Primary sources in physics teaching

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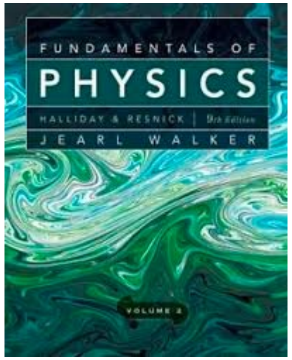
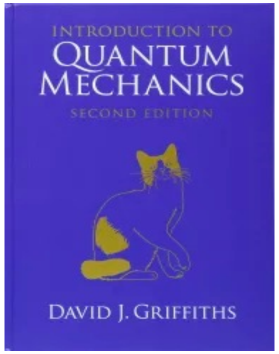
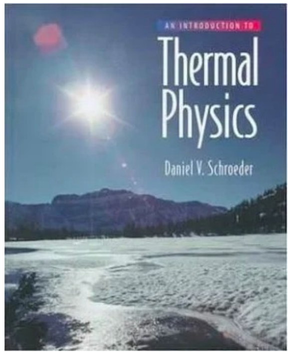
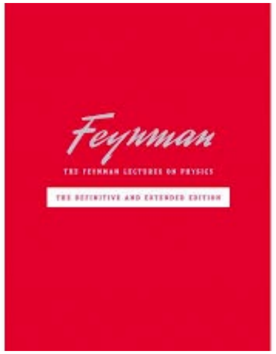
A thought…

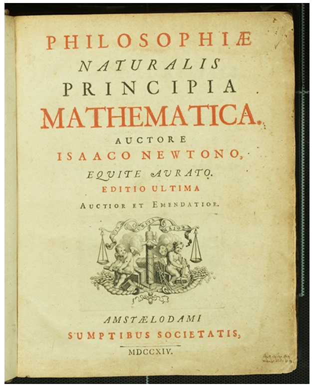


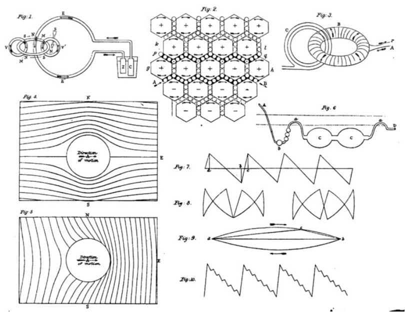


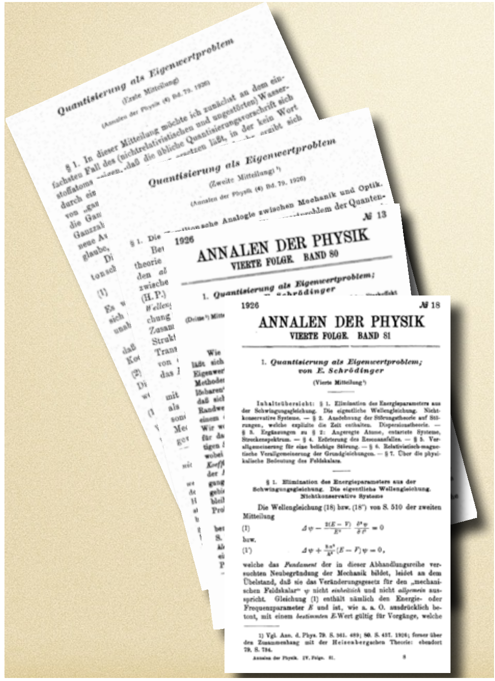




We teach/learn physics with textbooks

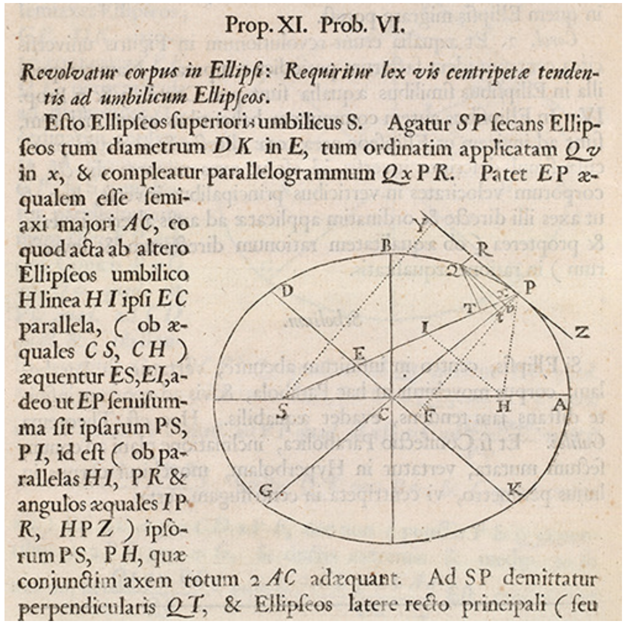






What if we used primary sources?

