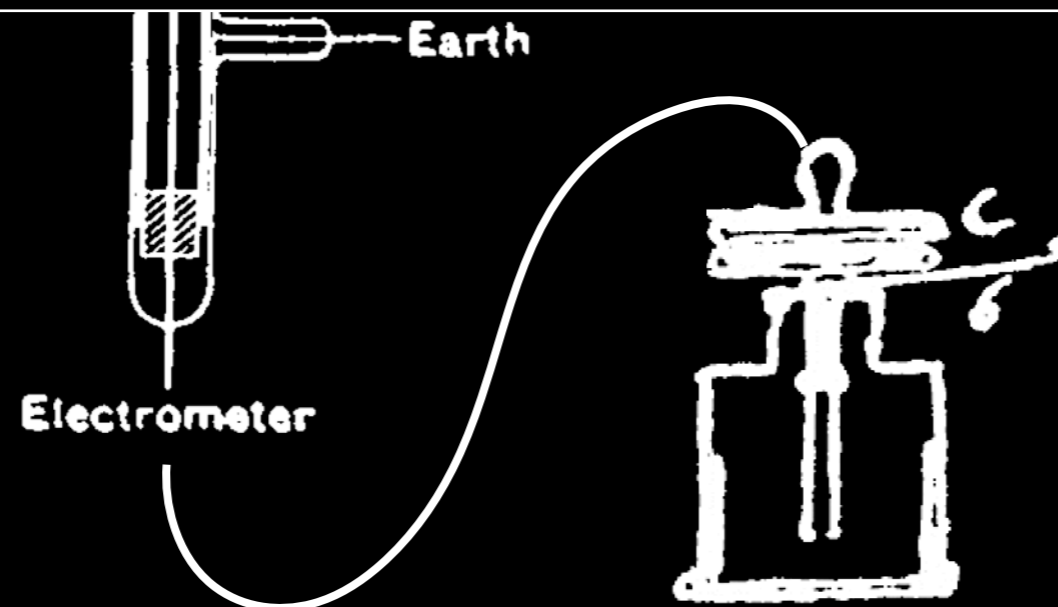
“The cathode rays do not fall upon the electrometer unless they are deflected by a magnet.”



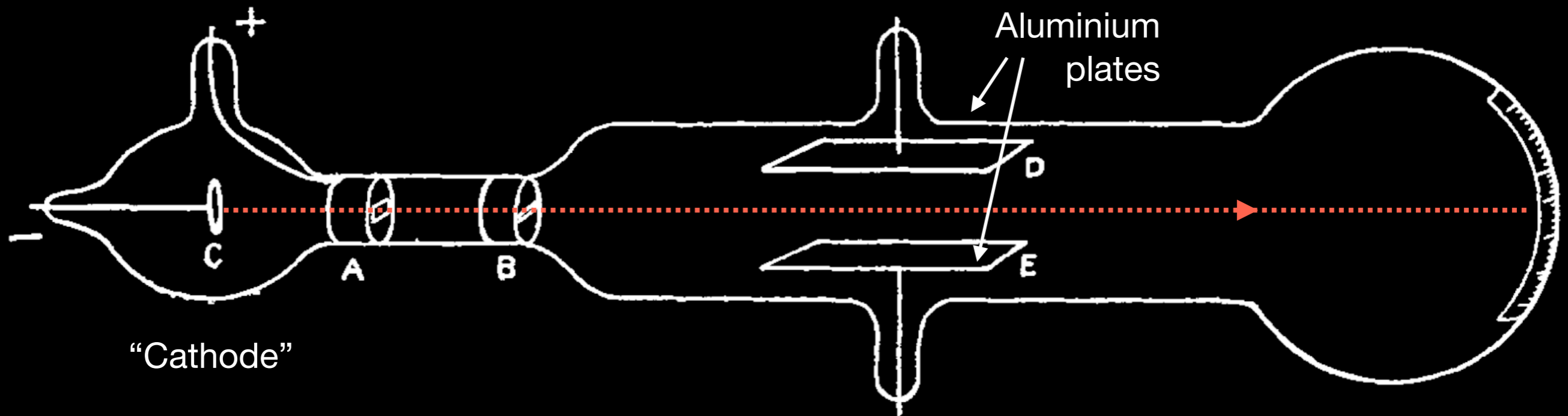
“When the rays were bent by a magnet so as to fall upon the electrometer, the negative electrification followed them, and the electrometer was deflected.”

“Thus this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays.”

the magnet that was passing to the action [...]”

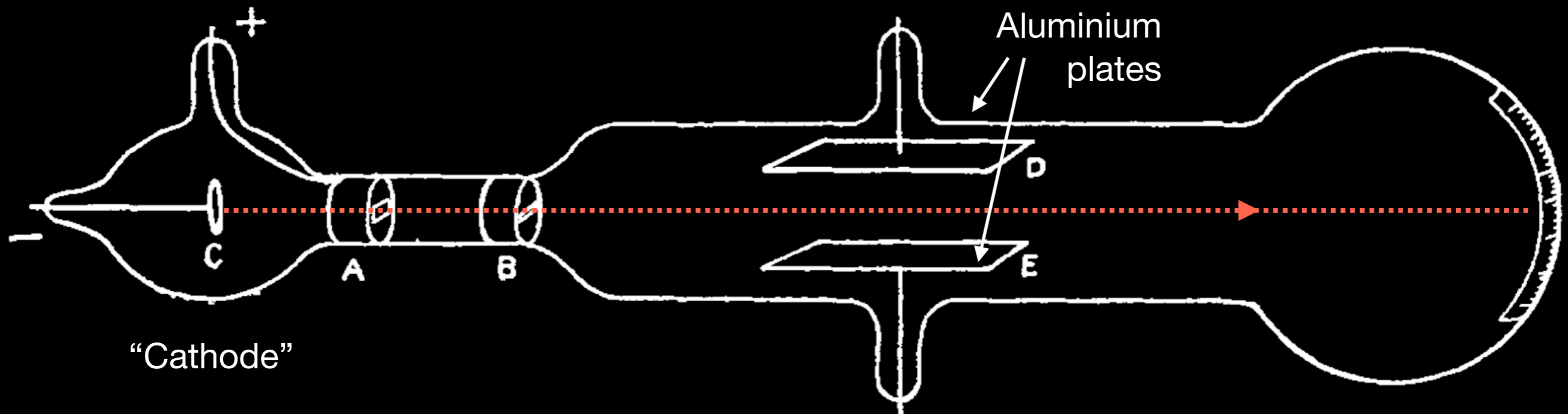


Electric deflection



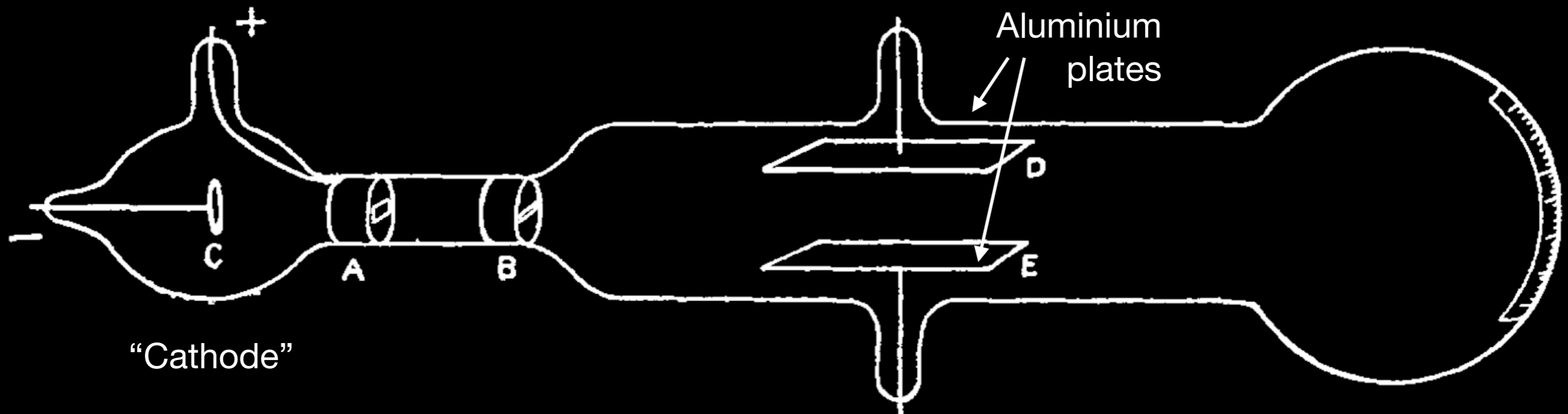
Electric deflection

“At high exhaustion the rays were deflected when the two aluminum plates were connected with the terminals of a battery of small storage cells.”



Electric deflection

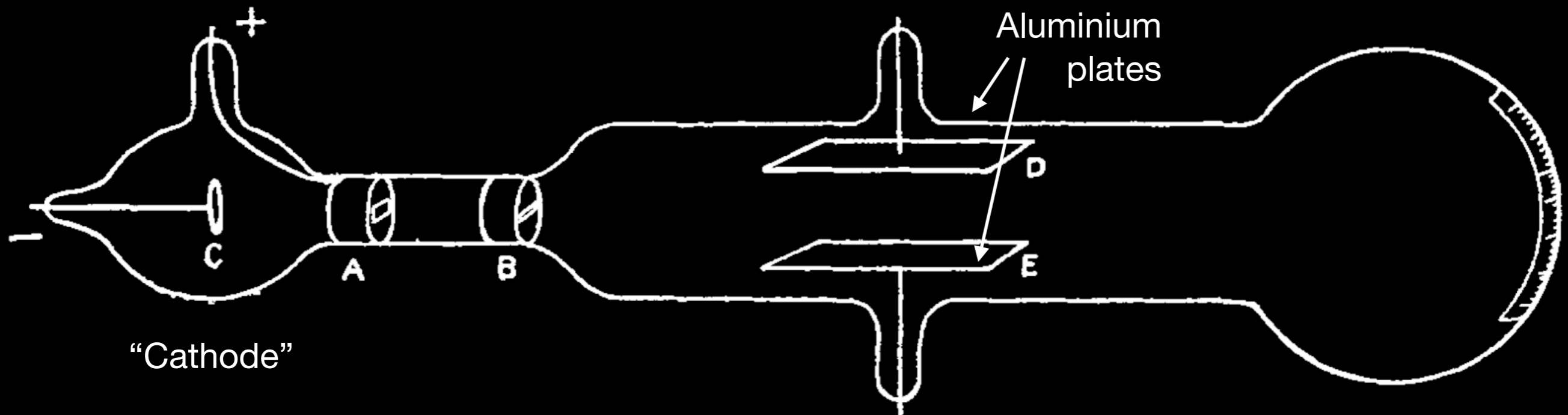
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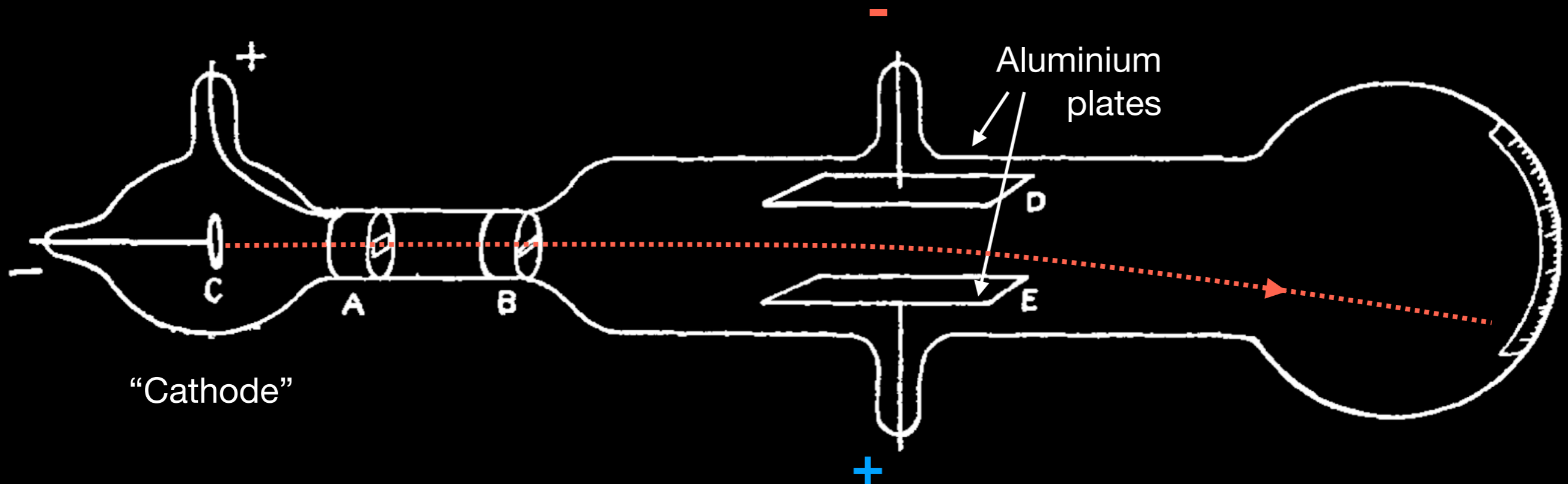
“The rays were depressed when the upper plate was connected with the negative pole of the battery, the lower with the positive ...”



Electric deflection

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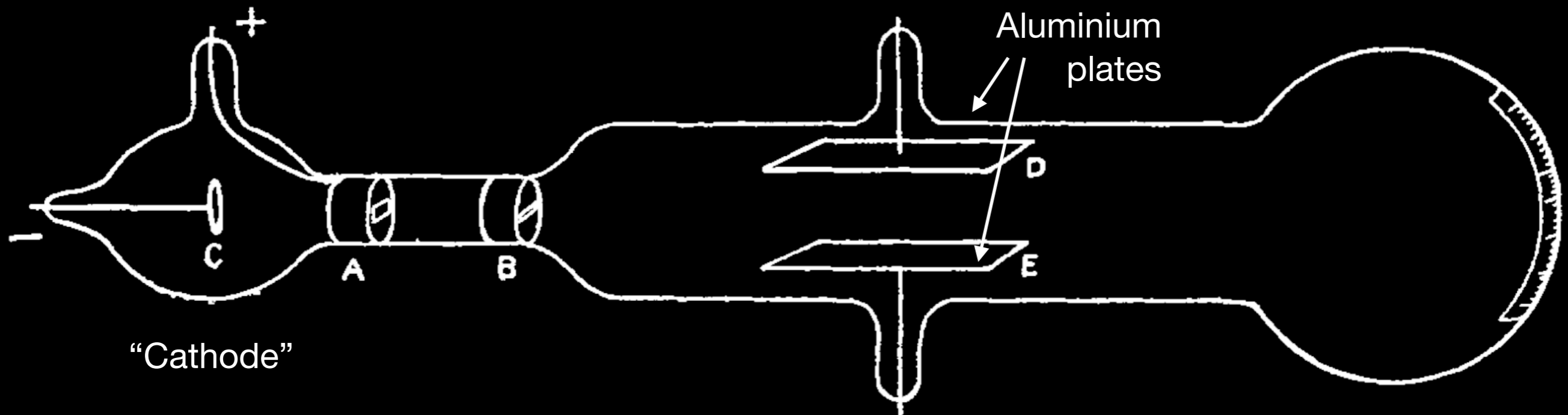
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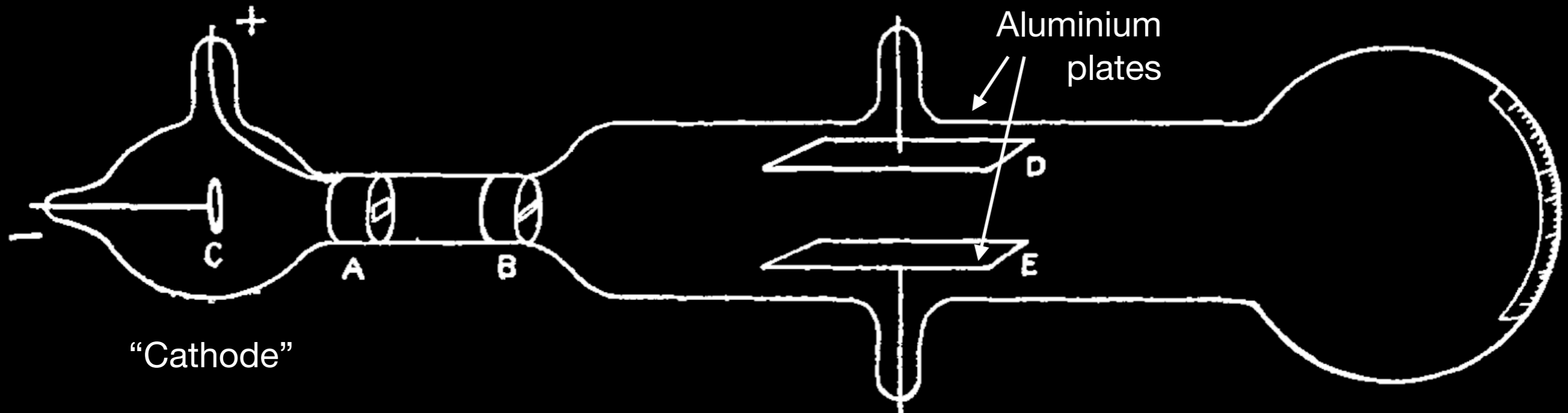


Electric deflection

“At high exhaustion the rays were deflected when the two aluminum plates were connected with the terminals of a battery of small storage cells.”

“The rays were depressed when the upper plate was connected with the negative pole of the battery, the lower with the positive ...”

“... and raised when the upper plate was connected with the positive, the lower with the negative pole.”

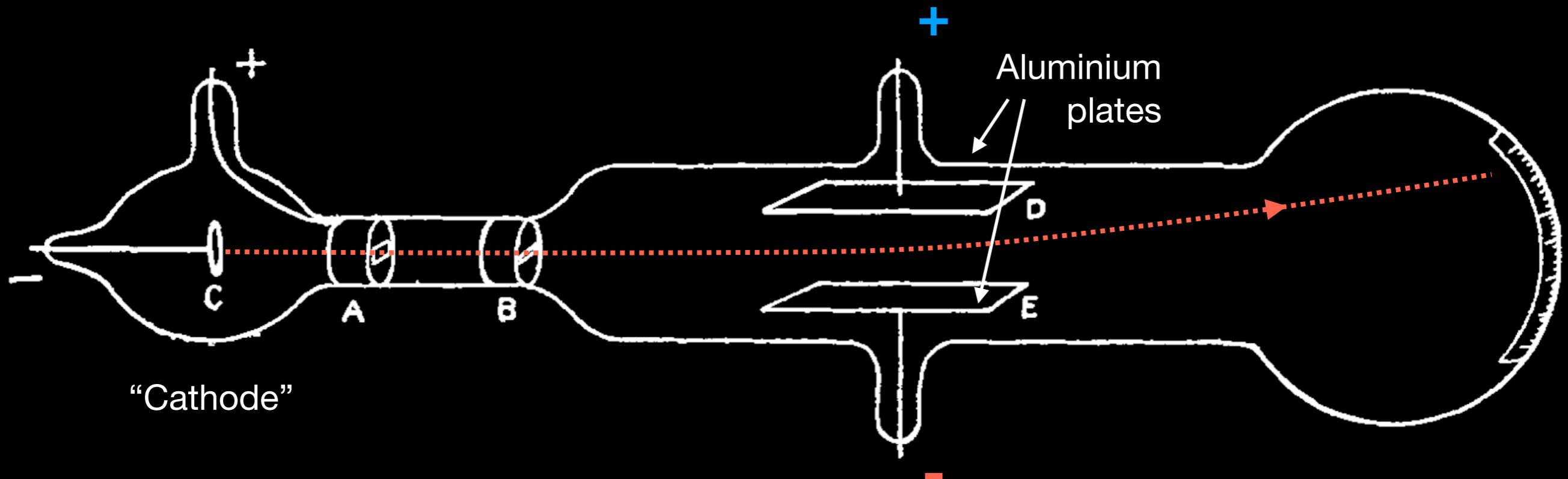


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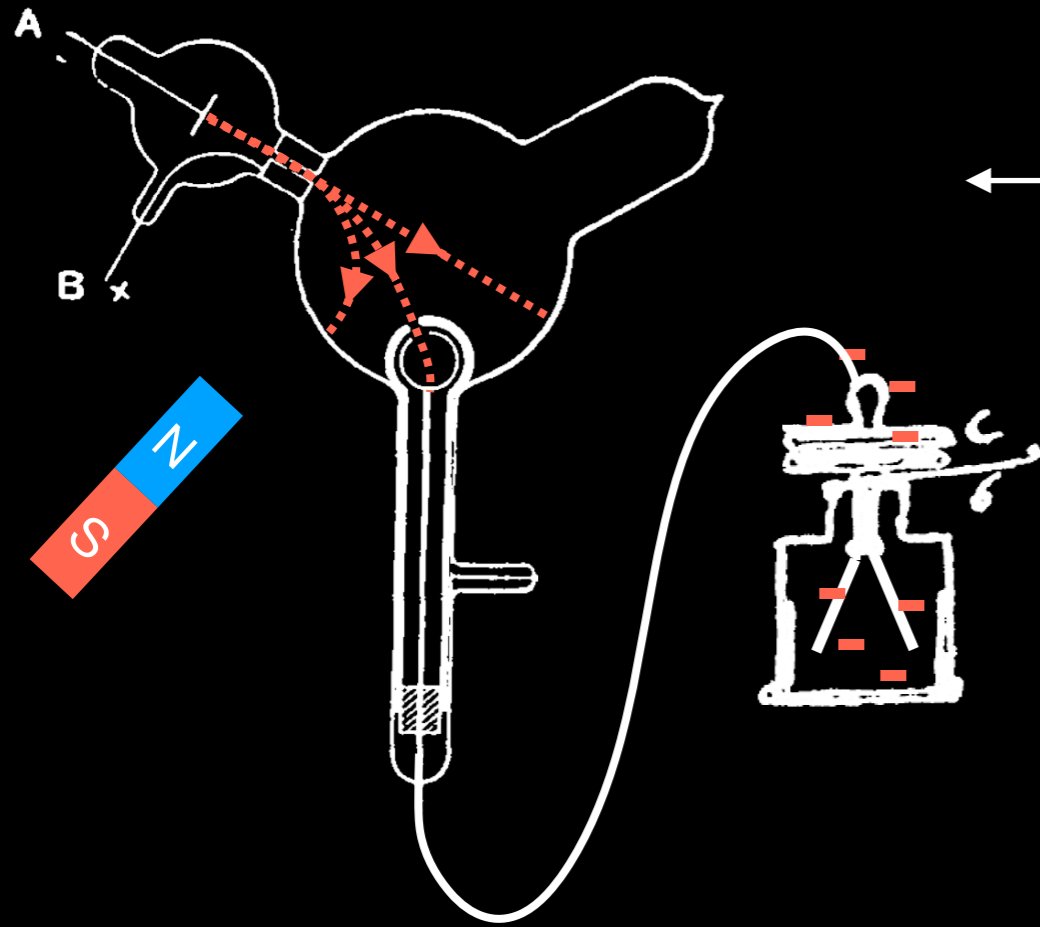
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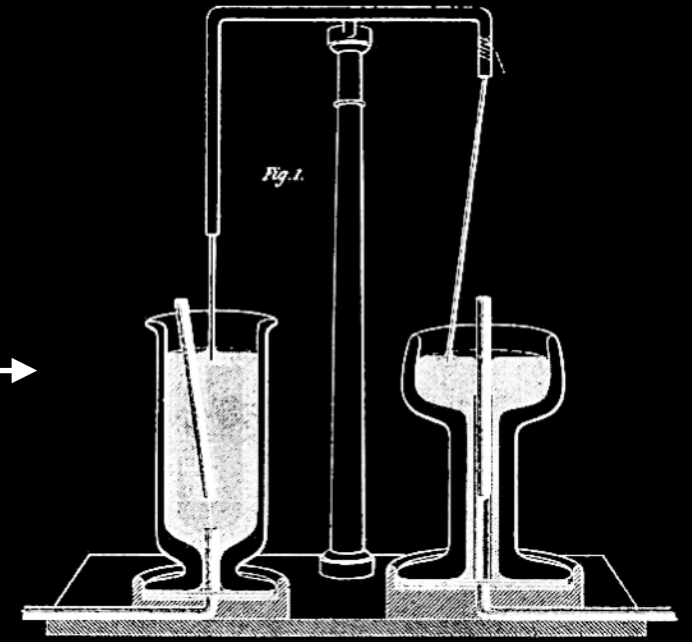