At a first glance: Unintelligible!



Prop. XI. Prob. VI.

Revolvatur corpus in Ellipſi: Requiritur lex vis centripetæ tendentis ad umbilicum Ellipſeos.

Eſto Ellipſeos ſuperioris umbilicus S. Agatur *SP* ſecans Ellipſeos tum diametrum *DK* in *E*, tum ordinatim applicatam *Qv* in *x*, & compleatur parallelogrammum *QxPR*. Patet *EP* æqualem eſſe ſemiaxi majori *AC*, eo quod acta ab altero Ellipſeos umbilico H linea *HI* ipſi *EC* parallela, (ob æquales *CS*, *CH*) æquentur ES, *EI*, adeo ut EP ſemiſumma ſit ipſarum PS, *PI*, id eſt (ob parallelas *HI*, *PR* & angulos æquales *IPR*, *HPZ*) ipſorum PS, PH, quæ conjunctim axem totum 2*AC* adæquant. Ad SP demittatur perpendicularis *QT*, & Ellipſeos latere recto principali (ſeu

Prop. XI Newton's Principia

$$p' = p + \frac{df}{dt},\quad q' = q + \frac{dg}{dt},\quad r' = r + \frac{dh}{dt} \qquad \text{(A)}$$

$$\mu\alpha = \frac{dH}{dy} - \frac{dG}{dz},\quad \mu\beta = \frac{dF}{dz} - \frac{dH}{dx},\quad \mu\gamma = \frac{dG}{dx} - \frac{dF}{dy} \qquad \text{(B)}$$

$$\frac{d\gamma}{dy} - \frac{d\beta}{dz} = 4\pi p',\quad \frac{d\alpha}{dz} - \frac{d\gamma}{dx} = 4\pi q',\quad \frac{d\beta}{dx} - \frac{d\alpha}{dy} = 4\pi r' \qquad \text{(C)}$$

(70) In these equations of the electromagnetic field we have assumed twenty variable quantities, namely,

For Electromagnetic Momentum	$F\ G\ H$
For Magnetic Intensity	$\alpha\ \beta\ \gamma$
For Electromotive Force	$P\ Q\ R$
For Current due to true Conduction	$p\ q\ r$
For Electric Displacement	$f\ g\ h$
For Total Current (including variation of displacement)	$p'\ q'\ r'$
For Quantity of Free Electricity	e
For Electric Potential	Ψ

Between these twenty quantities we have found twenty equations, viz.

Three equations of Magnetic Force	(B)
Three equations of Electric Currents	(C)
Three equations of Electromotive Force	(D)
Three equations of Electric Elasticity	(E)
Three equations of Electric Resistance	(F)
Three equations of Total Currents	(A)
One equation of Free Electricity	(G)
One equation of Continuity	(H)

These equations are therefore sufficient to determine all the quantities which occur in them, provided we know the conditions of the problem. In many questions, however, only a few of the equations are required.

Maxwell's 20(!) equations (1865)

I miss Griffiths!!!

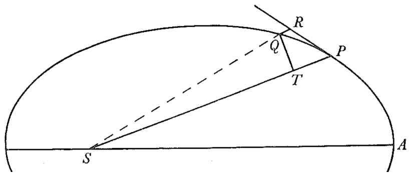
The solution: Didactical design

- Careful selection: short excerpts, deep insights
- Clear learning goals
- Good secondary sources
- Comparison with modern teaching

What makes good examples?

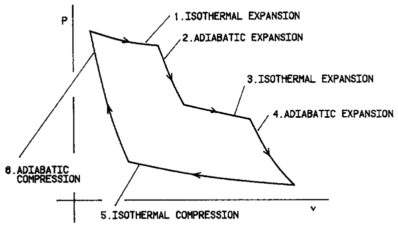
Newton's PQRST force

De motu (1684)



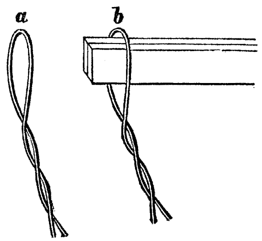
$$F \propto \frac{QR}{SP^2 \times QT^2}$$

Clausius' cycle



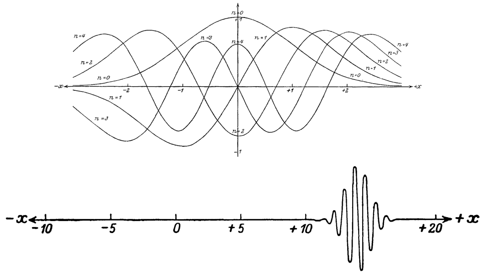
Faraday's moving wire

Fig. 2.

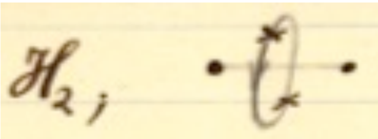


Schrödinger's real part of ψ

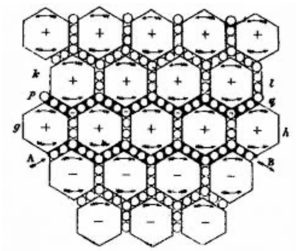
Micro-macro (1926)



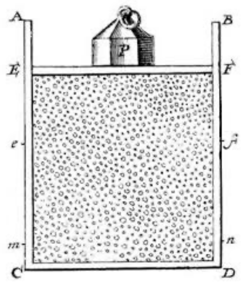
Bohr atom



Maxwell's wheels



Bernoulli's piston



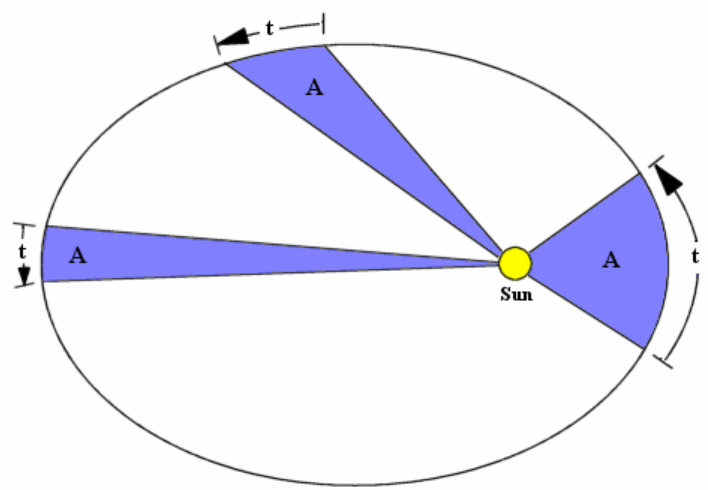
Boltzmann statistics

		𝔓			𝔓
1.	0000007	7	9.	0001114	140
2.	0000016	42	10.	0001123	420
3.	0000025	42	11.	0001222	140
4.	0000034	42	12.	0011113	105
5.	0000115	105	13.	0011122	210
6.	0000124	210	14.	0111112	42
7.	0000133	105	15.	1111111 [1])	1
8.	0000223	105			

- New insights (a-ha moments)
- Conceptual/"mechanistic"/visual
- First times; often pedagogical
- Unfamiliar; foster questions

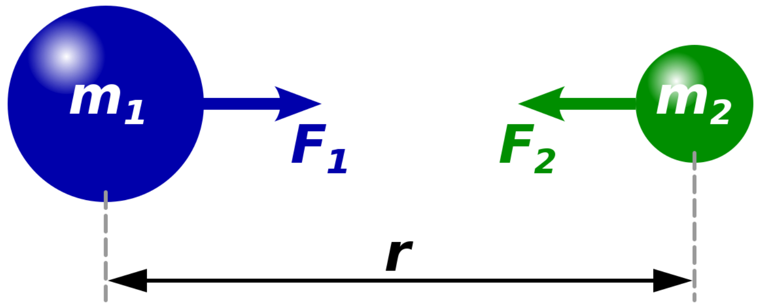
Prelude

Kepler's laws



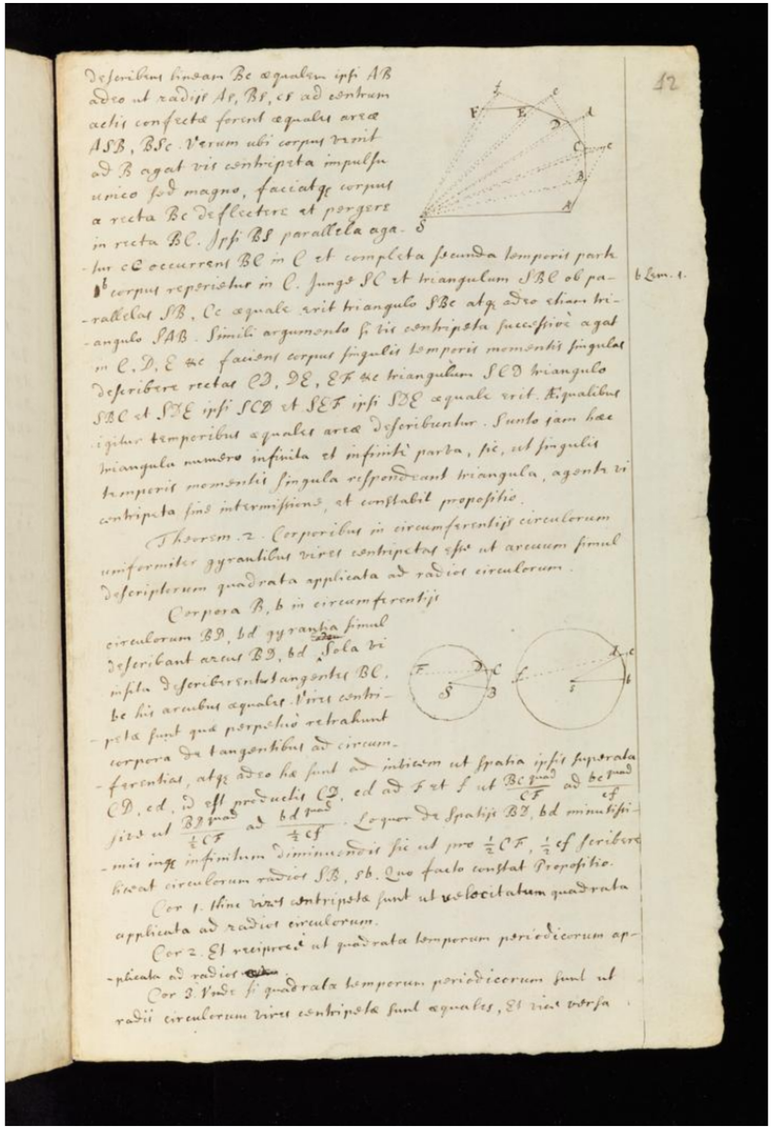
????