Thomson's conclusion

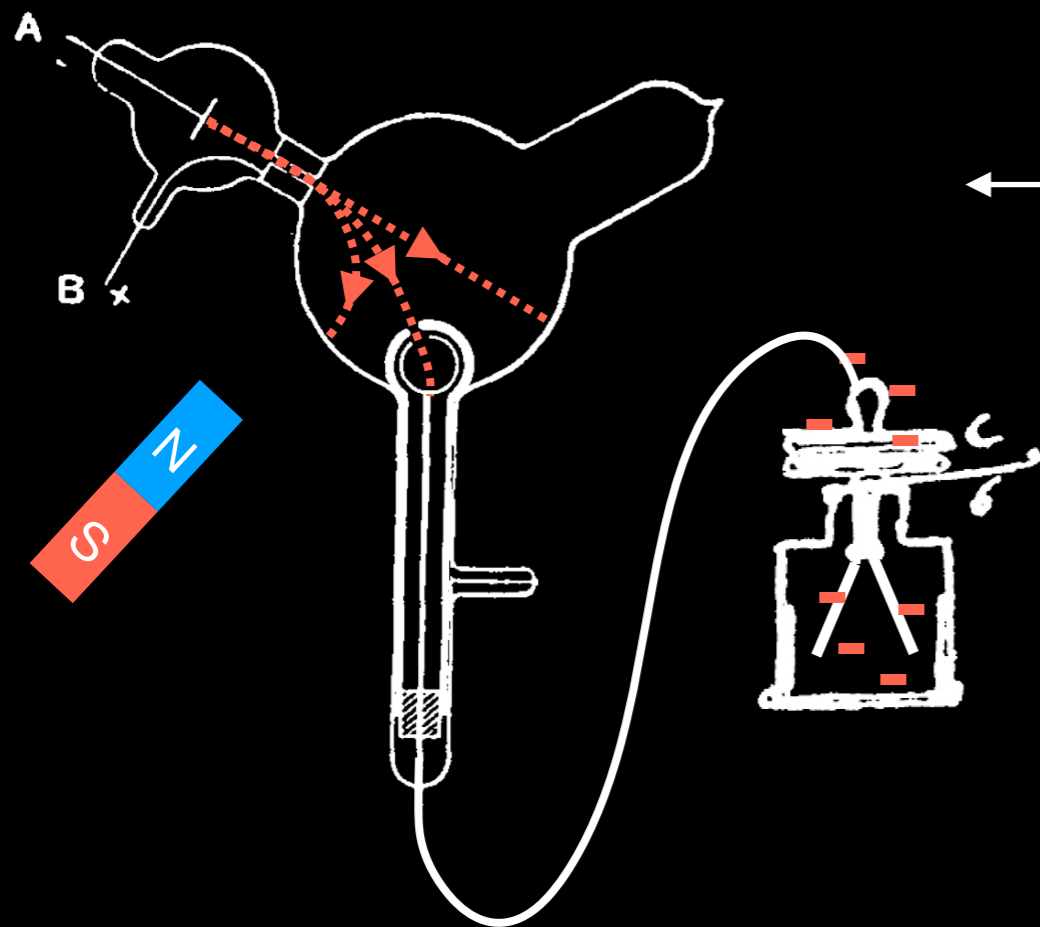
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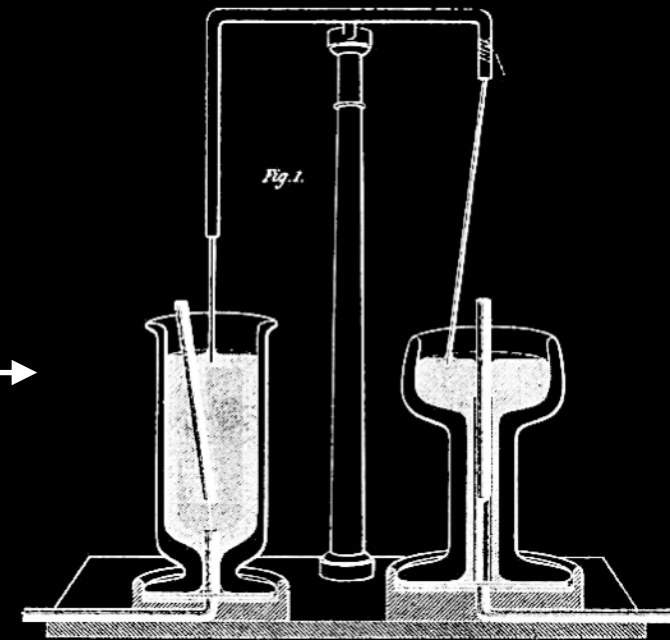
Magnets deflect electric currents



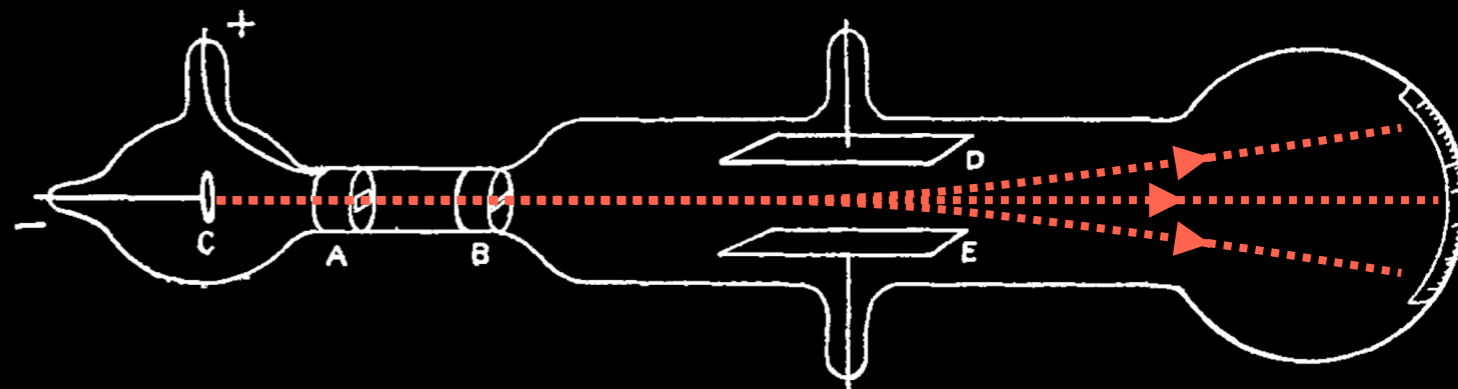
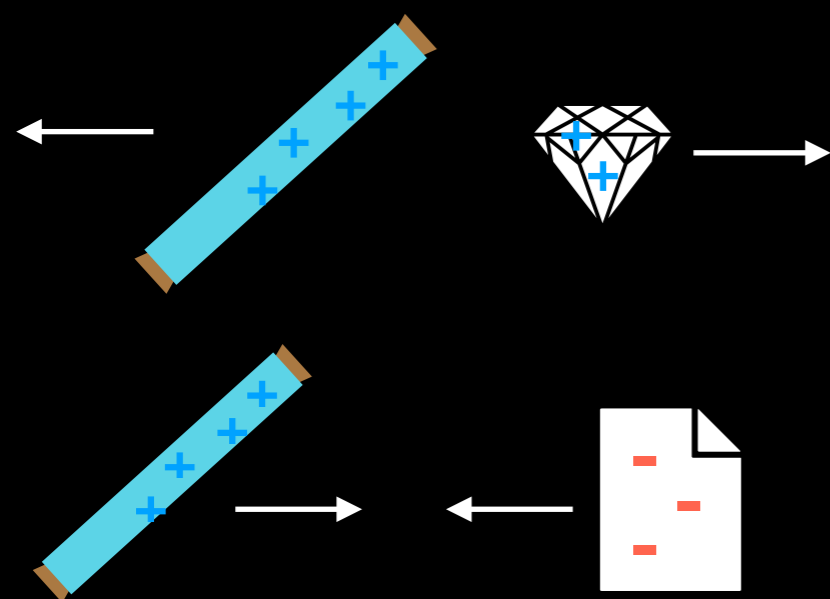
Thomson's conclusion



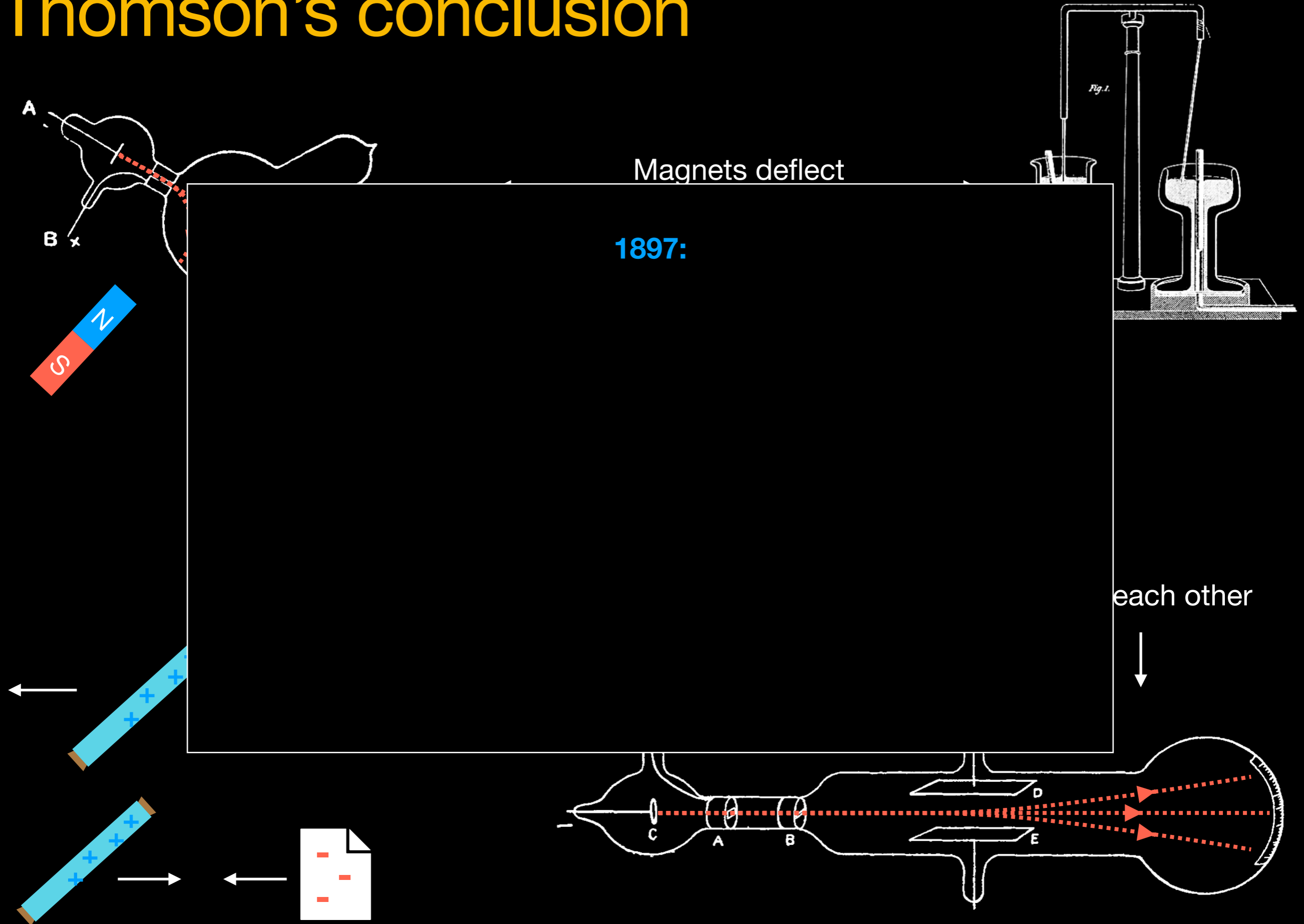
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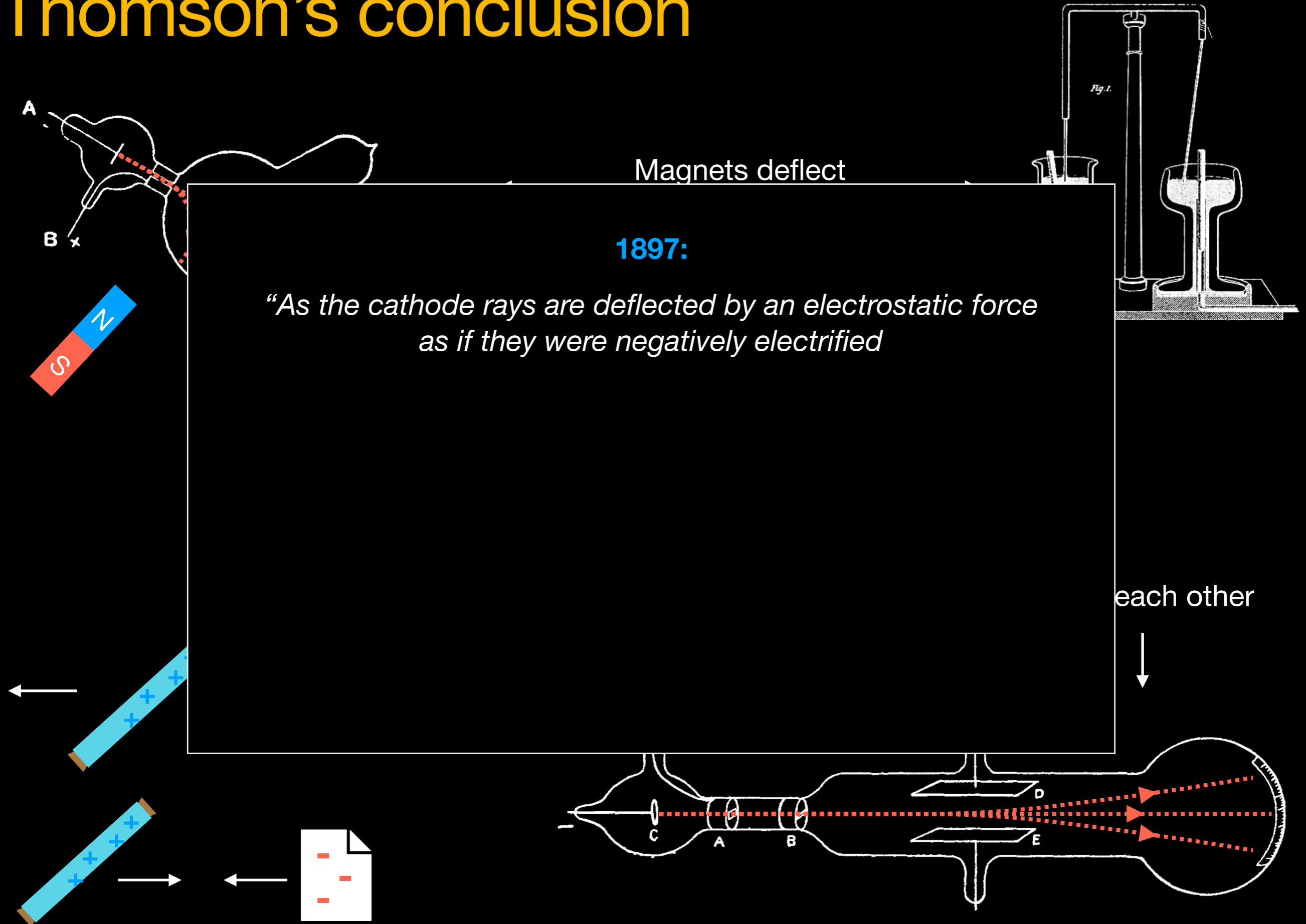
Electrically charged objects attract or repel each other



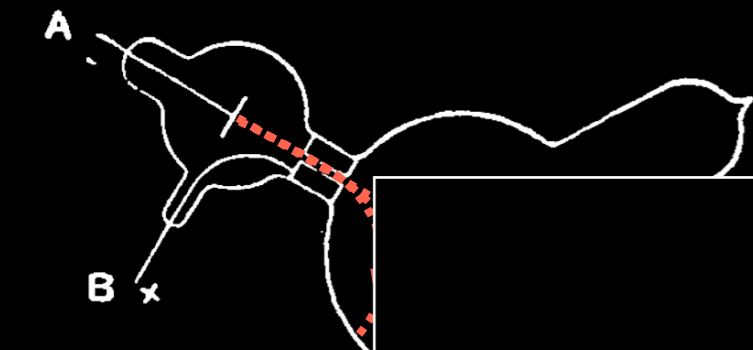
Thomson's conclusion



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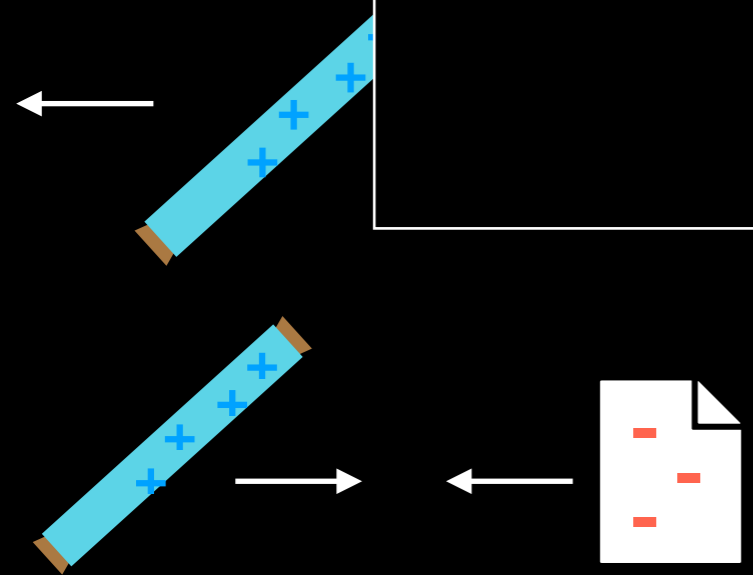
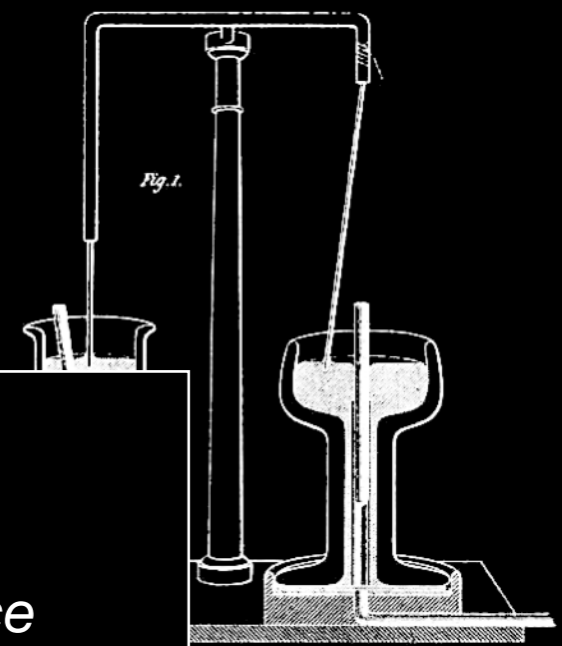
Thomson's conclusion



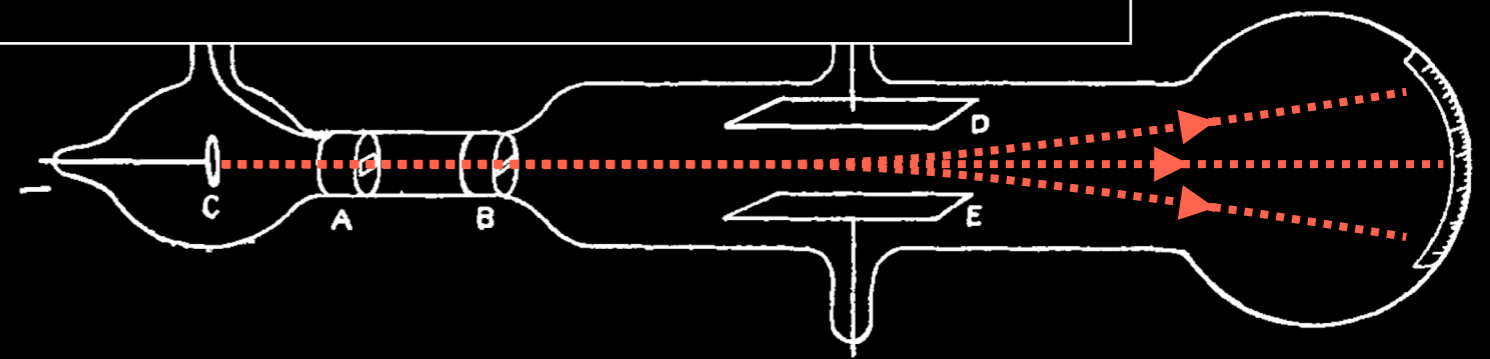
Magnets deflect

1897:

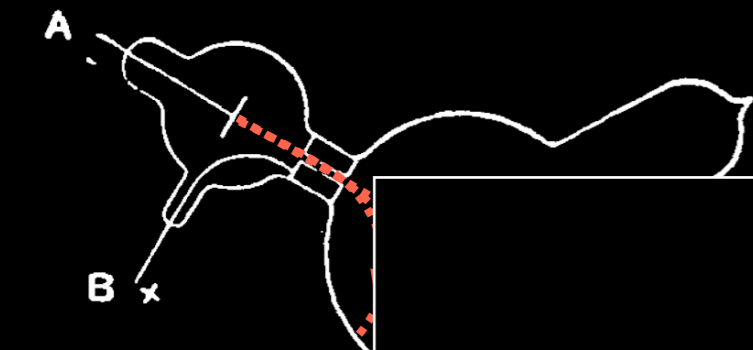
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each other



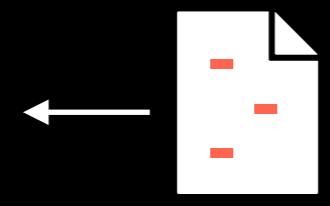
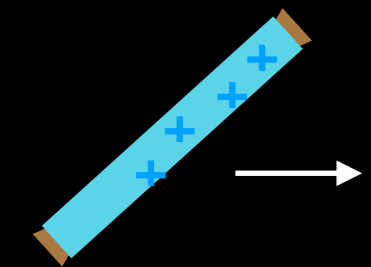
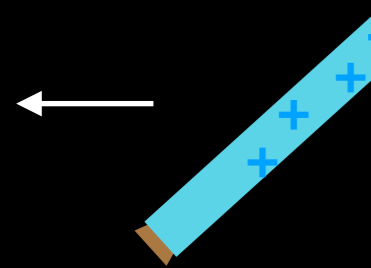
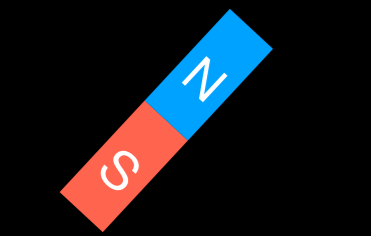
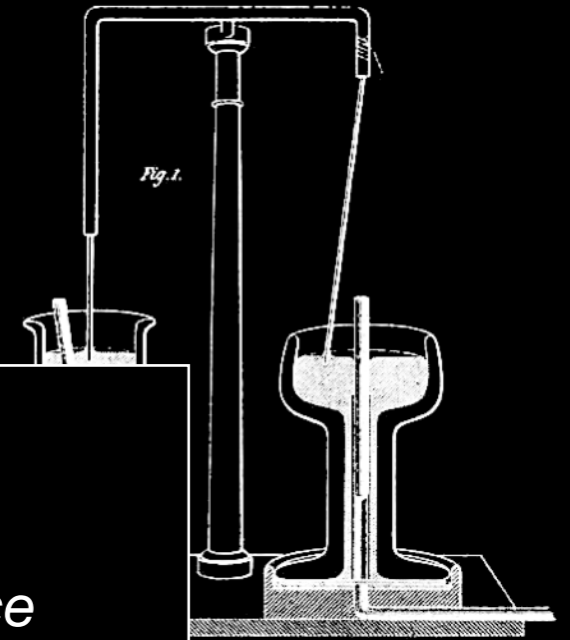
Thomson's conclusion



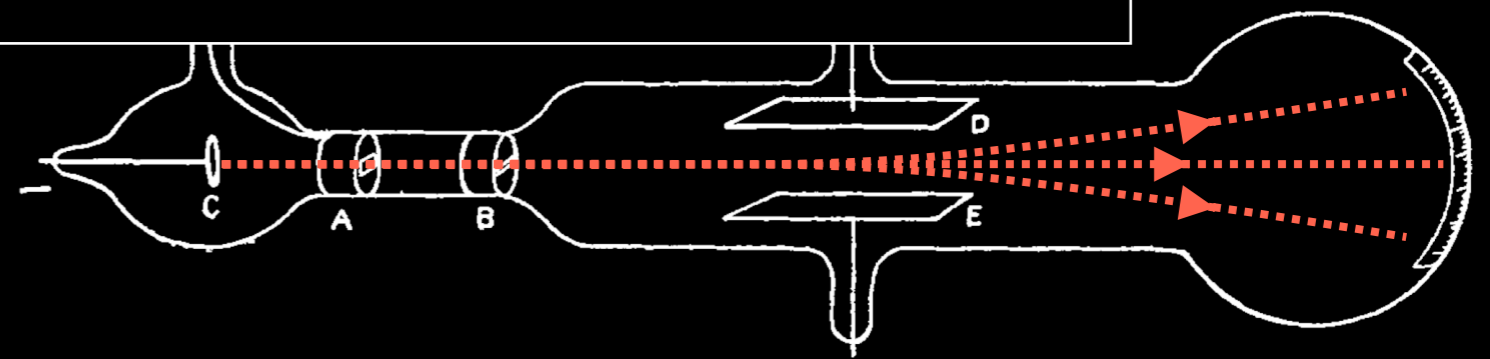
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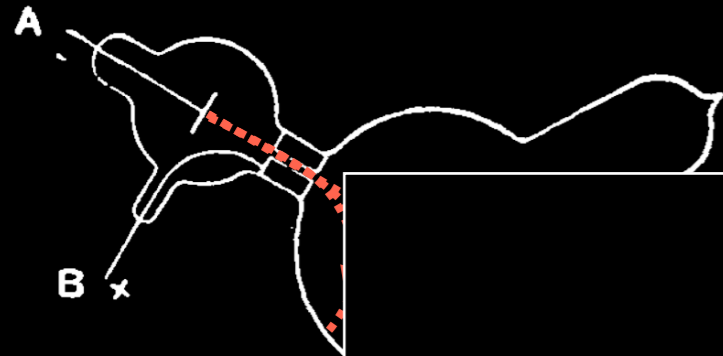
“As the cathode rays are deflected by an electrostatic force as if they were negatively electrified and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.”



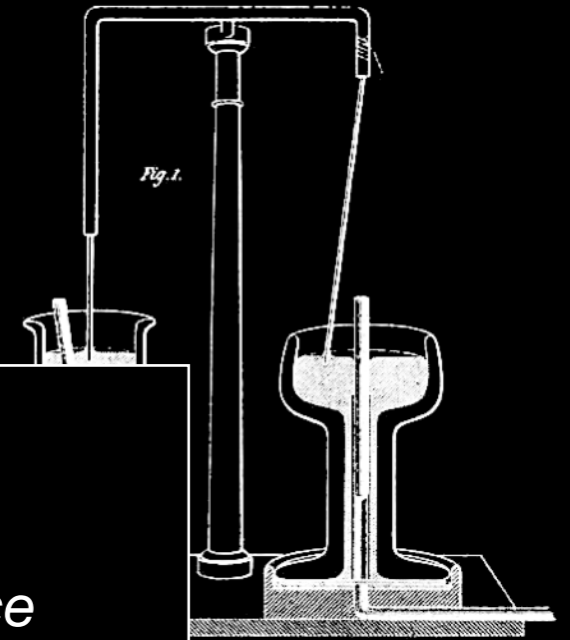
each other



Thomson's conclusion



Magnets deflect

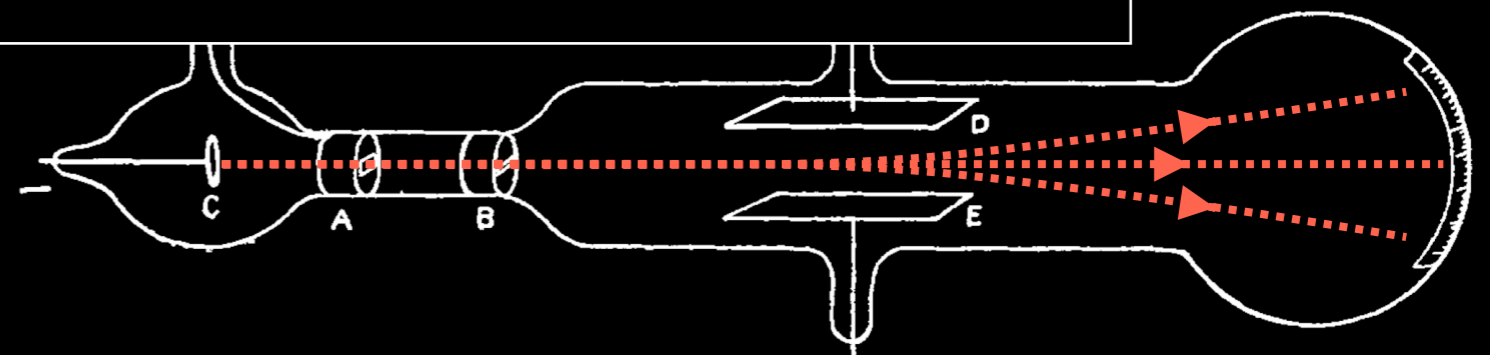
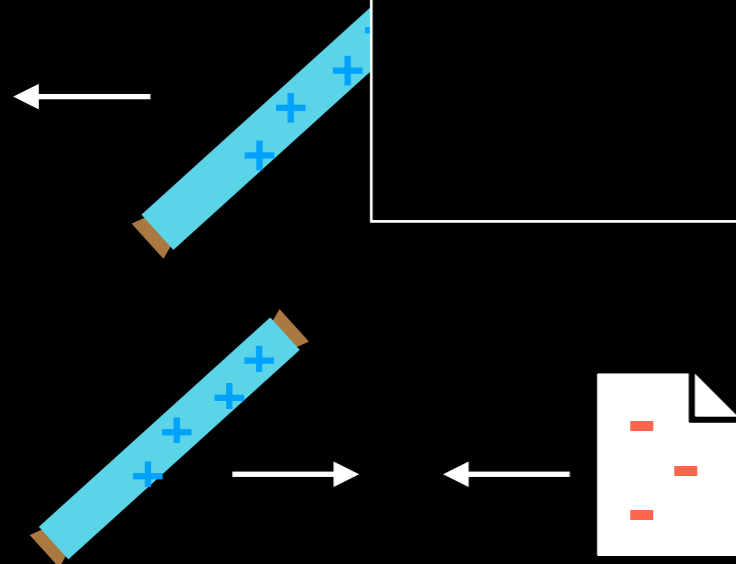


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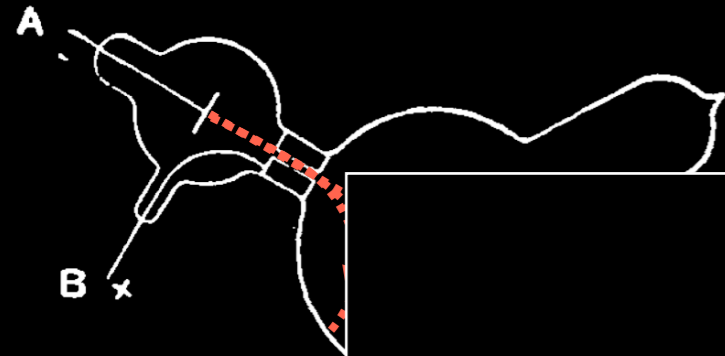
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Electricity is carried by particles!!
(There is a “smallest amount” of electricity.)

each other



Thomson's conclusion



Magnets deflect

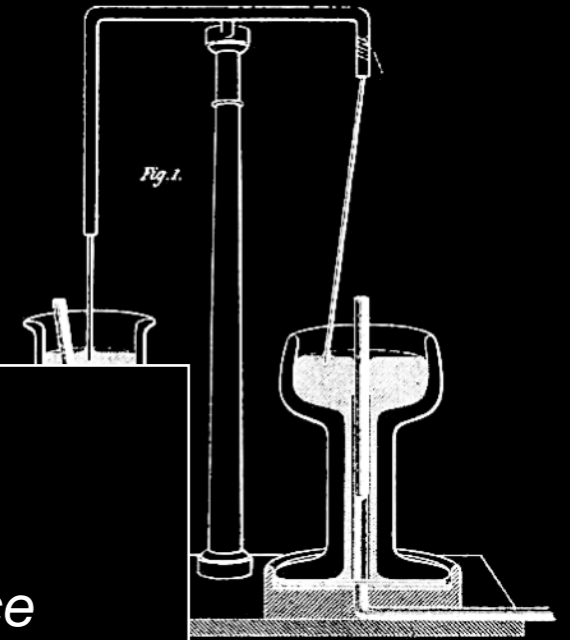
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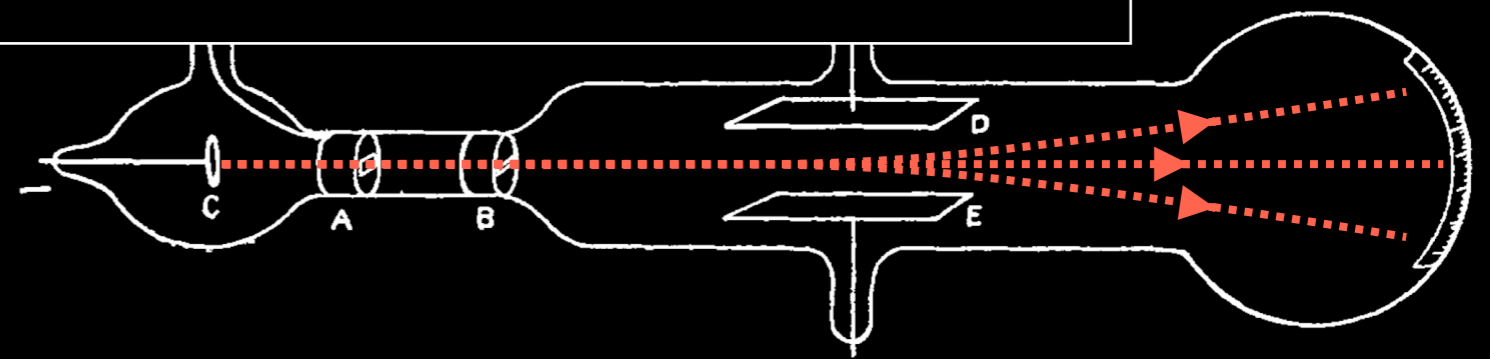
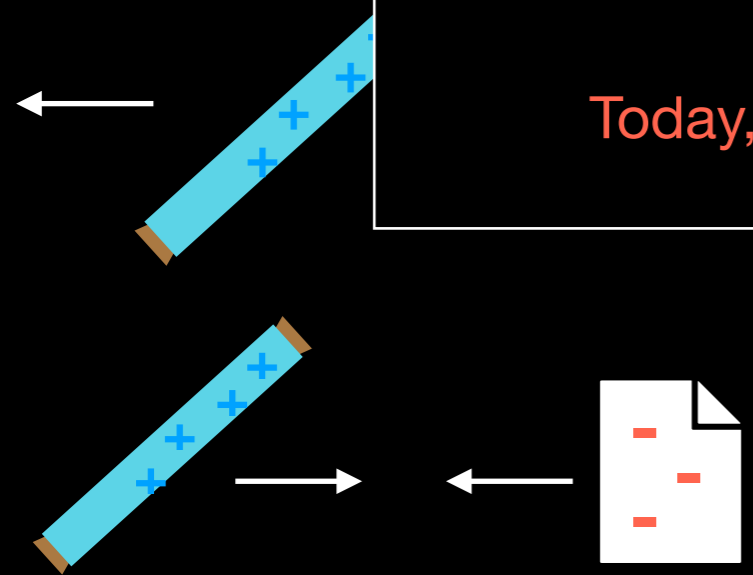
Electricity is carried by particles!!

(There is a “smallest amount” of electricity.)

Today, we call this “particle of electricity” the “electron”.



each other



Thomson's questions

Thomson's questions

And so, the question next arises,

Thomson's questions

And so, the question next arises,

What are these particles?

Thomson's questions

And so, the question next arises,

What are these particles?

Are they atoms?

Thomson's questions

And so, the question next arises,

What are these particles?

Are they atoms?

Or molecules?

Thomson's questions

And so, the question next arises,

What are these particles?

Are they atoms? Or molecules?

Or matter in a still finer state of subdivision?

The particles of electricity

The particles of electricity

“To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it.”

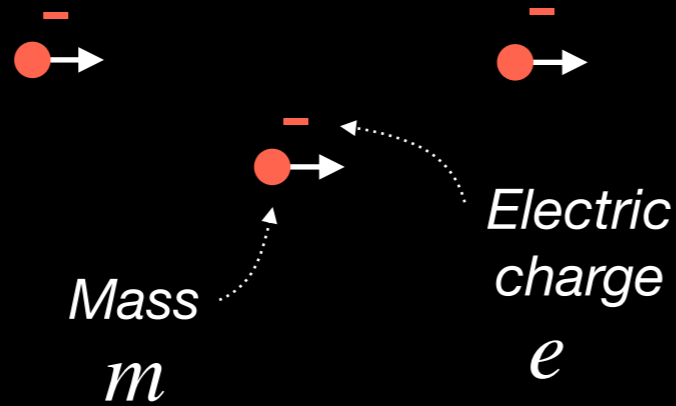
The particles of electricity

“To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it.”

Crookes’
“molecular rays”



A stream of
electrons



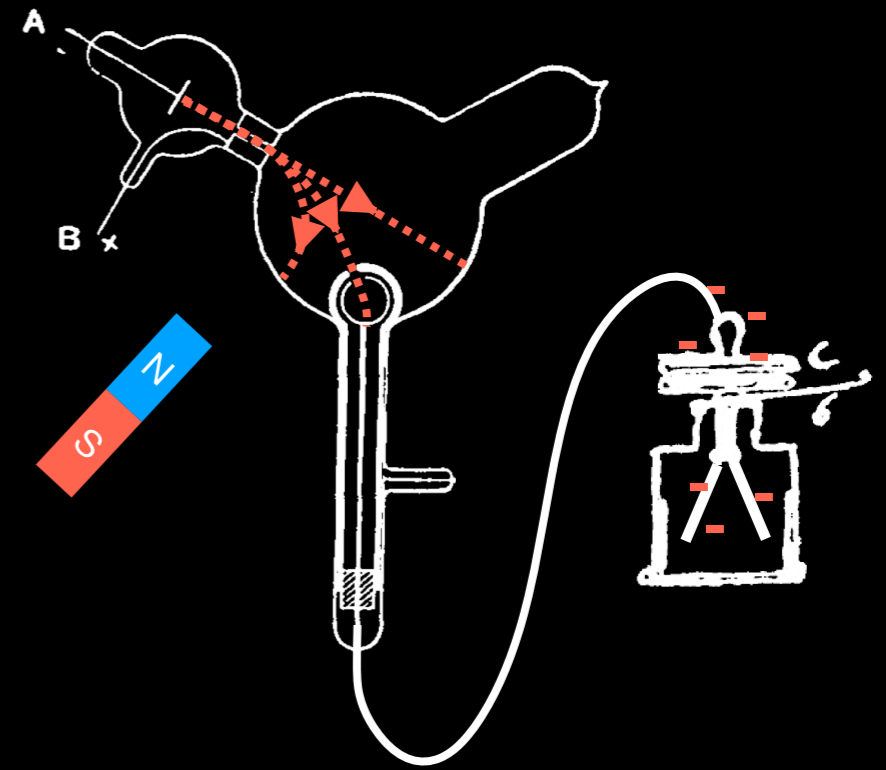
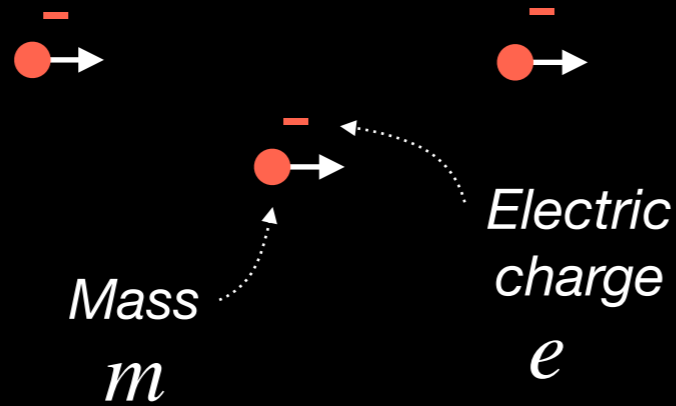
The particles of electricity

“To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it.”