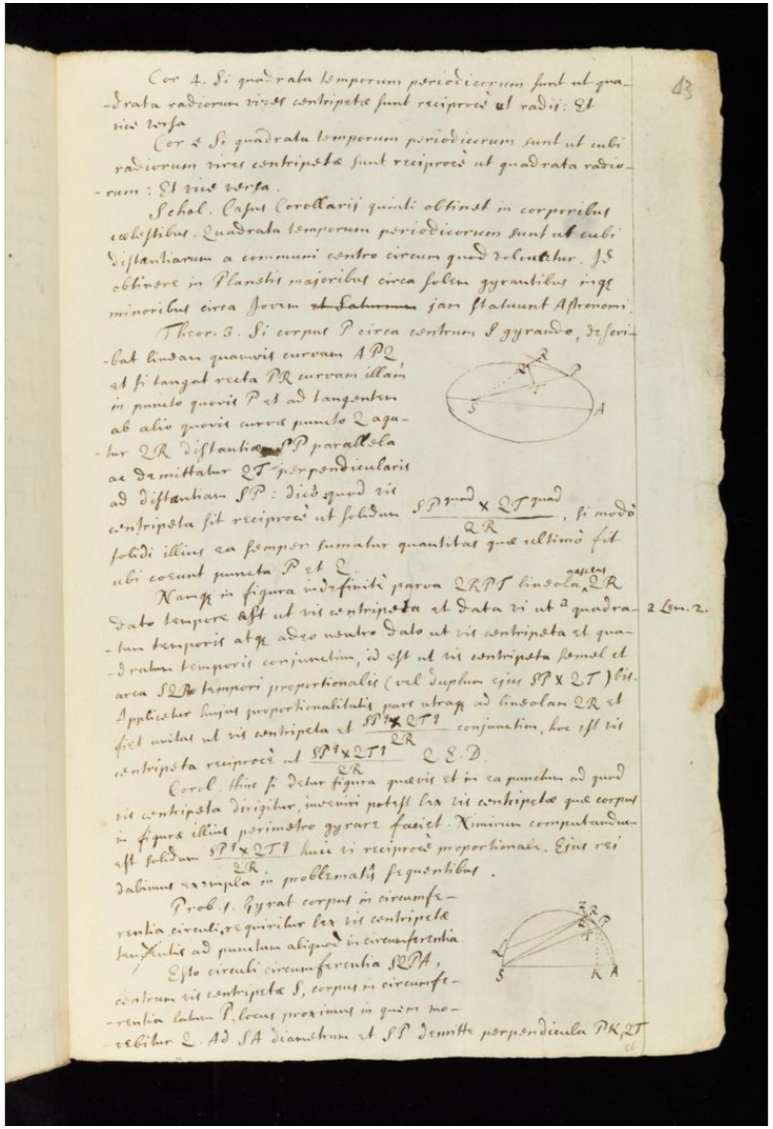
Newton's gravitational law



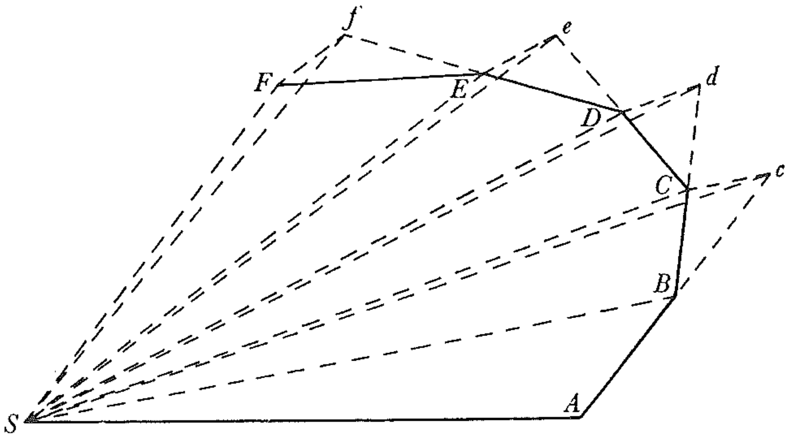
$$F_1 = F_2 = G\,\frac{m_1 \times m_2}{r^2}$$