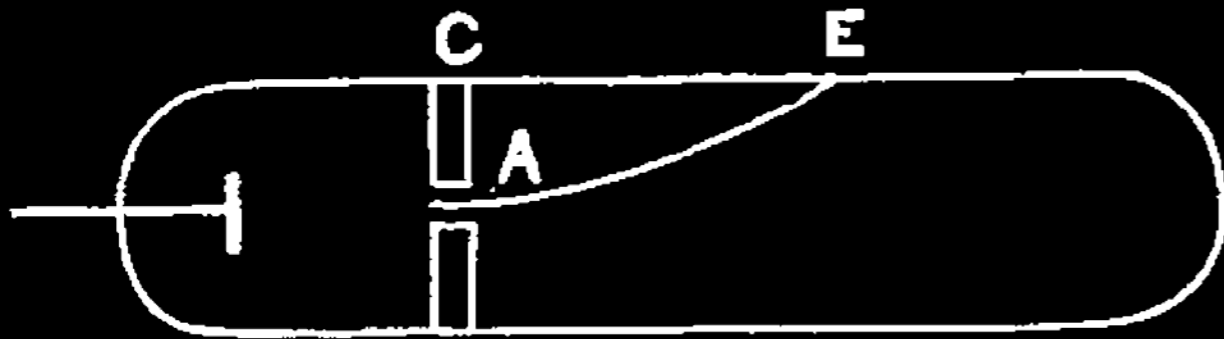
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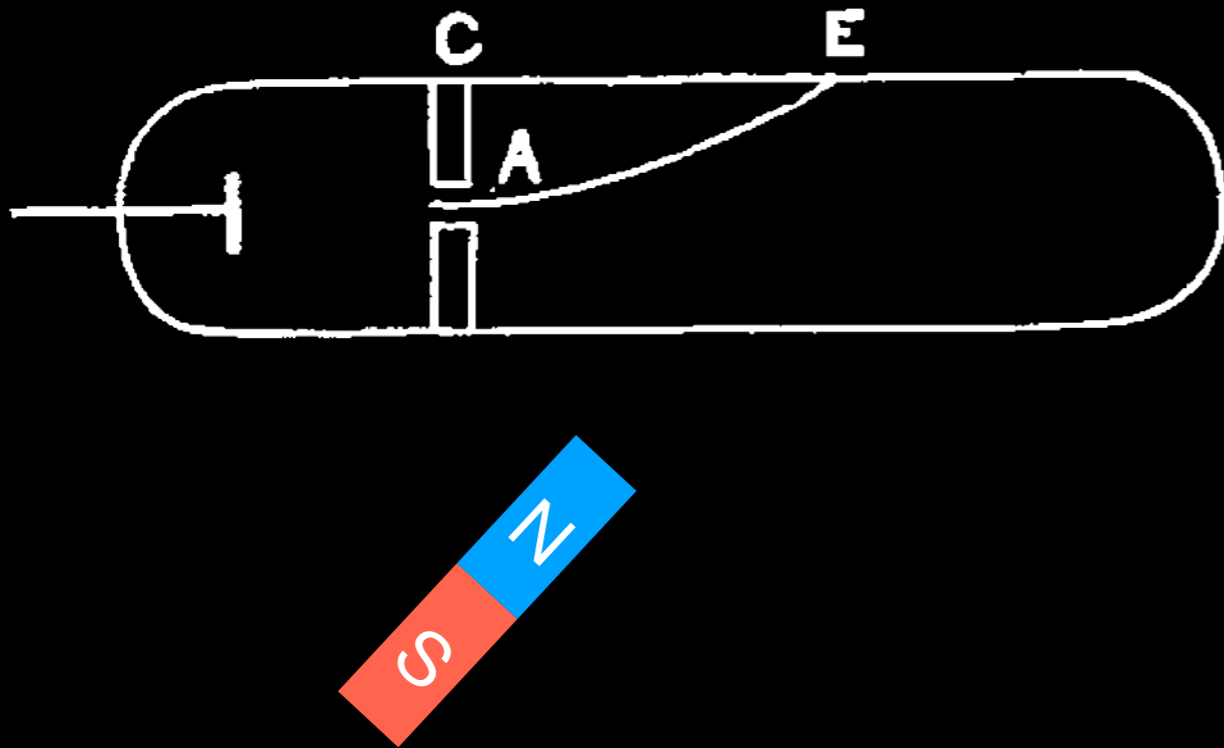
A stream of
electrons



Thomson's measurements

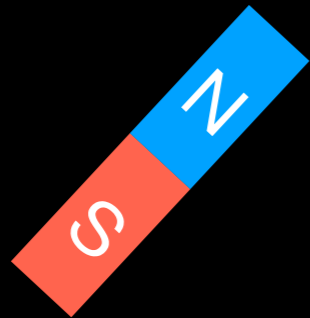
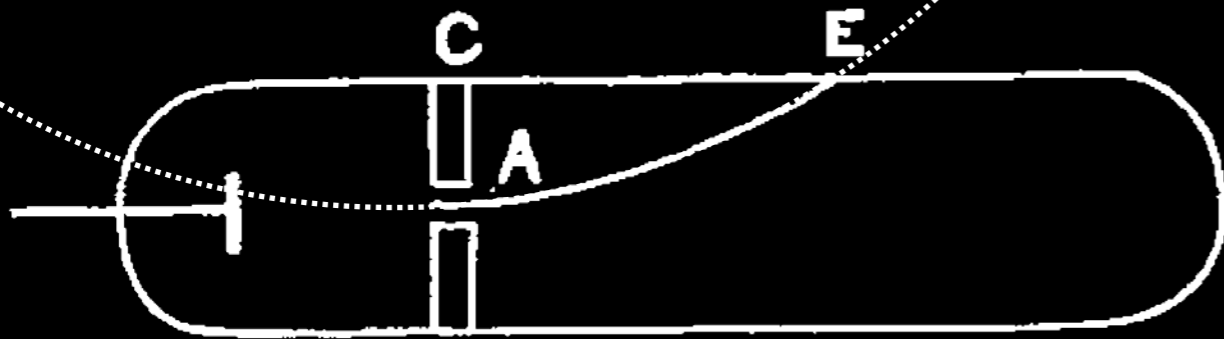


Thomson's measurements

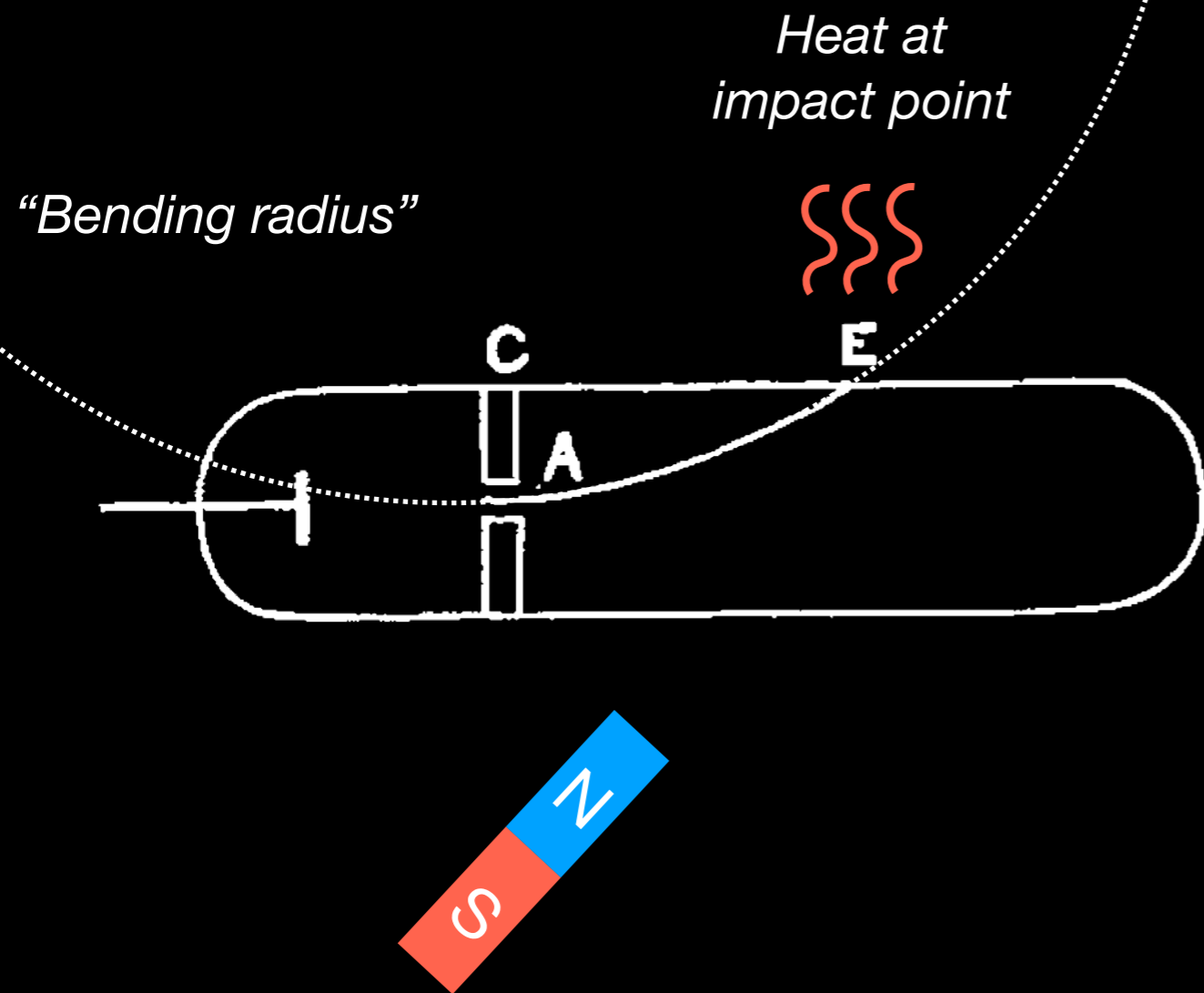


Thomson's measurements

"Bending radius"



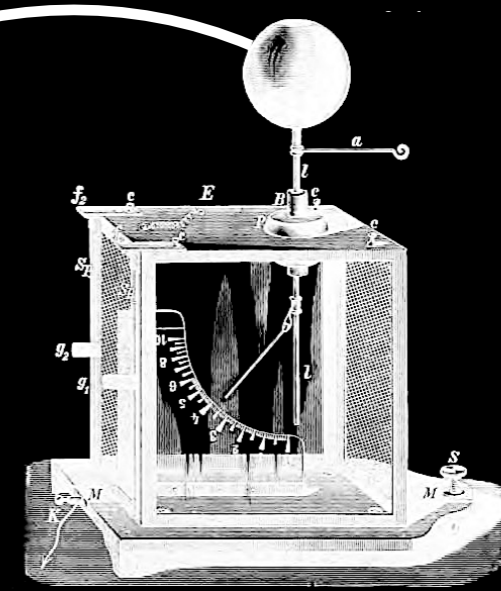
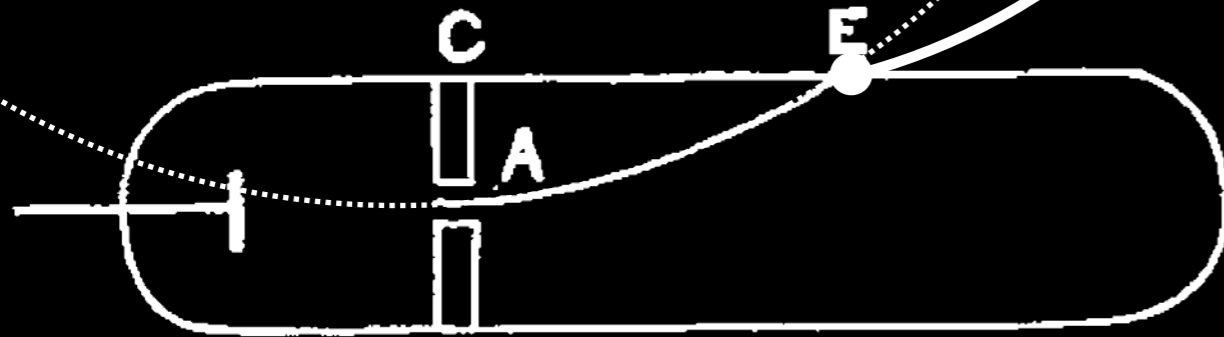
Thomson's measurements



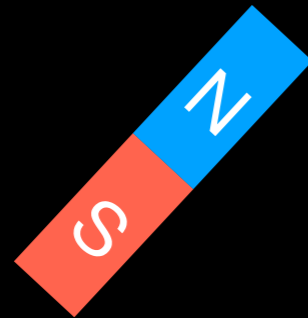
Thomson's measurements

"Bending radius"

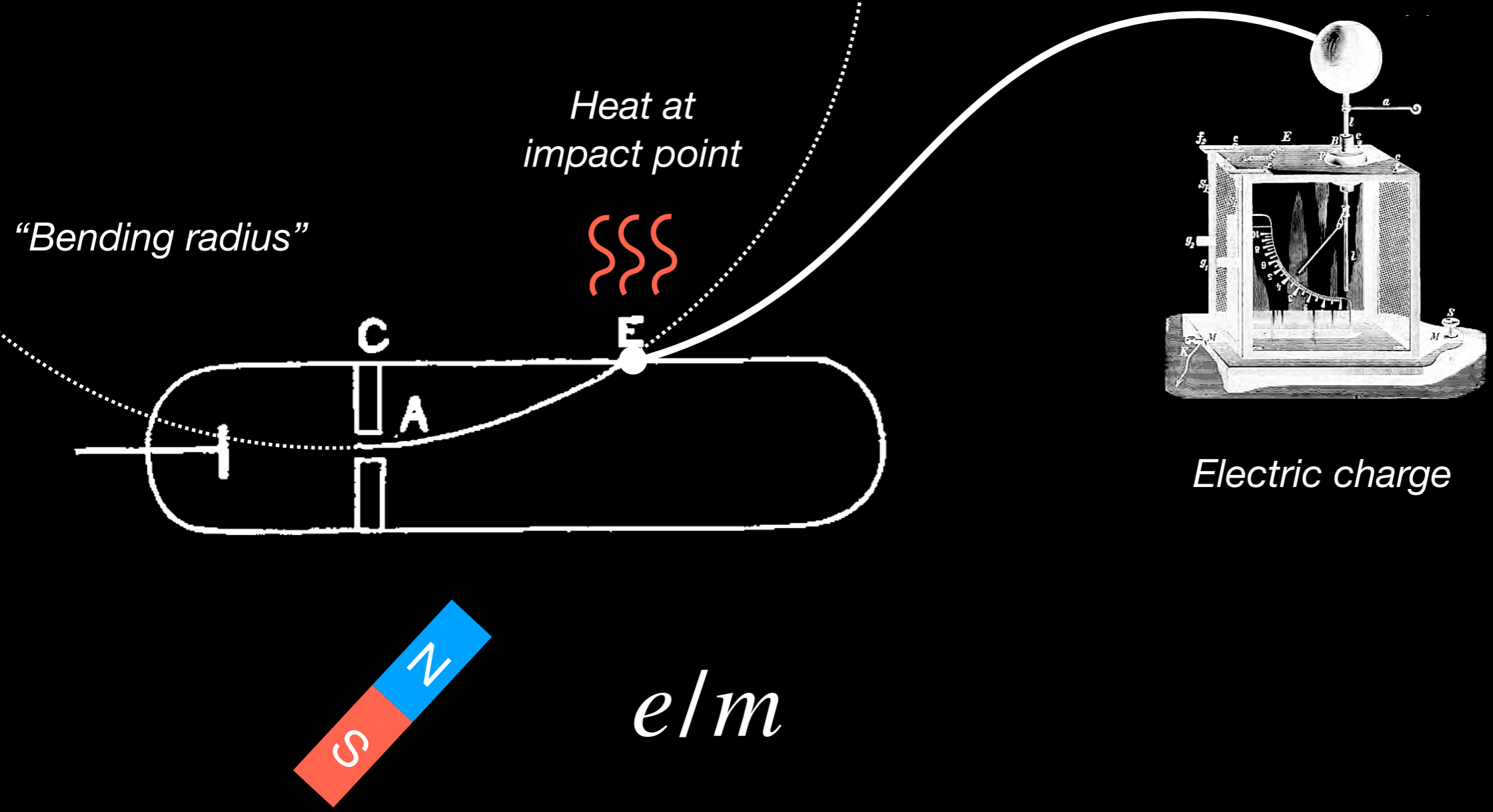
Heat at impact point



Electric charge



Thomson's measurements

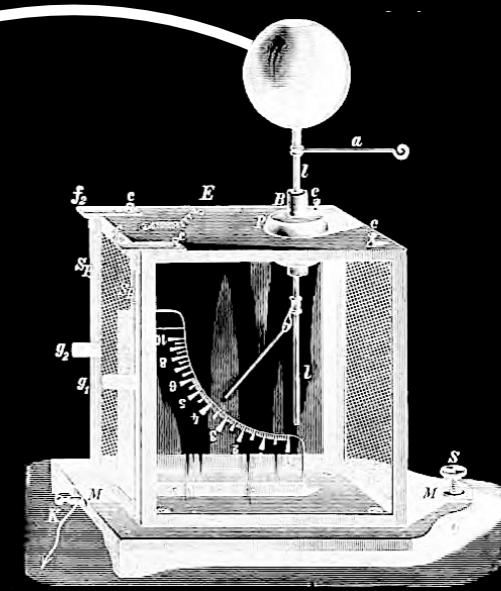
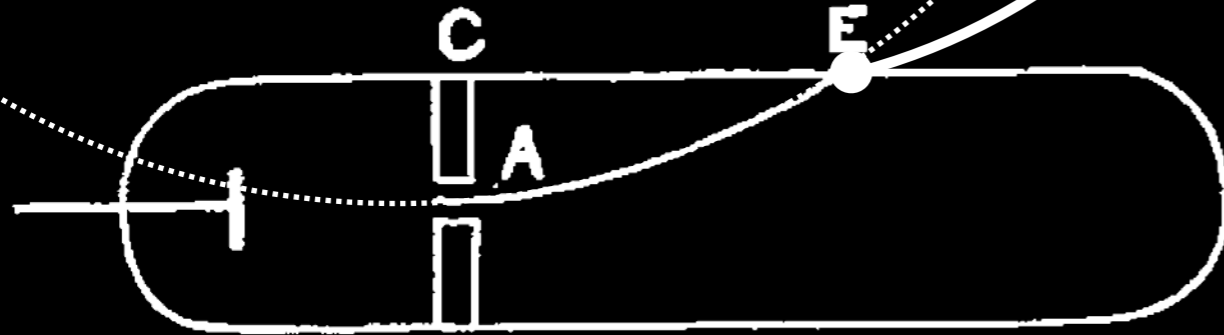


e/m

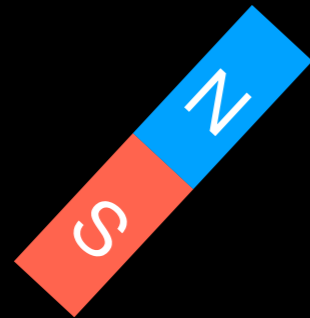
Thomson's measurements

"Bending radius"

Heat at impact point



Electric charge



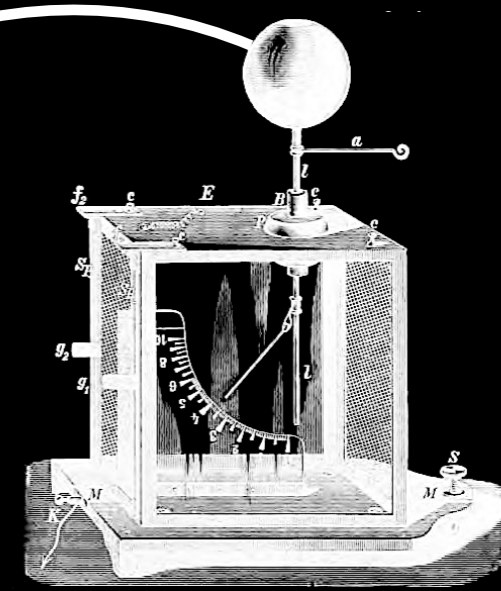
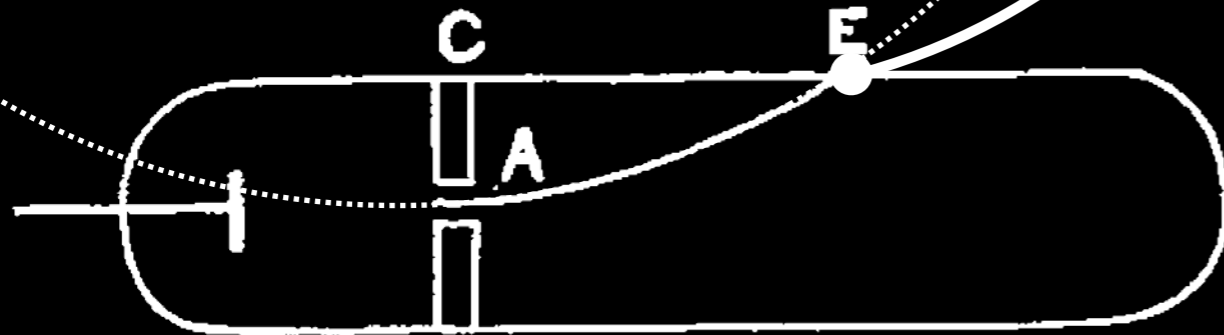
e/m

Gas.	m/e .
Air	$\cdot 4 \times 10^{-7}$
Hydrogen	$\cdot 35 \times 10^{-7}$
Carbonic acid	$\cdot 4 \times 10^{-7}$

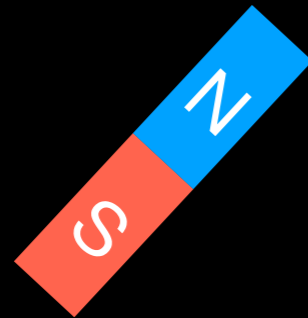
Thomson's measurements

"Bending radius"

Heat at impact point



Electric charge



e/m

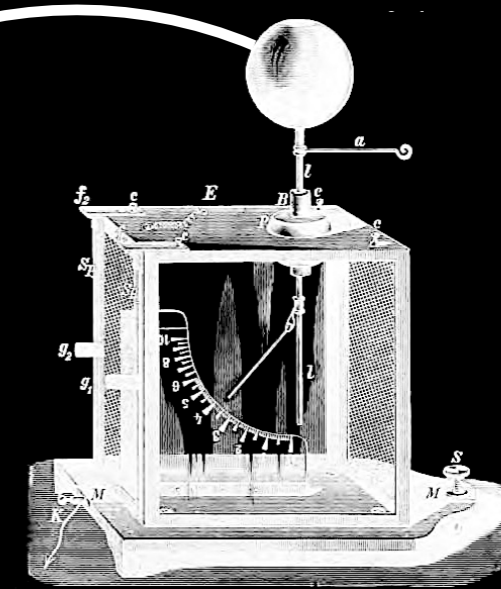
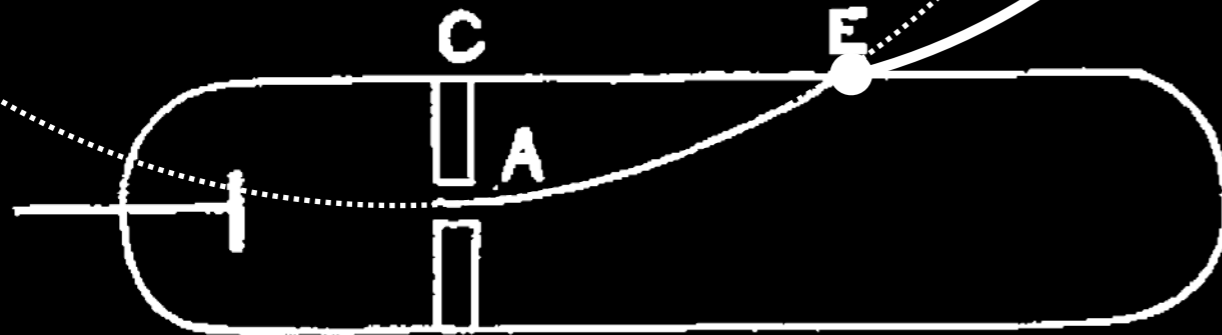
Independent of (dilute) gas remaining in the tube!