De Motu Corporum in Gyrum (1684)





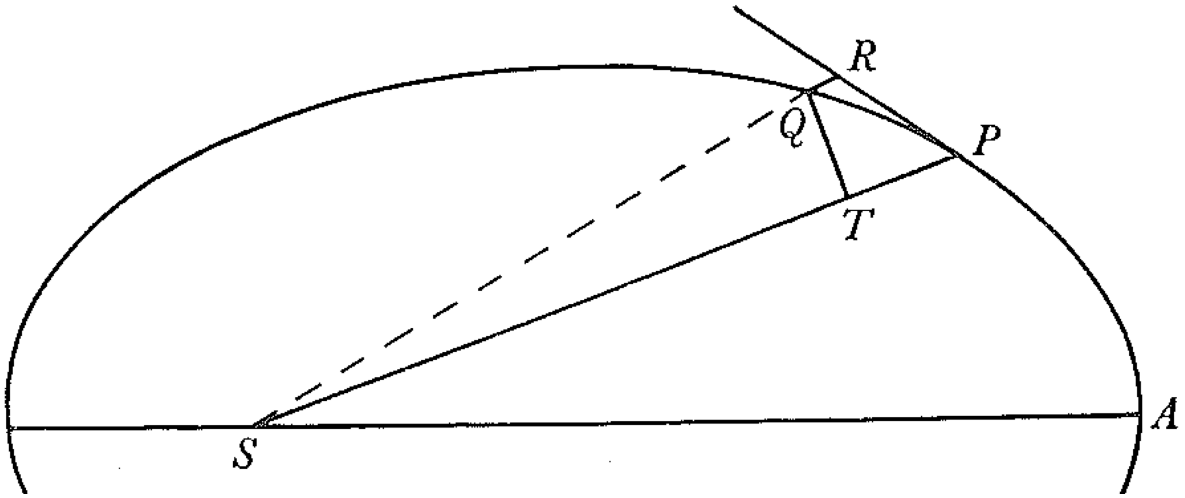
Theorem 1: Central force ➔ Equal areas in equal times



Wikipedia: Newton’s proof of Kepler’s second law.gif

Theorem 3: PQRST formula

$Q \longrightarrow P$



Constant acceleration

$$F \propto \frac{d}{t^2}$$

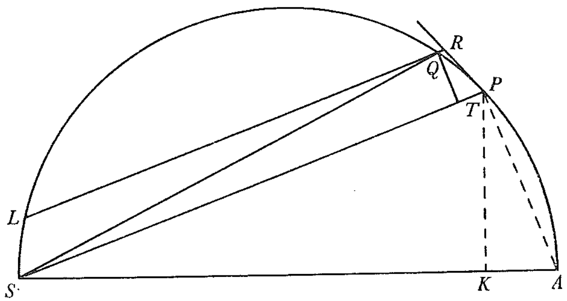
$$F \propto \frac{QR}{SP^2 \times QT^2}$$