Gas.	m/e .
Air	$\cdot 4 \times 10^{-7}$
Hydrogen	$\cdot 35 \times 10^{-7}$
Carbonic acid	$\cdot 4 \times 10^{-7}$

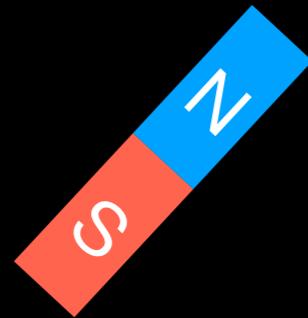
Thomson's measurements

"Bending radius"

Heat at impact point



Electric charge



e/m

Independent of (dilute) gas remaining in the tube!

→ Is a property of the electron itself!

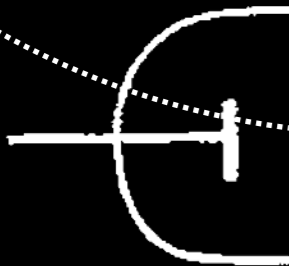
Gas.	$m/e.$
Air	$\cdot 4 \times 10^{-7}$
Hydrogen	$\cdot 35 \times 10^{-7}$
Carbonic acid	$\cdot 4 \times 10^{-7}$

Thomson's measurements

Heat at impact point



"Bending radius"



Electrons are not just molecules of gas!

1897:

"The smallness of m/e is, I think, due to the largeness of e as well as the smallness of m ."

"Thus on this view, we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state."

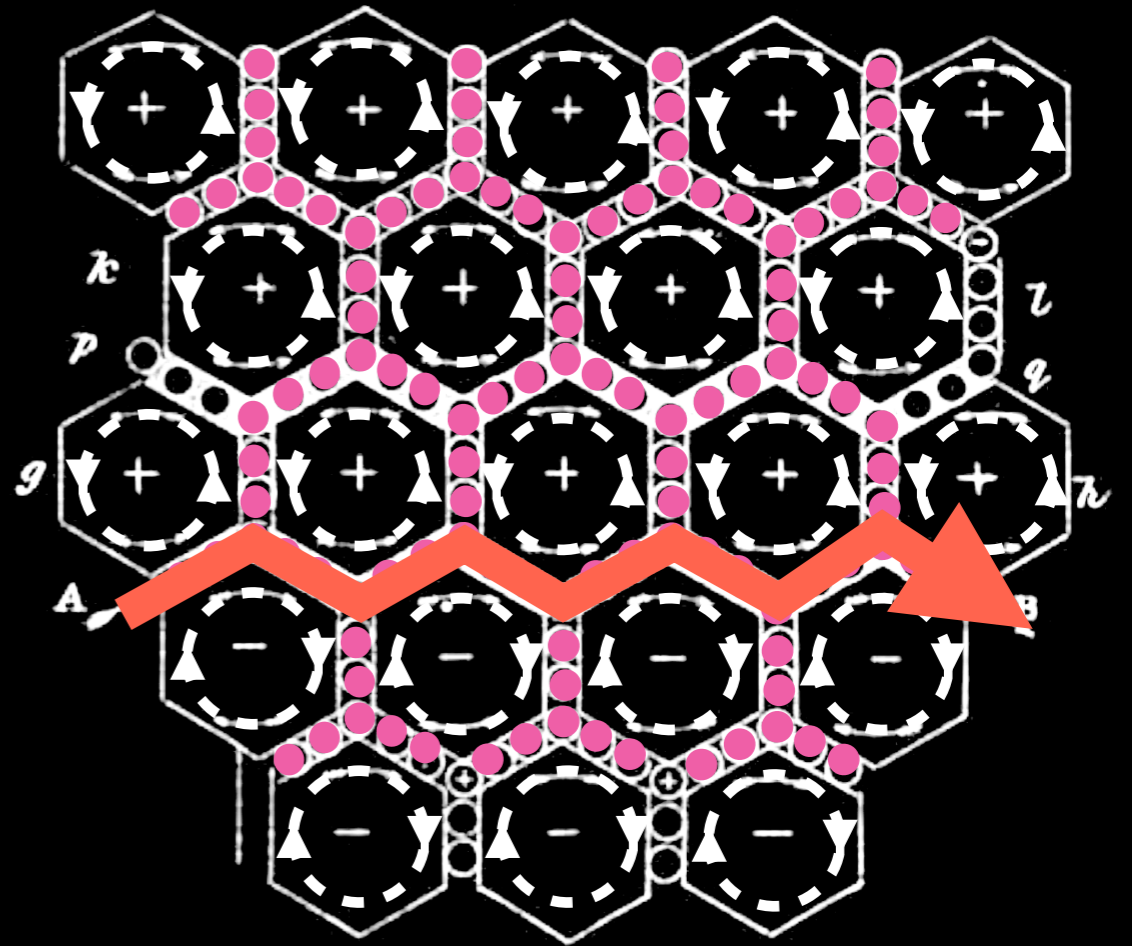
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	m/e
Air	4×10^{-7}
Hydrogen	35×10^{-7}
Carbonic acid	4×10^{-7}

So, what is electricity?

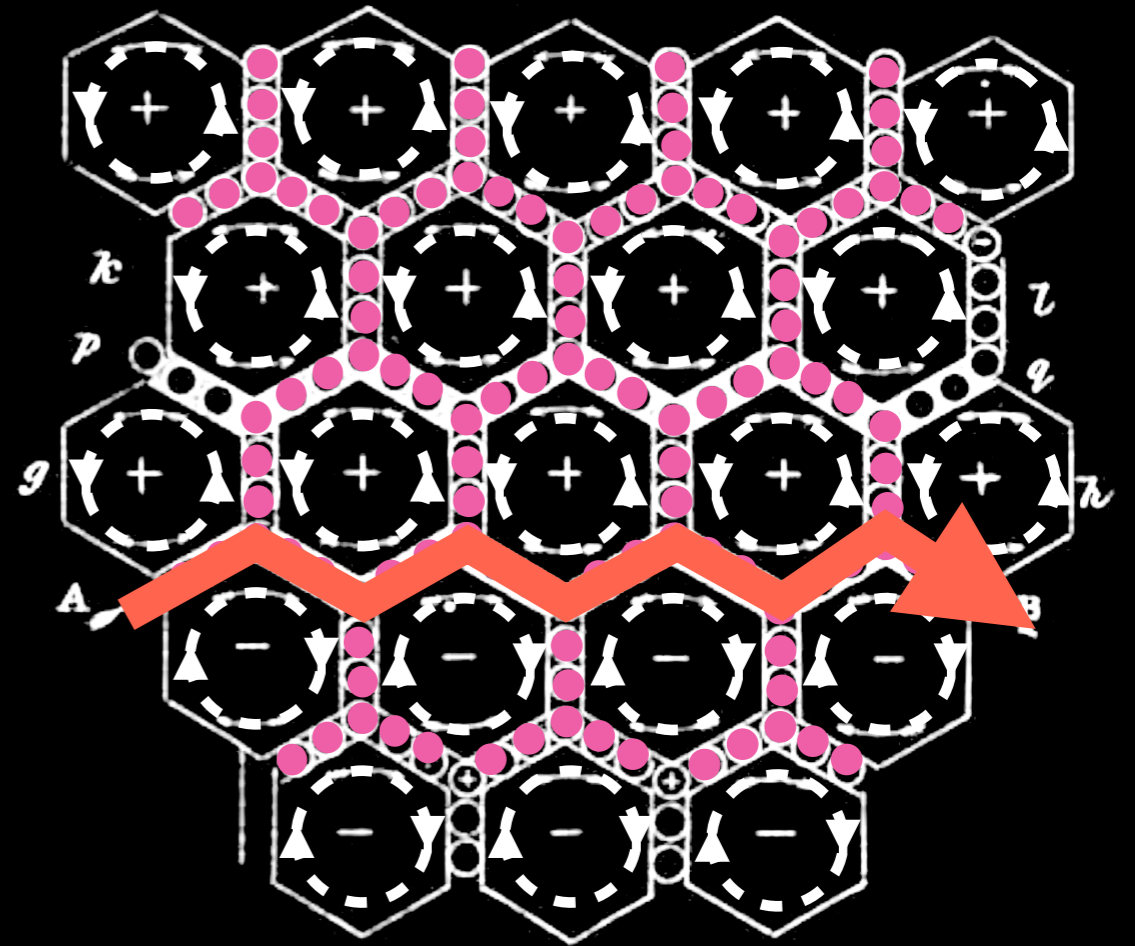
So, what is electricity?



So, what is electricity?

Maxwell:

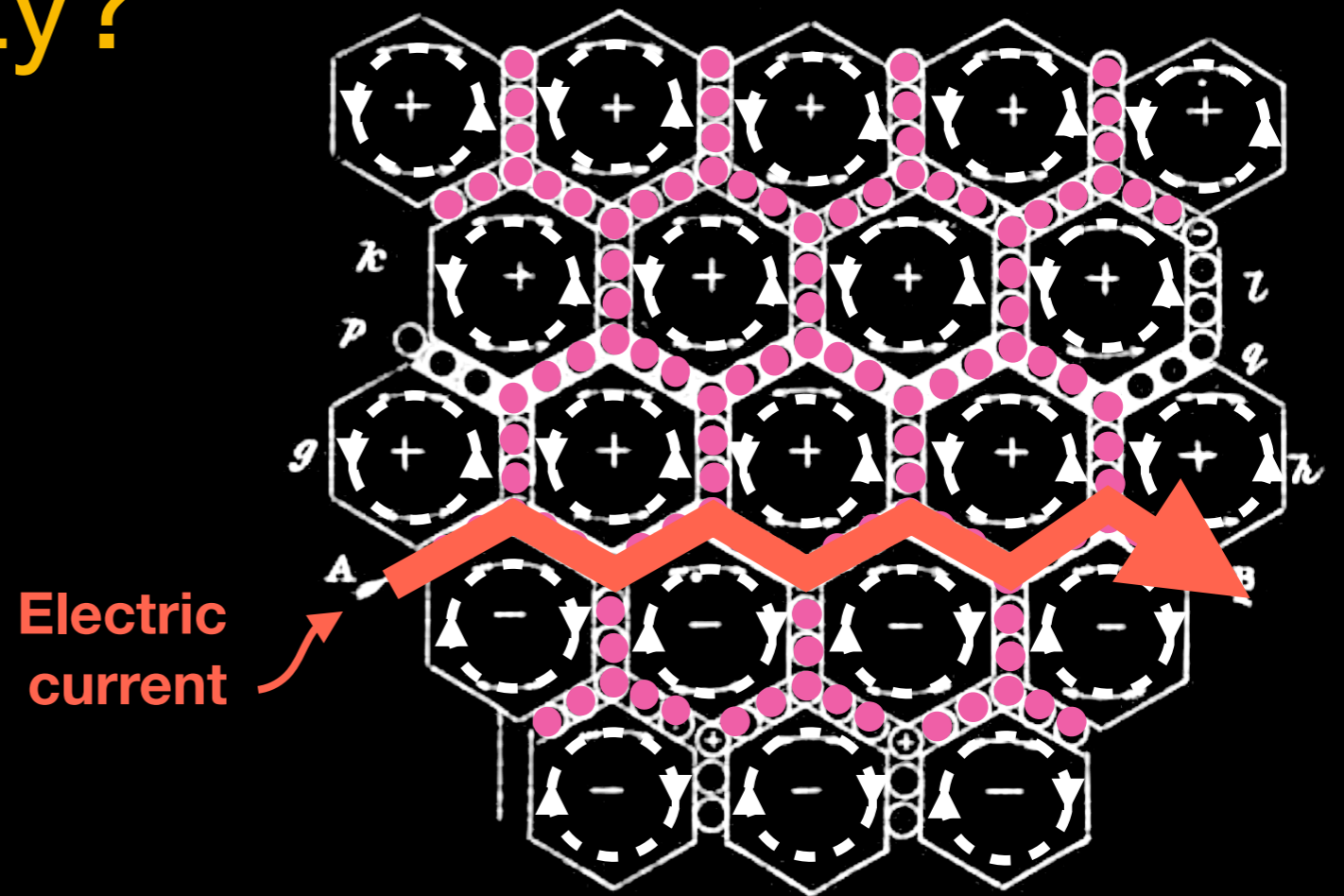
Electricity flows when vortices
spinning clockwise meet vortices
spinning counterclockwise



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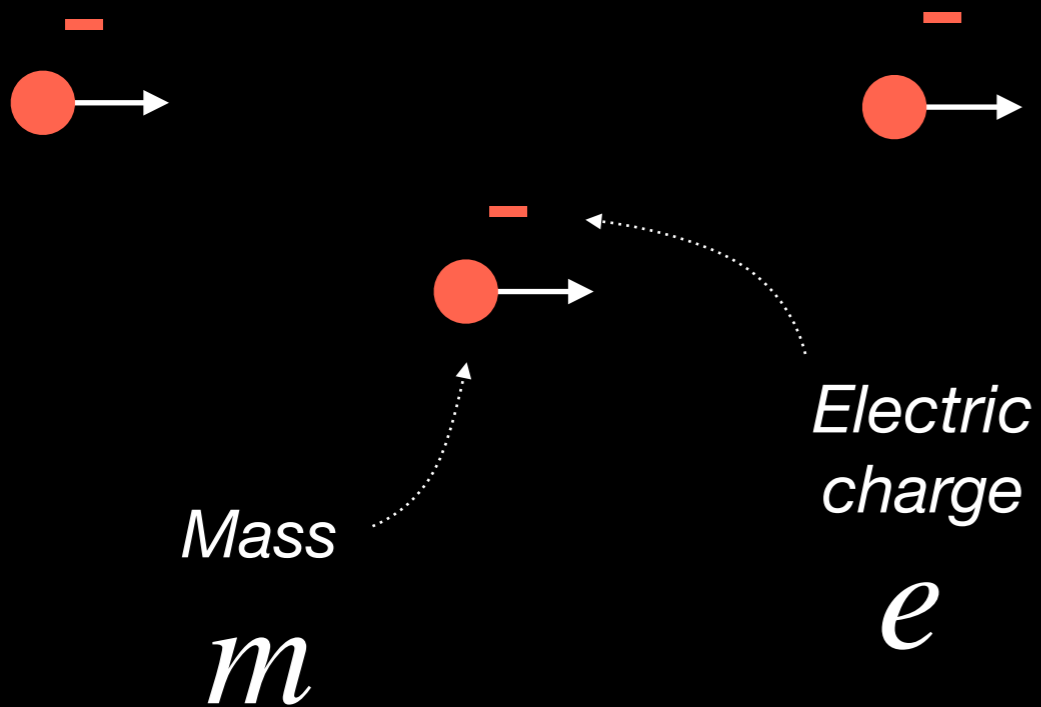
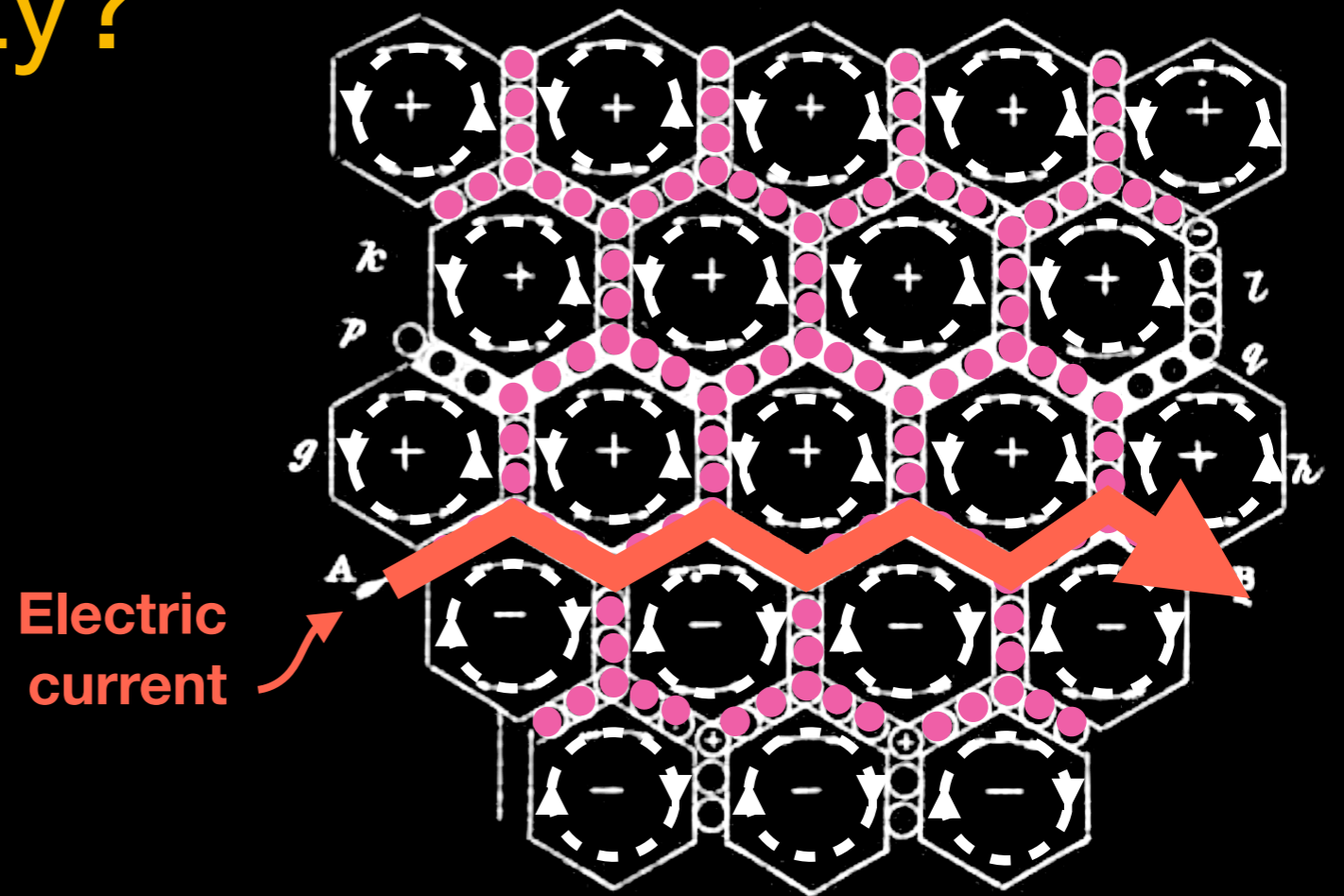
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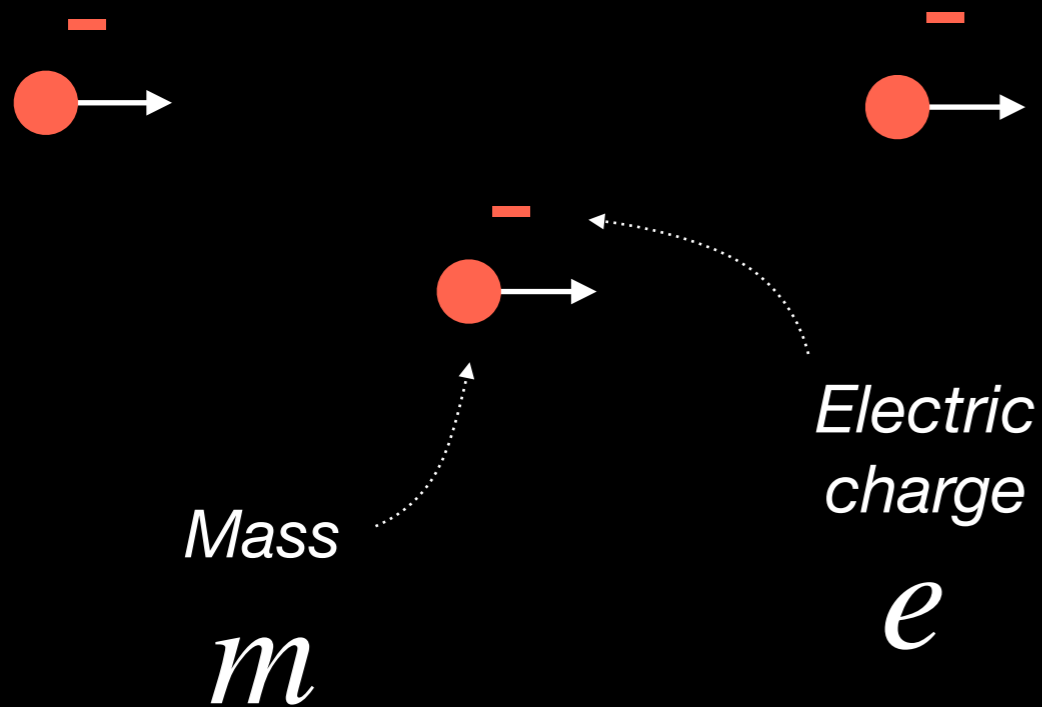
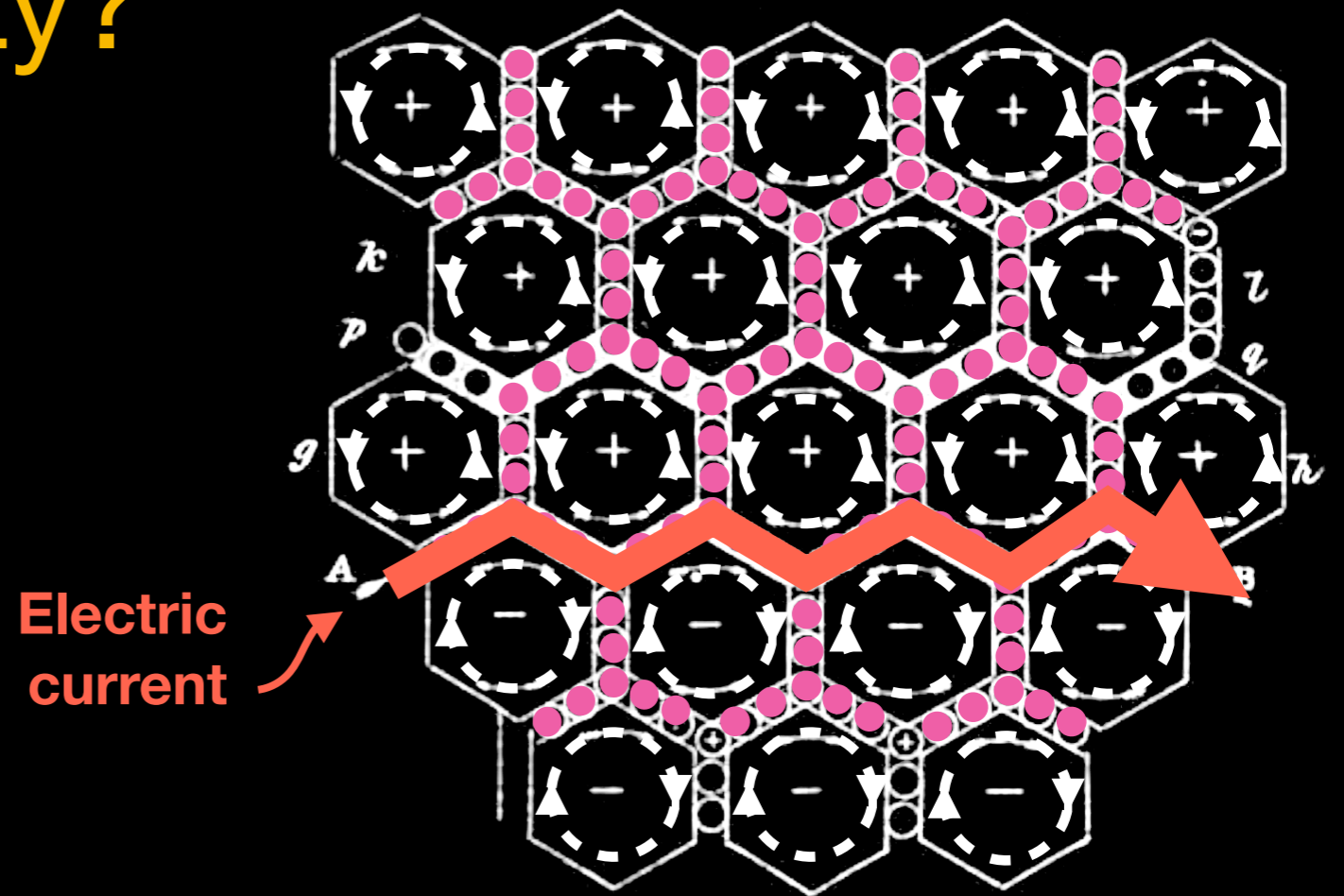
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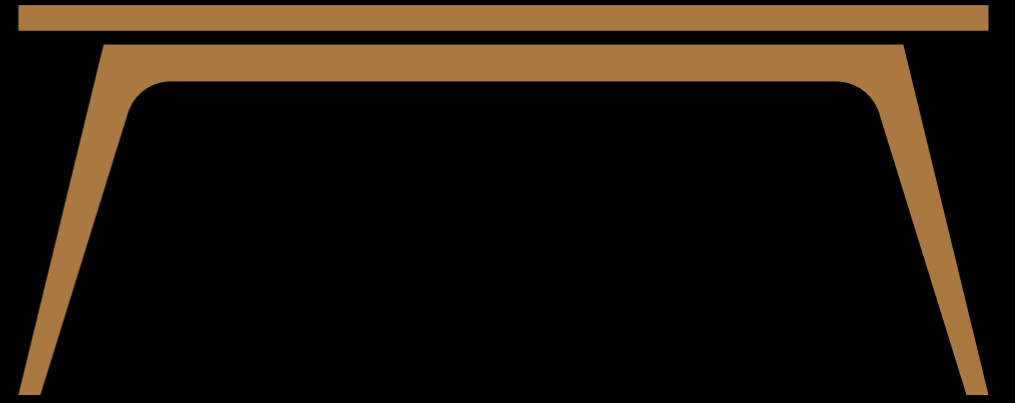