Kepler problem

Orbit's shape and sun's postion ⟷ **Force law**

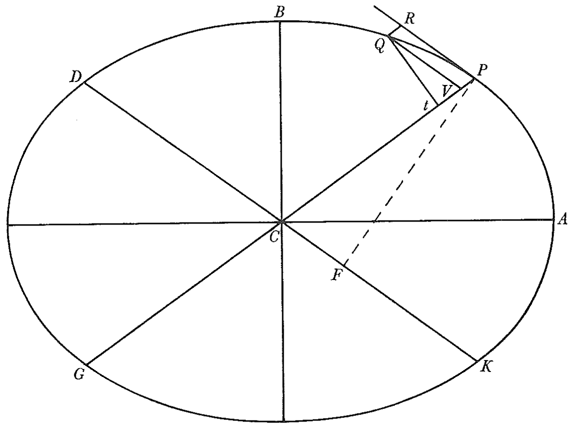
Problems 1, 2 e 3: Applying PQRST

$$F \propto QR/(SP^2 \times QT^2)$$



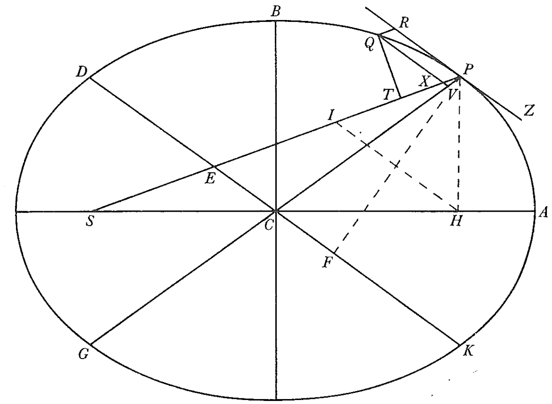
Prob. 1

$F(r) \propto 1/r^5$



Prob. 2

$F(r) \propto r$



Prob. 3

$F(r) \propto 1/r^2$

A proposal for high school

Elliptical Orbit ⇨ $1/r^2$ Force

Newton's Recipe

Given only two ingredients—the *shape of the orbit* and the *center of the force*—"Newton's Recipe" allows one to calculate the relative force at any orbital point. The recipe consists of the following steps:

1. *The inertial path:* Draw the tangent line to the orbit curve at the point P where the force is to be calculated.
2. *The future point:* Locate any future point Q on the orbit that is close[6] to the initial point P.
3. *The deviation line:* Draw the line segment from Q to R, where R is a point on the tangent, such that QR (line of deviation) is parallel to SP (line of force).
4. *The time line:* Draw the line segment from Q to T, where T is a point on the radial line SP, such that QT (height of "time triangle") is perpendicular to SP (base of triangle).
5. *The force measure:* Measure the shape parameters QR, SP, and QT, and calculate the force measure $QR/(SP \times QT)^2$.
6. *The calculus limit:* Repeat steps two to five for several future points Q around P to obtain several force measures. Take the limit Q→P of the sequence of force measures to find the exact value of the force measure at P.[7]

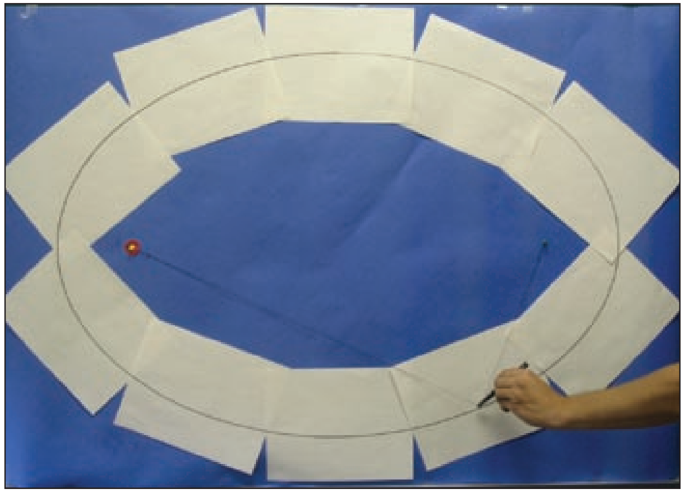


Fig. 5. The class constructs an elliptical orbit. Each student gets a small piece (arc) of the whole ellipse and measures the force responsible for the shape of his or her arc.

Table II. Values of the force *F* measured by a team of students at nine different radii *r* along their elliptical orbit. The team uncovers a simple pattern in the data: $F = 1.23/r^{2.12}$.

r (m)	F (m^{-3})
0.324	14.0
0.359	10.0
0.419	8.60
0.460	6.00
0.560	4.00
0.607	3.66
0.625	3.42
0.644	3.46
0.647	2.80

Prentis et al. (2007)

Some lessons from Newton's PQRST force

- For Newton, force and time are geometrical entities

- Force was assumed constant for a small Δt (linear approximation); Geometrical calculus ("ultimate ratio")

- PQRST formula is a general recipe: Nature tells us the orbit shape and we determine the force law (where $1/r^2$ comes from?)

- *Hypotheses non fingo*: Compare Newton's PQRST with Kepler's and/or Hooke's force laws

- Sun at the center ($F \propto r$) *vs.* at the focus ($F \propto 1/r^2$) of an ellipse: very different albeit small eccentricities.

Prelude

What is entropy? Why do we need this concept?

How physicists disagree on the meaning of entropy

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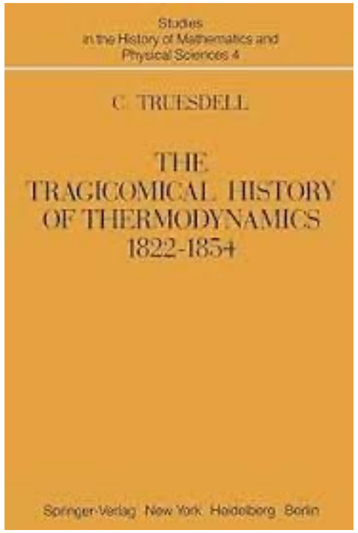
Discussions of the foundations of statistical mechanics, how they lead to thermodynamics, and the appropriate definition of entropy have occasioned many disagreements. I believe that some or all of these disagreements arise from differing, but unstated assumptions, which can make opposing opinions difficult to reconcile. To make these assumptions explicit, I discuss the principles that have guided my own thinking about the foundations of statistical mechanics, the microscopic origins of thermodynamics, and the definition of entropy. The purpose of this paper will be fulfilled if it paves the way to a final consensus, whether or not that consensus agrees with my point of view.