Thomson:

An electric current is a stream of negatively charged electrons moving in the same direction

What is a table?

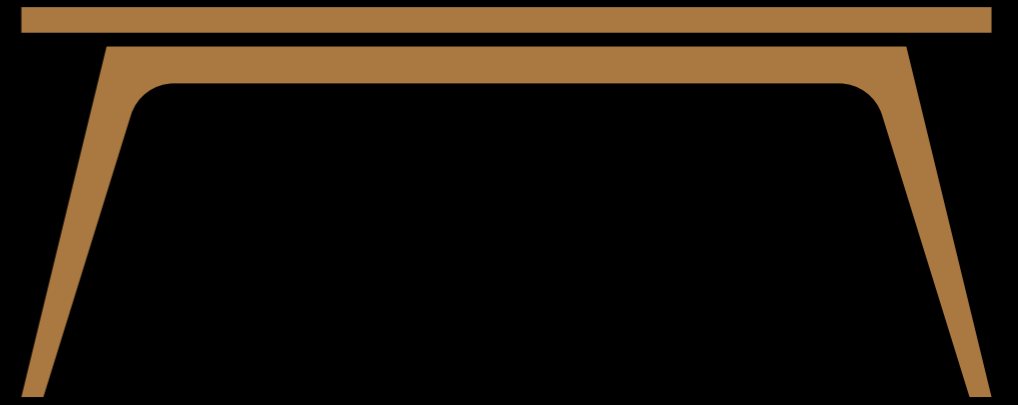
What is a table?



What is a table?

The Oxford English Dictionary:

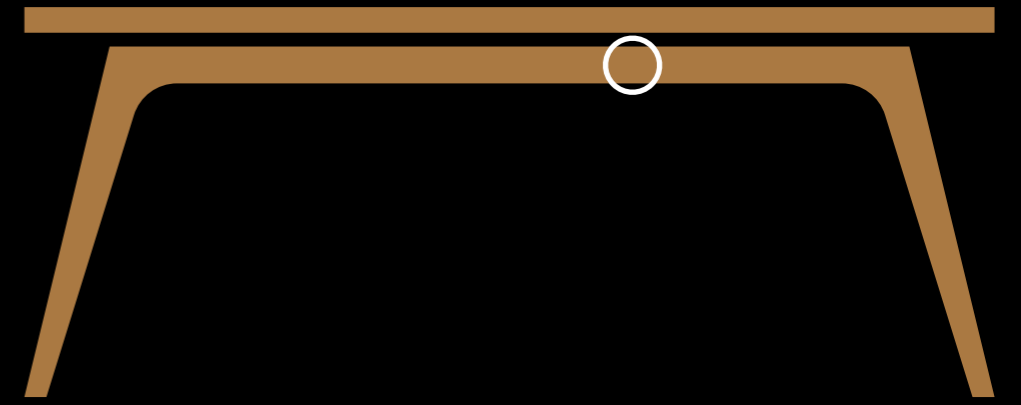
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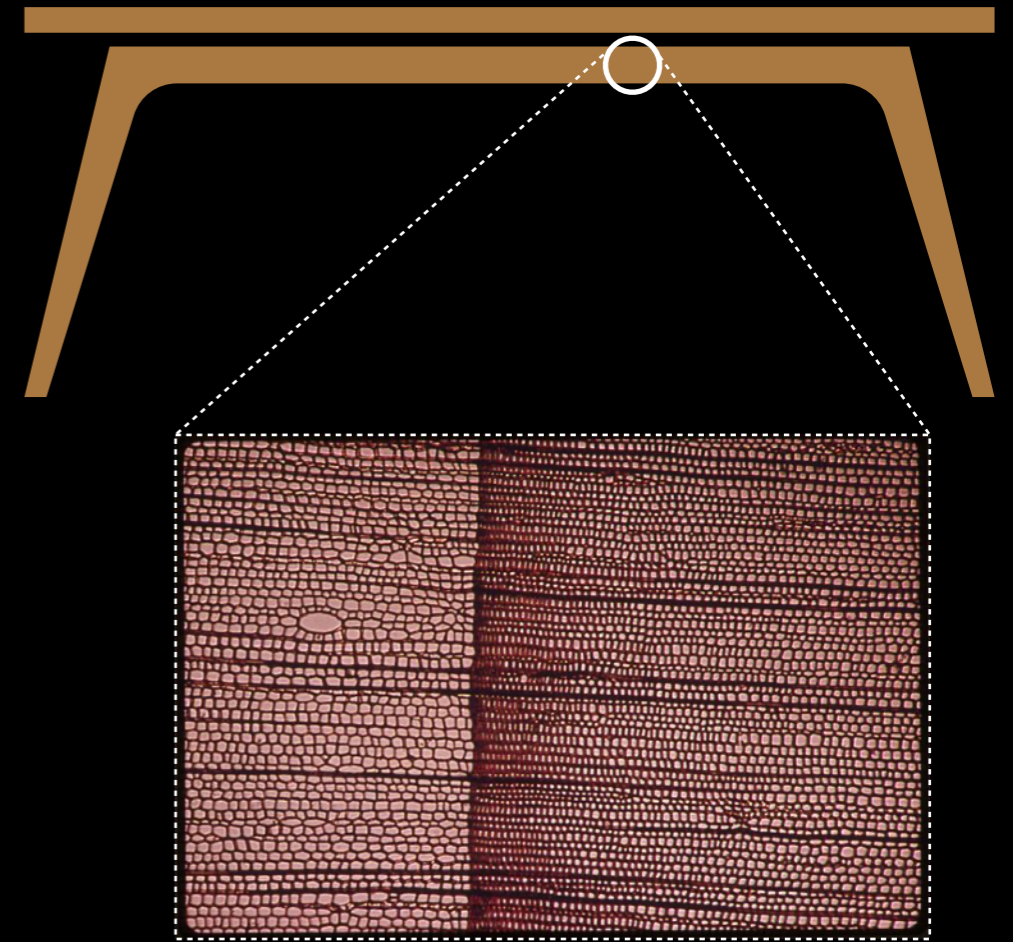
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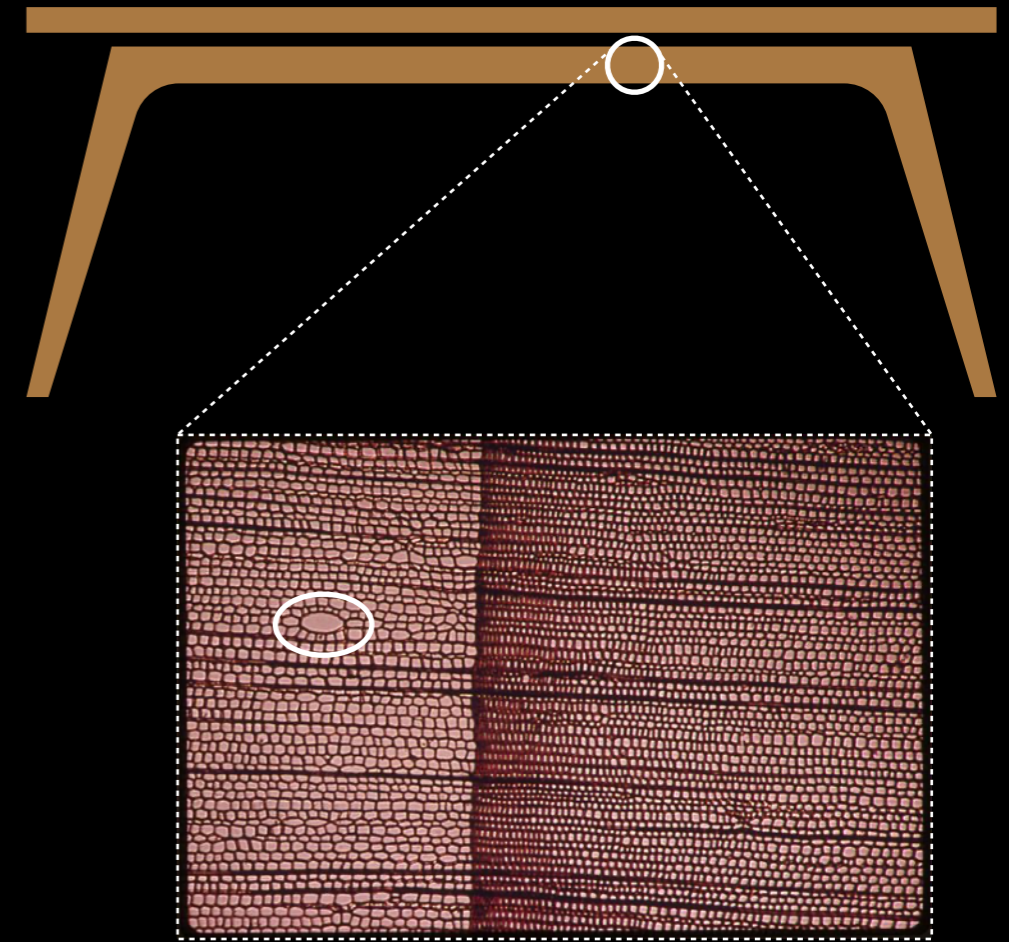
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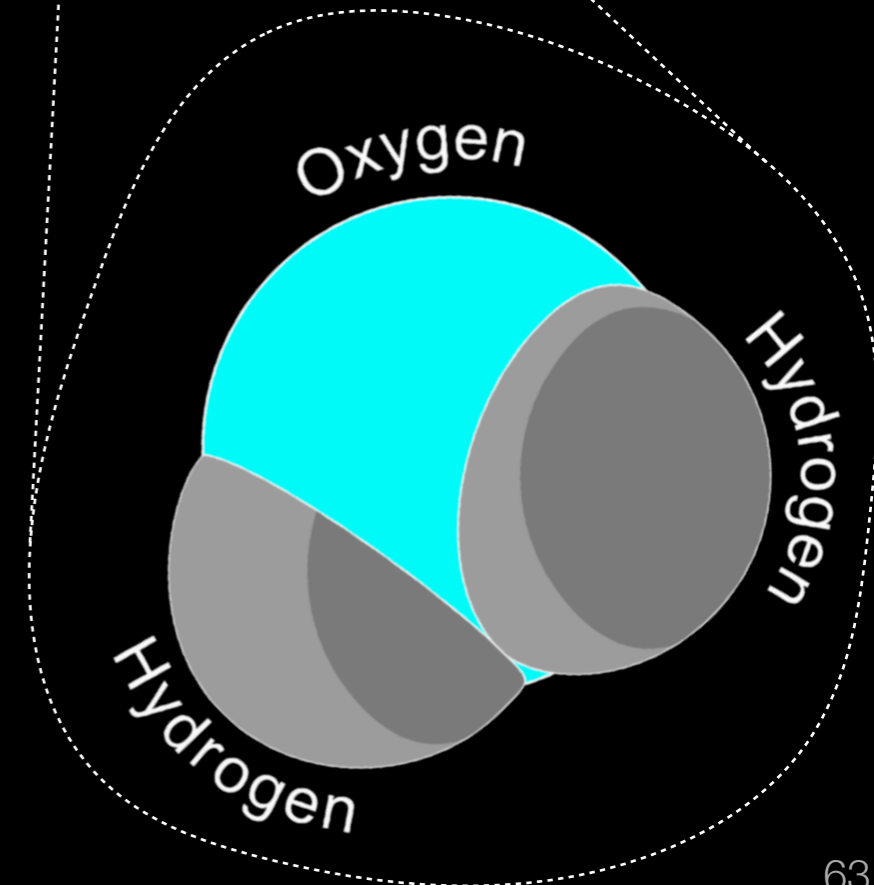
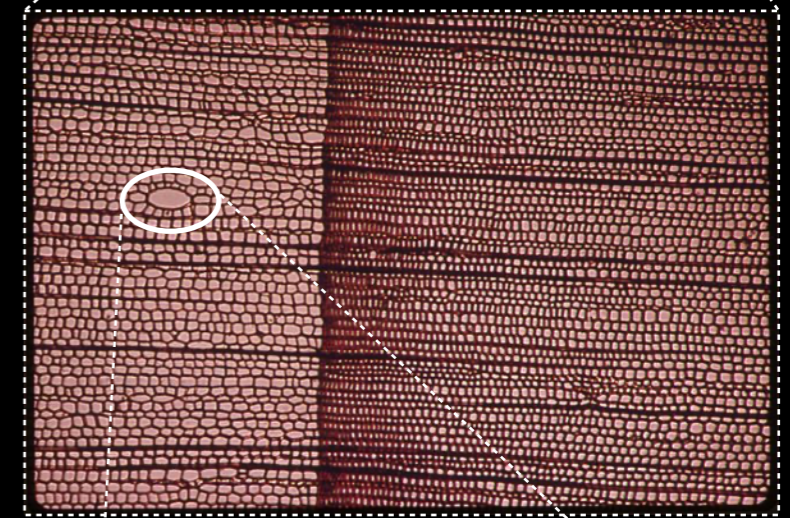
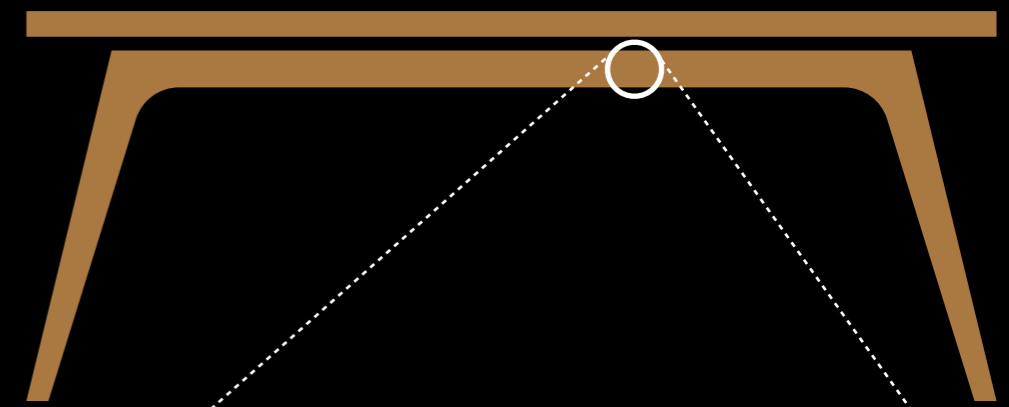
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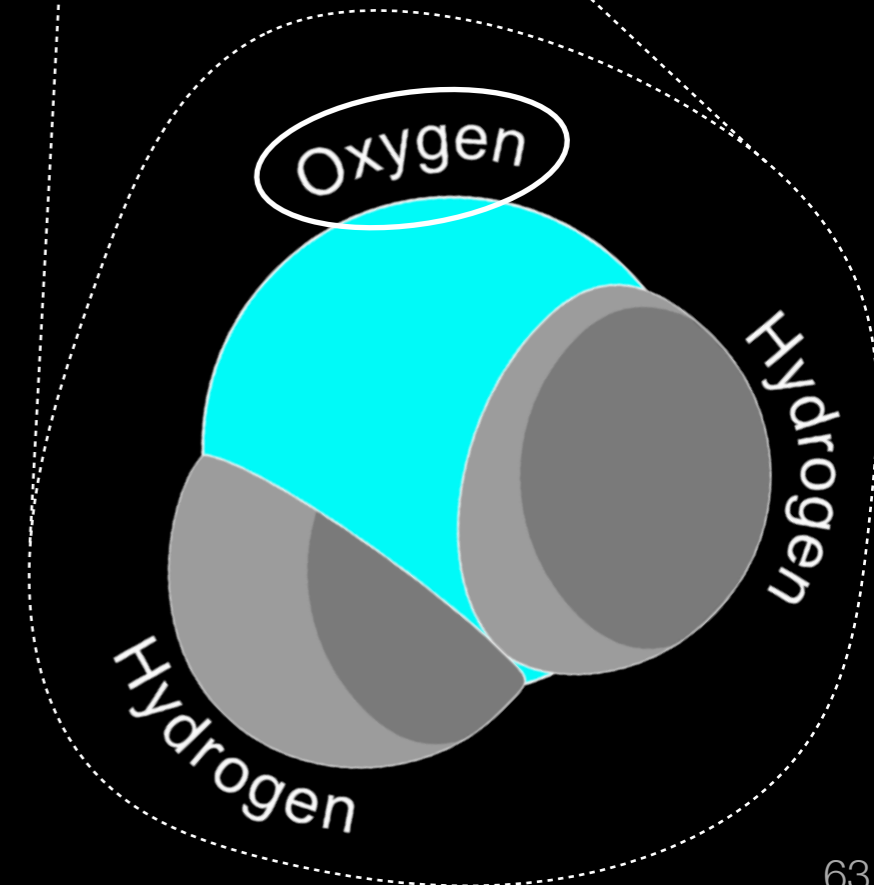
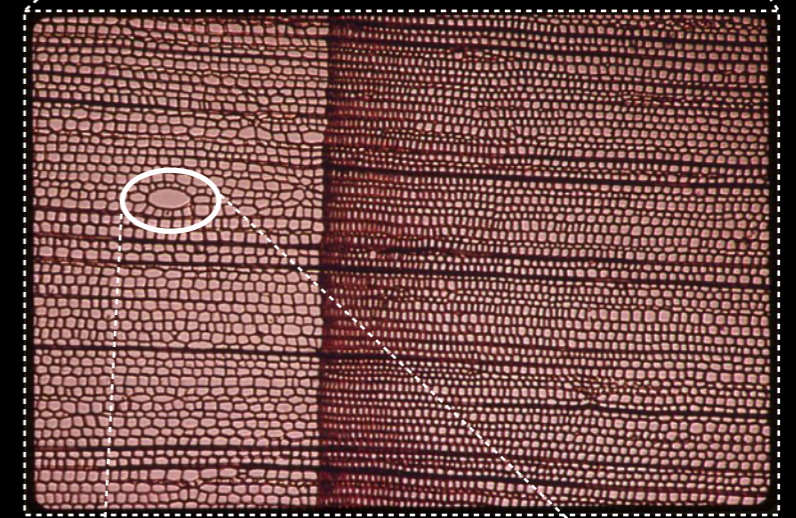
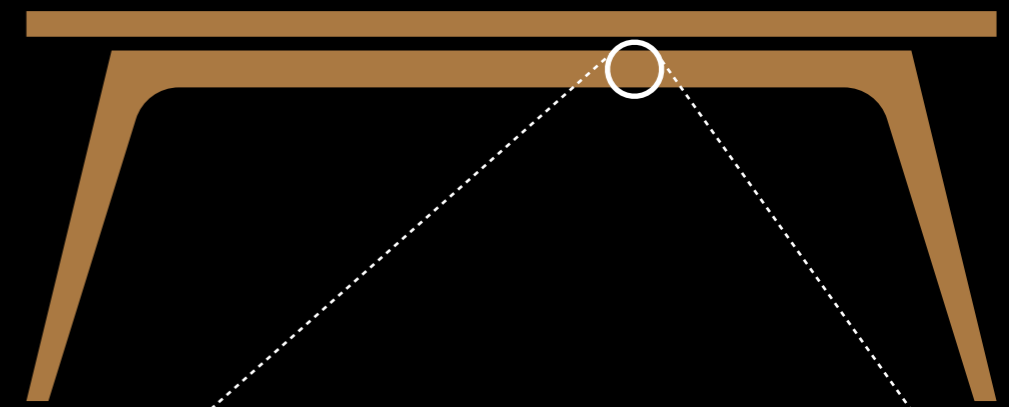
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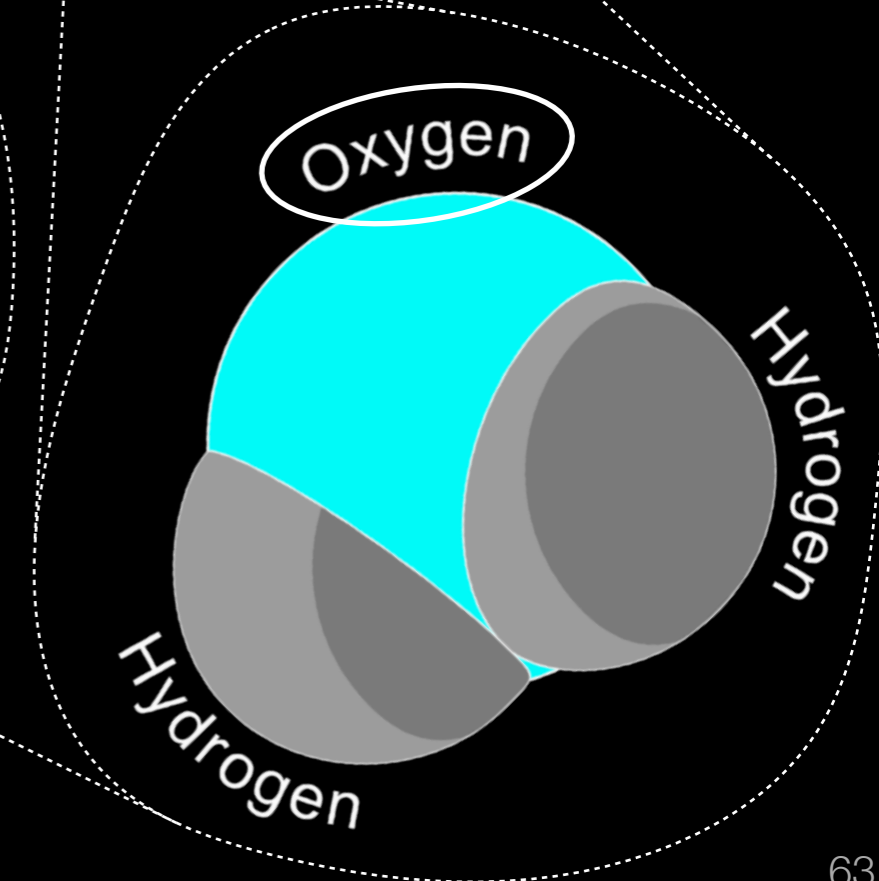
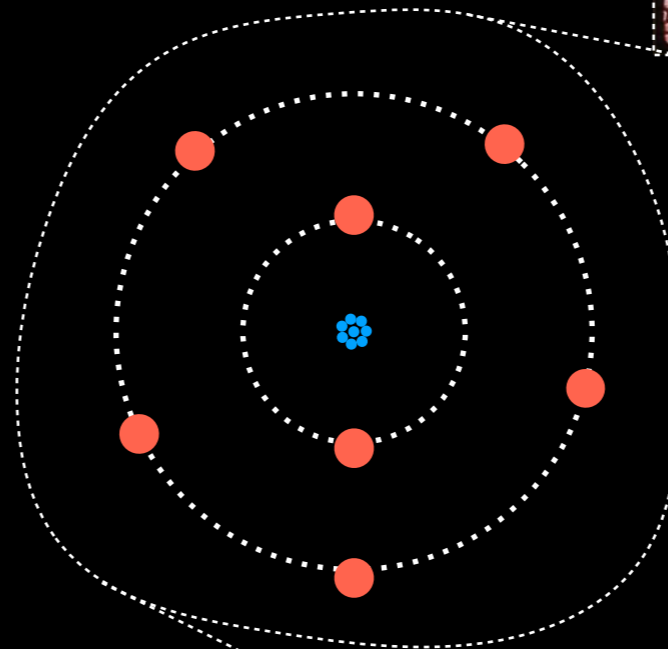
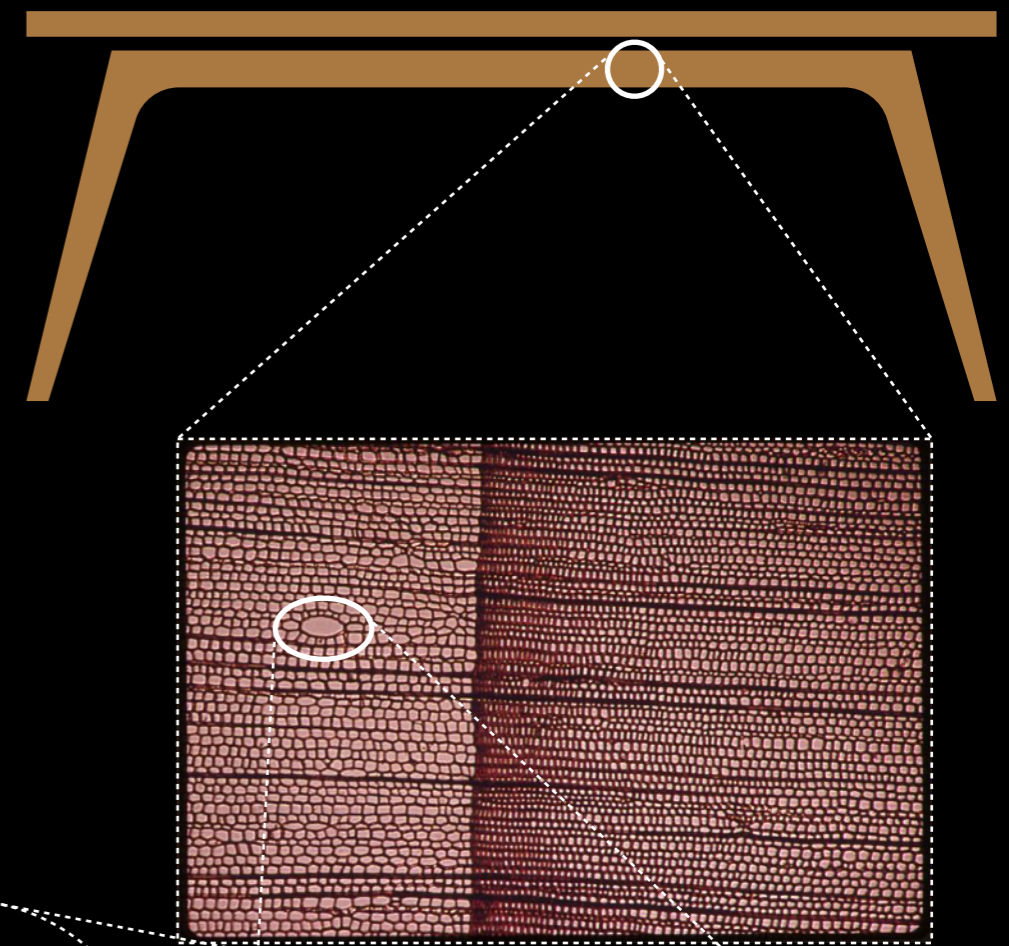
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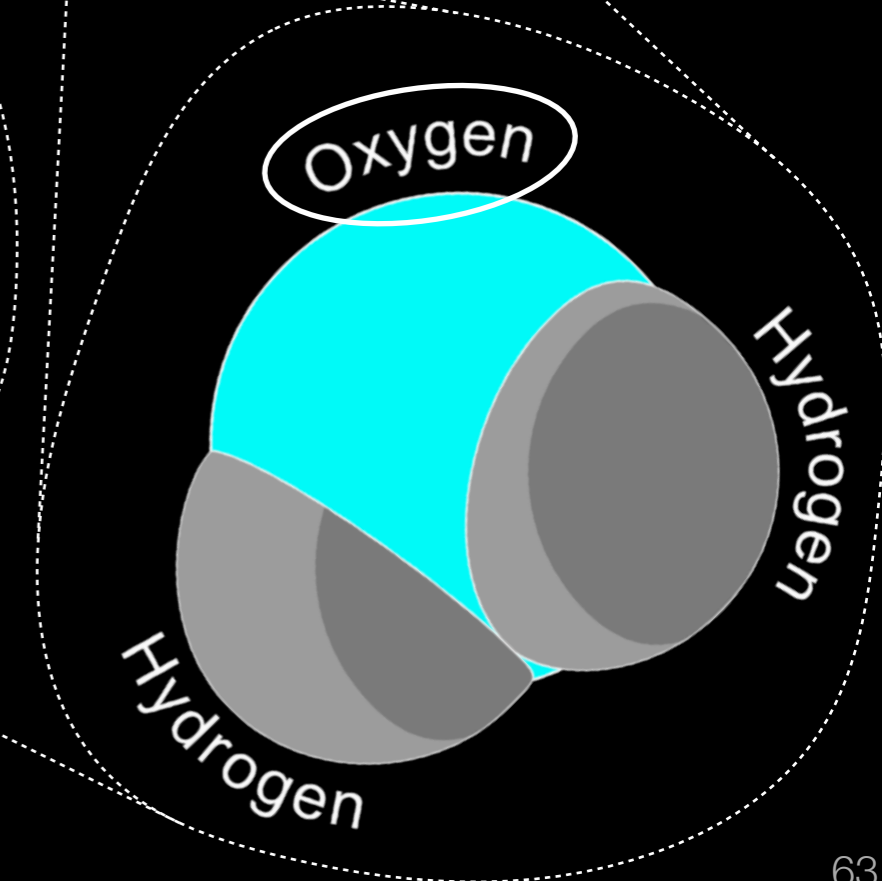
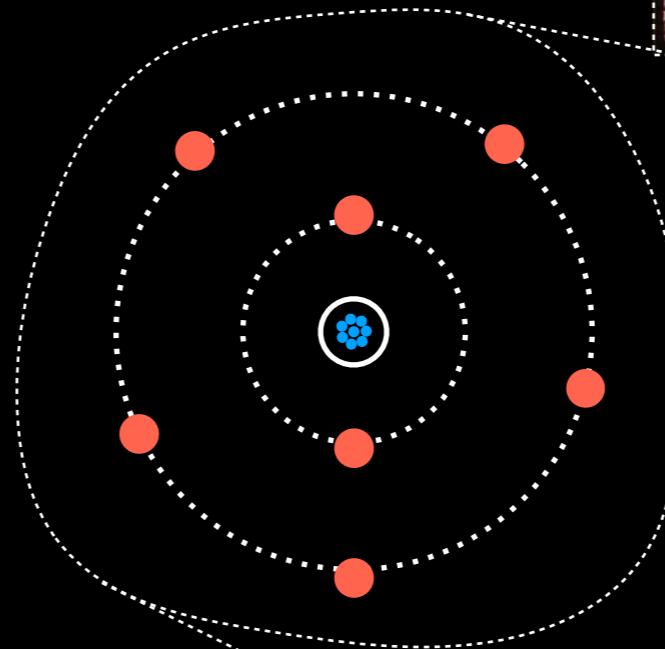