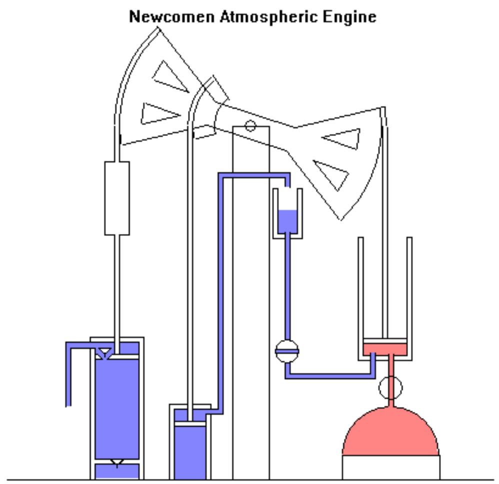
[DOI: 10.1119/1.3536633]



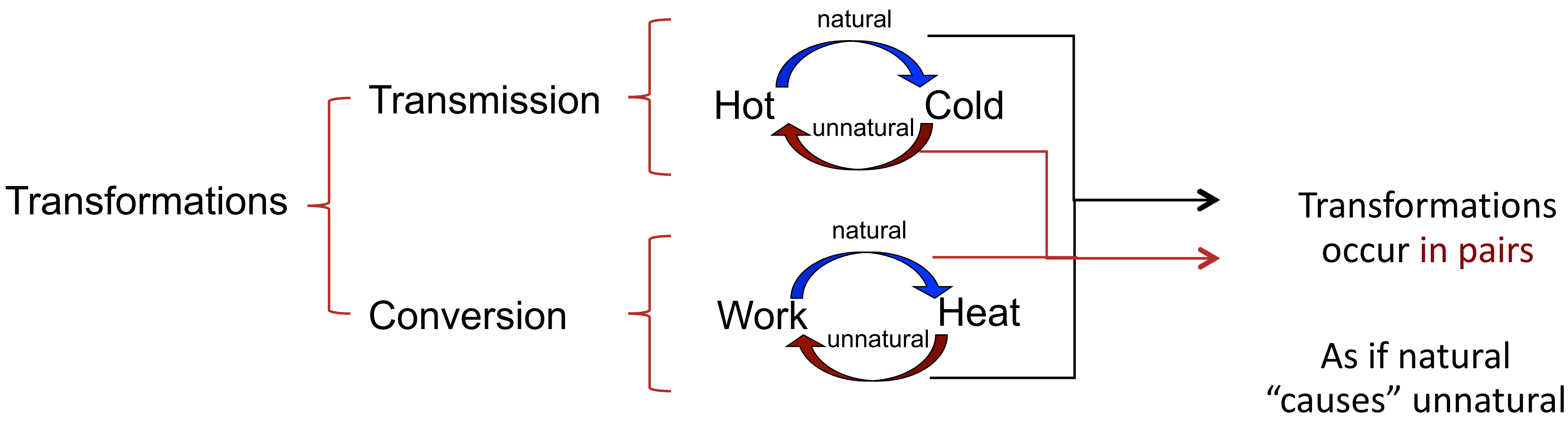
Genesis of entropy

On a modified form of the second fundamental theorem in the mechanical theory of heat (Clausius, 1854)

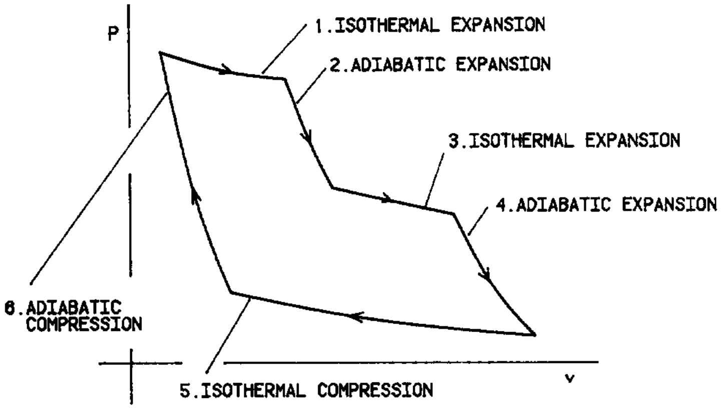
"This is one of the strangest memoirs in the entire history of physics" (Darrigol)