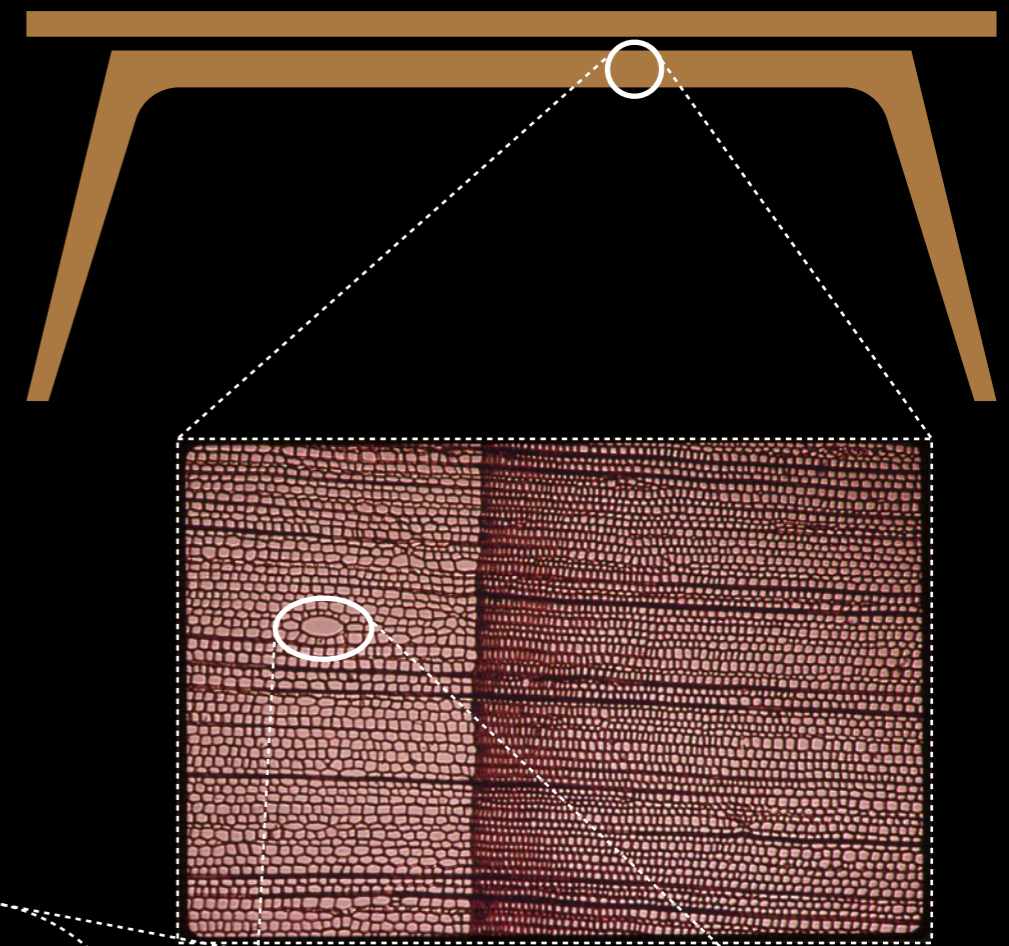
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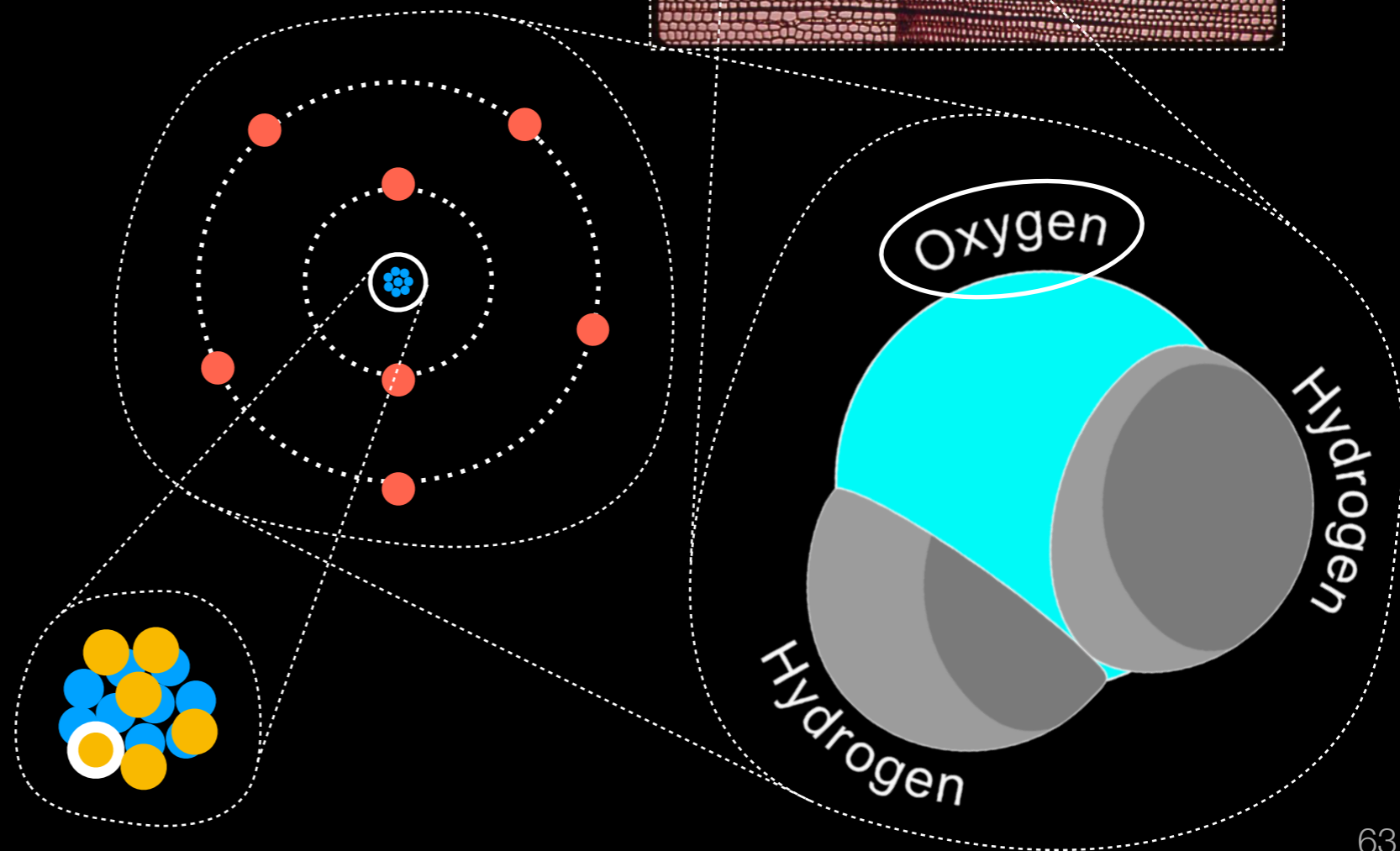
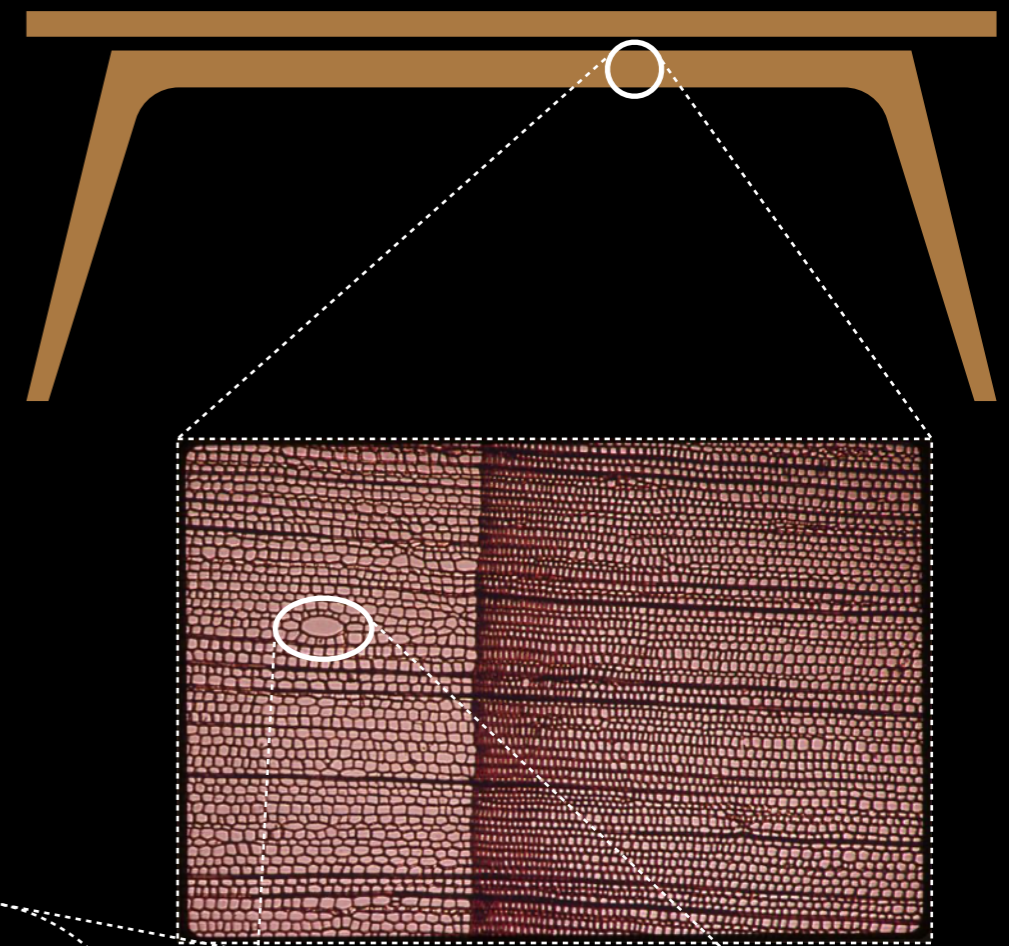
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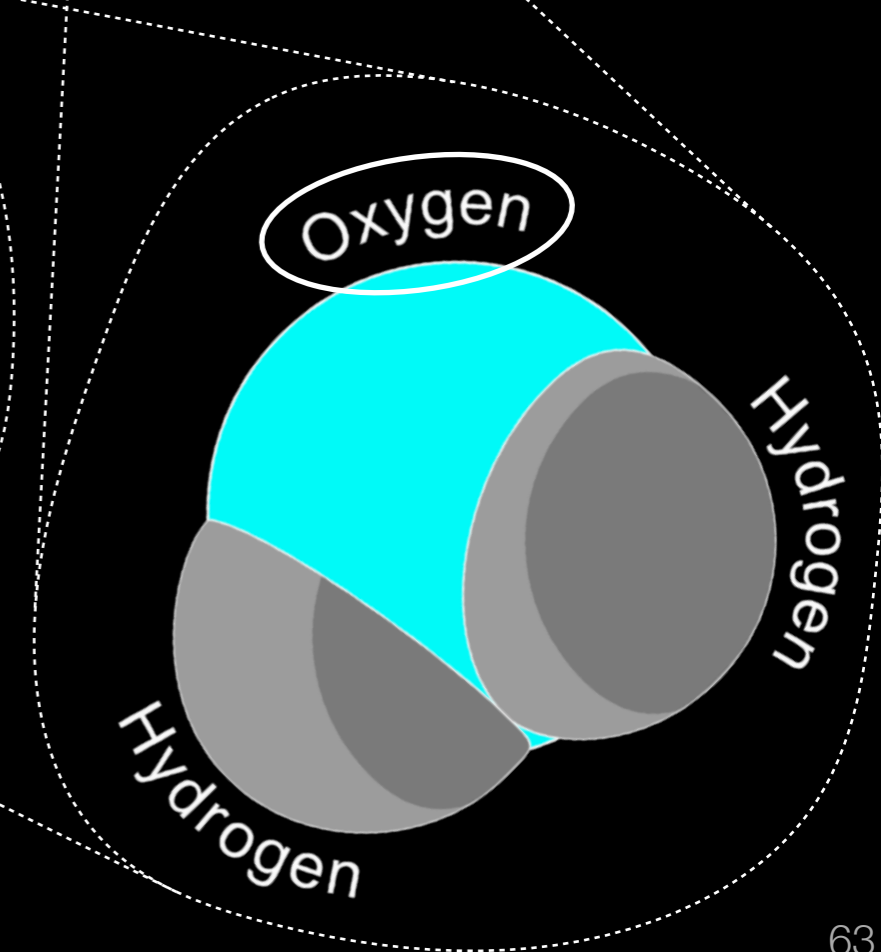
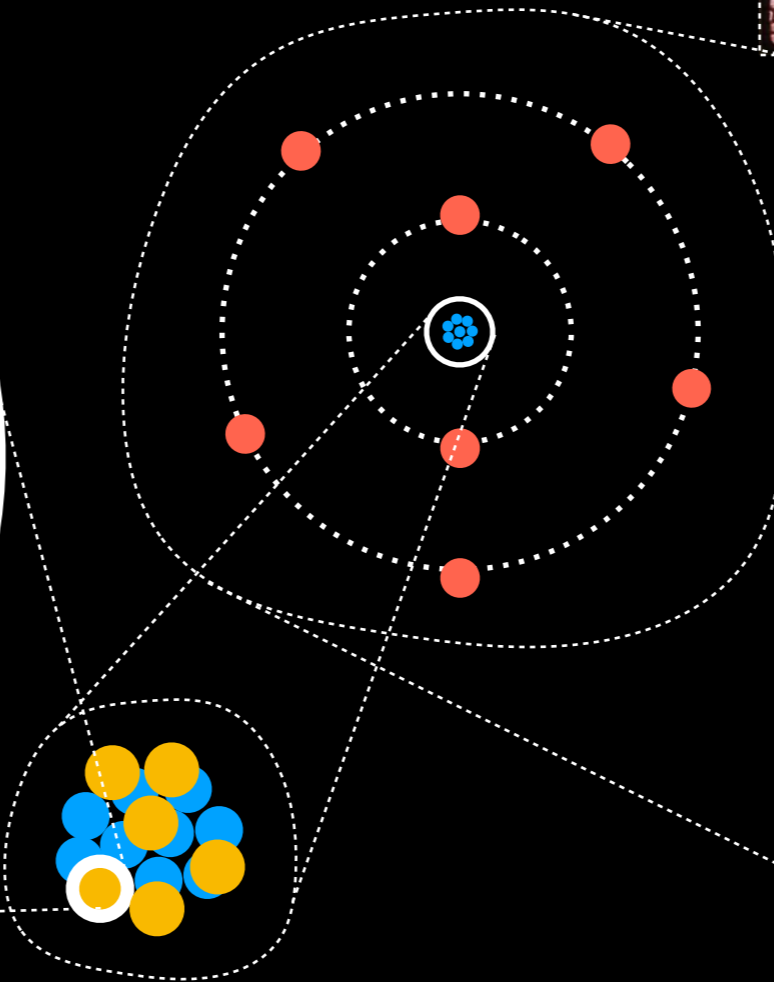
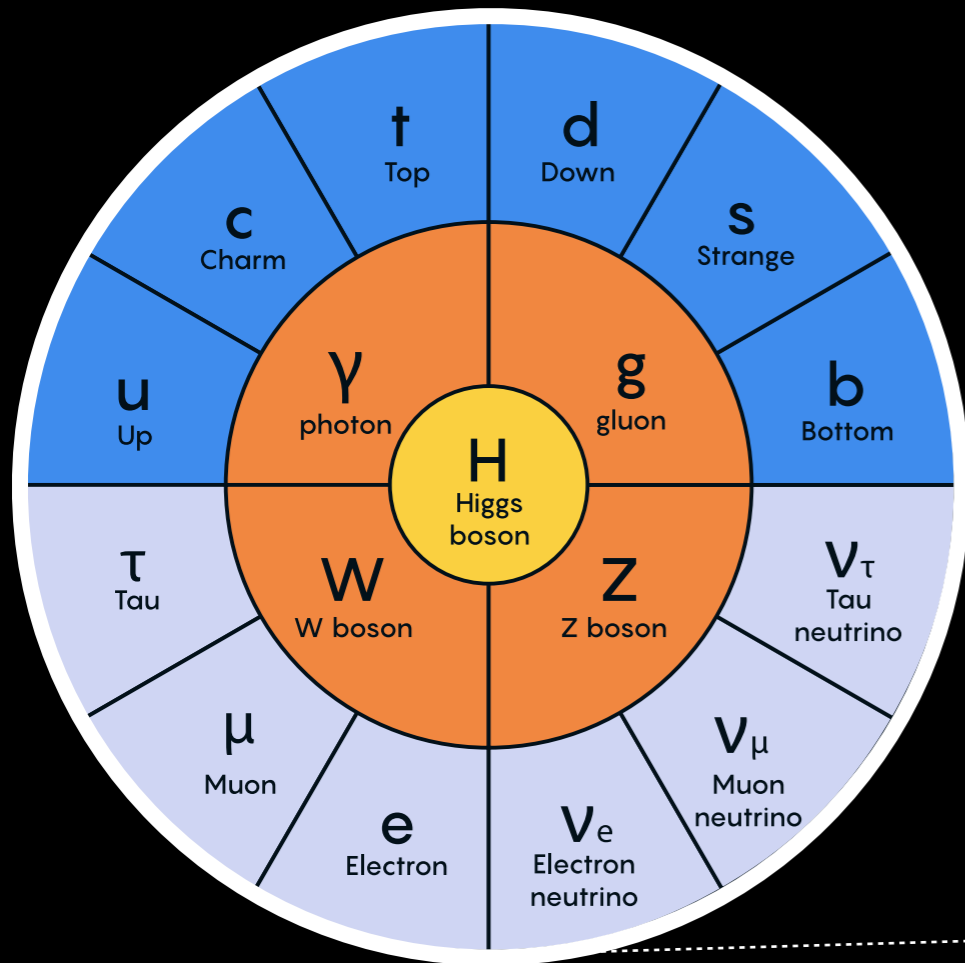
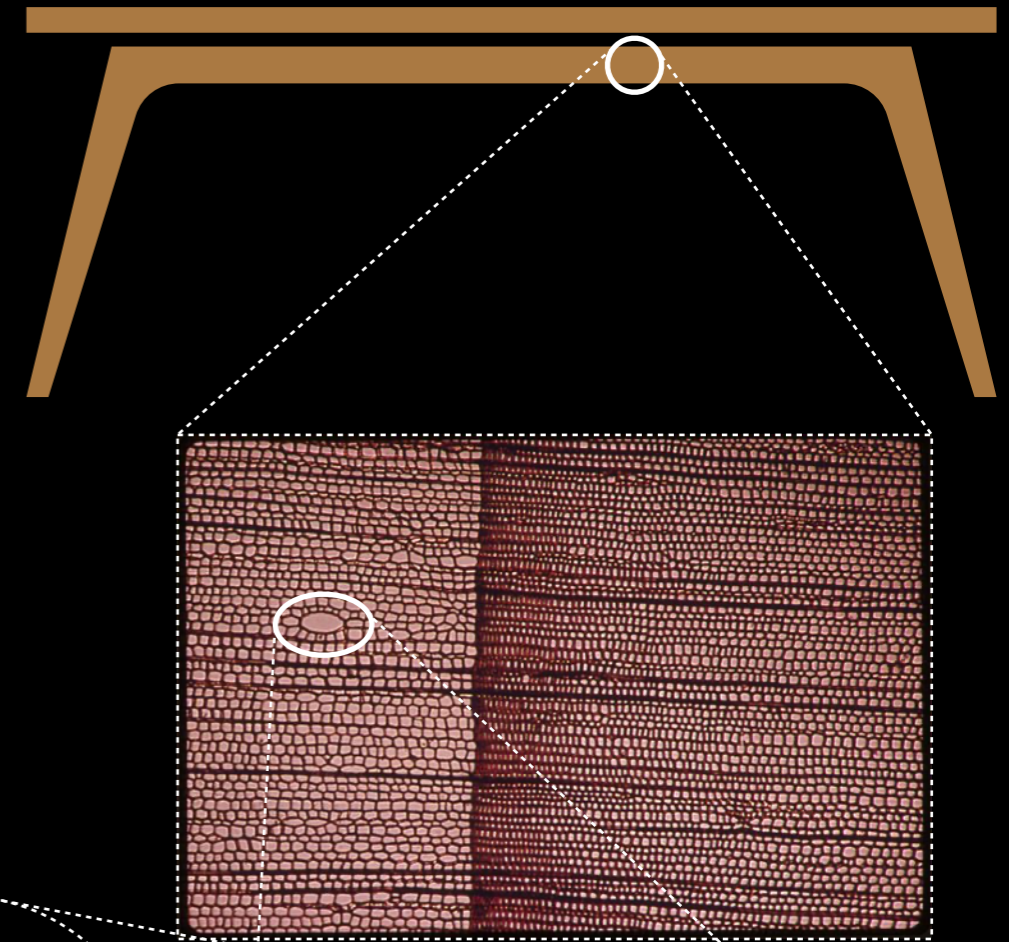
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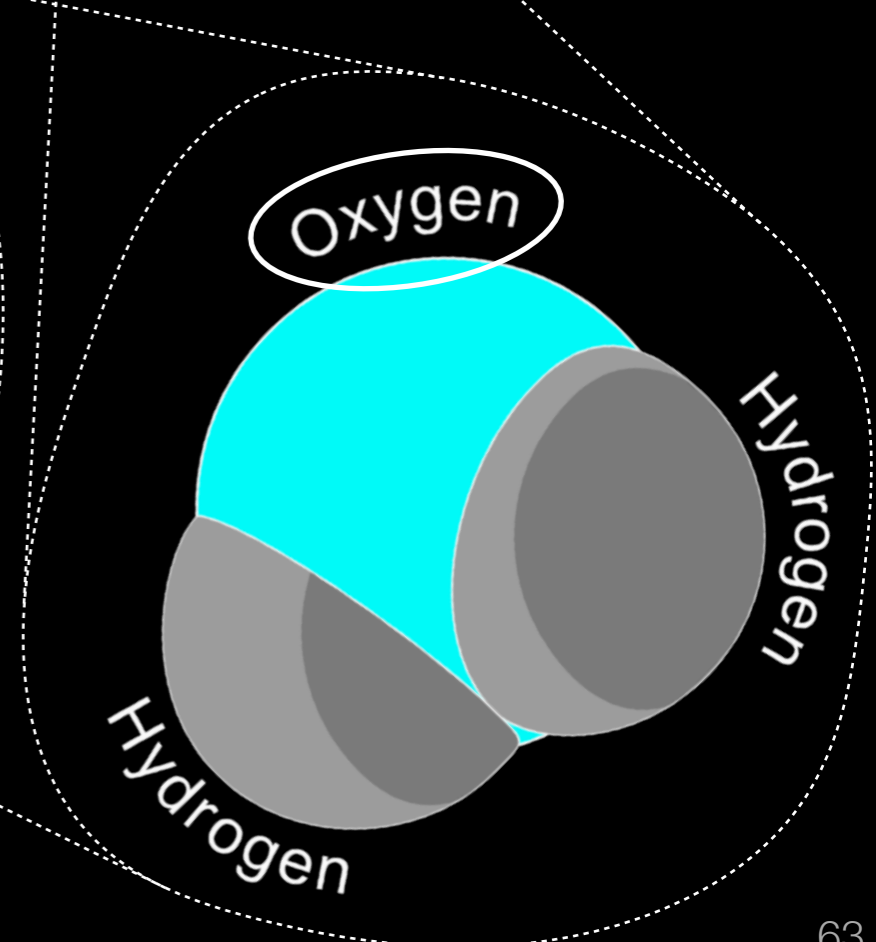
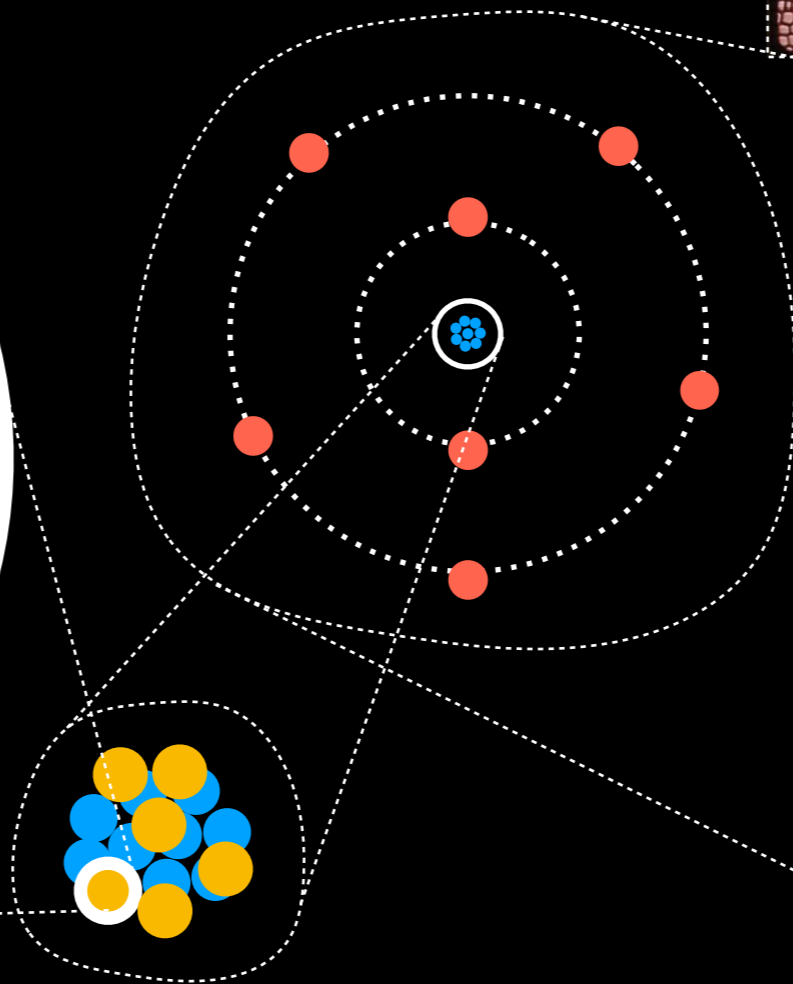
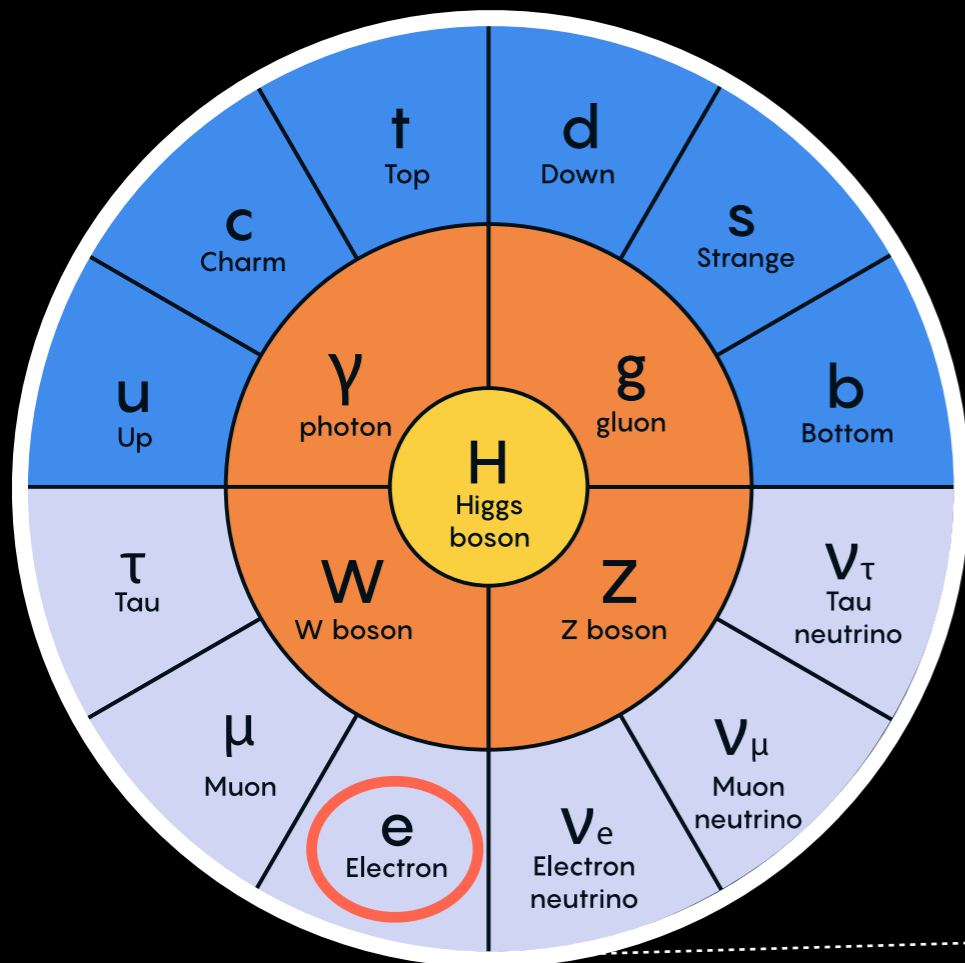
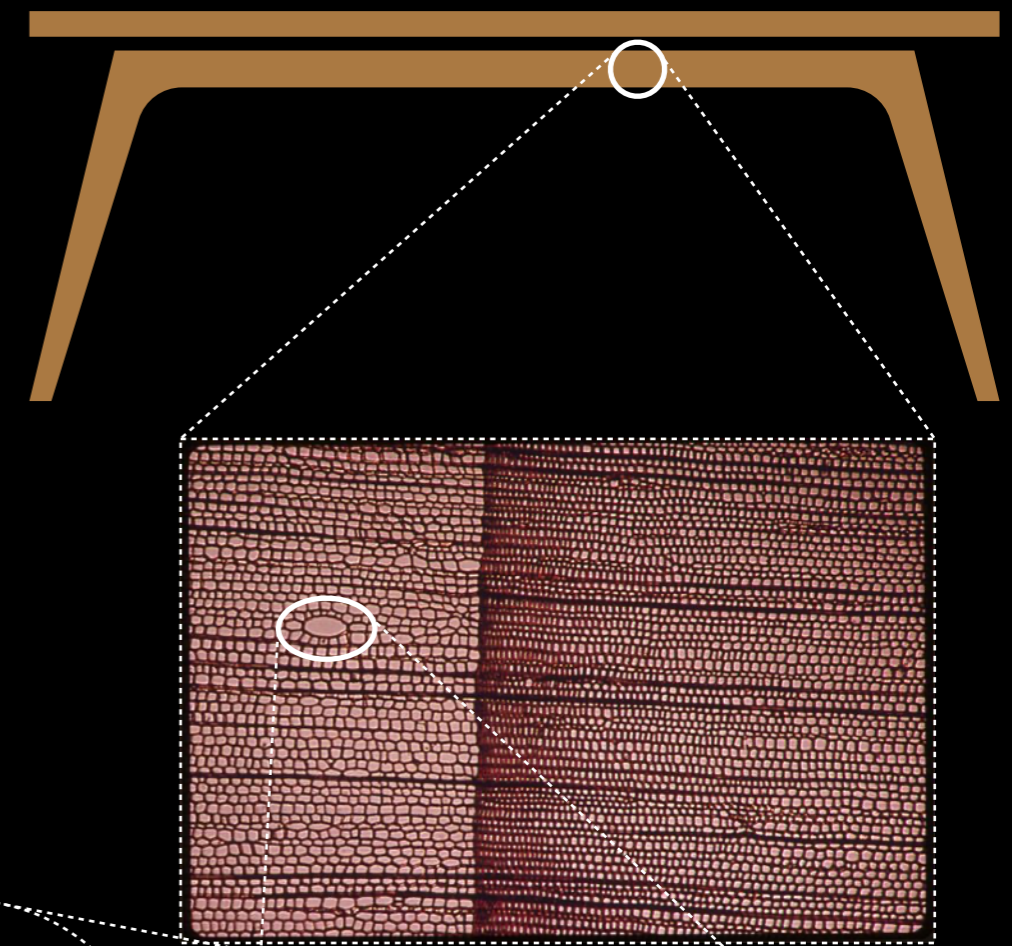
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What is the
nature of electricity?

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matter



**HOW FUNDAMENTAL SCIENCE
HAS CHANGED THE WORLD**

A STORY OF INVENTION AND DISCOVERY

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