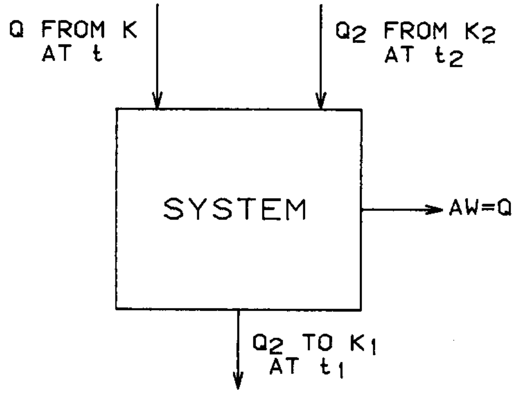


https://en.wikipedia.org/wiki/Newcomen_atmospheric_engine



Clausius 6-step cycle





"Equivalent" transfor-mations in Clausius cycle

$$\begin{Bmatrix} Q[t] \rightarrow W \\ Q_2[t_2] \rightarrow Q_2[t_1] \end{Bmatrix}$$

"Equivalent" transfor-mations in Clausius (reverse) cycle

$$\begin{Bmatrix} W \rightarrow Q[t] \\ Q_2[t_1] \rightarrow Q_2[t_2] \end{Bmatrix}$$

We see, therefore, that these two transformations may be regarded as phenomena of the same nature, and we may call two tranformations which can thus mutually replace one another *equivalent*. We have now to find the law according to which the transformations must be expressed as mathematical magnitudes, in order that the equivalence of two transformations may be evident from the equality of their values. The mathematical value of a transformation thus determined may be called its *equivalence-value* (Aequivalenzwerth).

Cropper (1986) AJP

Äquivalenzwert: Mathematizing the equivalence

Clausius cycle

$$\begin{Bmatrix} Q[t] \rightarrow W \\ Q_2[t_2] \rightarrow Q_2[t_1] \end{Bmatrix} \quad F(t_2,t_1)Q_2 - f(t)Q = 0.$$

Another Clausius cycle

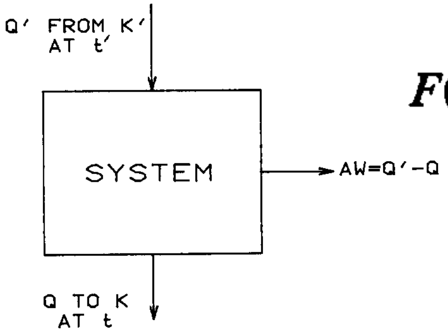
$$\begin{Bmatrix} Q'[t'] \rightarrow W \\ Q_2[t_2] \rightarrow Q_2[t_1] \end{Bmatrix} \quad F(t_2,t_1)Q_2 - f(t')Q' = 0$$

Thus

$$f(t)Q = f(t')Q'$$

The magnitude of *f(t)* is inversely proportional to the amount of heat transformed

Yet another [Carnot] cycle



$$F(t',t)Q - f(t')(Q' - Q) = 0$$

Combined with f(t)Q = f(t’)Q’

$$F(t',t) = f(t) - f(t')$$

Meaning: Only one function (*f(t)*) is needed

Back to Clausius cycle

$$f(t_2)Q_2 - f(t_1)Q_2 + f(t)Q = 0$$

Back to Carnot cycle

$$f(t')Q' - f(t)Q = 0$$

Both equations of the form

$$\sum f(t)Q = 0$$

Äquivalenzwert: Mathematizing the equivalence

Back to Clausius cycle

$$f(t_2)Q_2 - f(t_1)Q_2 + f(t)Q = 0$$

Back to Carnot cycle

$$f(t')Q' - f(t)Q = 0$$

Both equations of the form

$$\sum f(t)Q = 0$$

According to Kelvin, for a Carnot cycle:

$$\frac{Q'}{T'} - \frac{Q}{T} = 0 \quad \text{thus} \quad f(t) = \frac{1}{T}$$

For infinitesimal processes

$$\int \frac{dQ}{T} = 0$$

What about *non-reversible* cycles?

The algebraical sum of all transformations occurring in a cyclical process can only be positive.

A transformation which thus remains at the conclusion of a cyclical process without another opposite one, and which according to this theorem can only be positive, we shall, for brevity, call an *uncompensated* transformation.

The different kinds of operations giving rise to uncompensated transformations are, as far as external appearances are concerned, rather numerous, even though they may not differ very essentially. One of the most frequently occurring examples is that of the transmission of heat by mere conduction, when two bodies of different temperatures are brought into immediate contact; other cases are the production of heat by friction, and by an electric current when overcoming the resistance due to imperfect conductibility, together with all cases where a force, in doing

$$\int \frac{dQ}{T} \geq 0$$

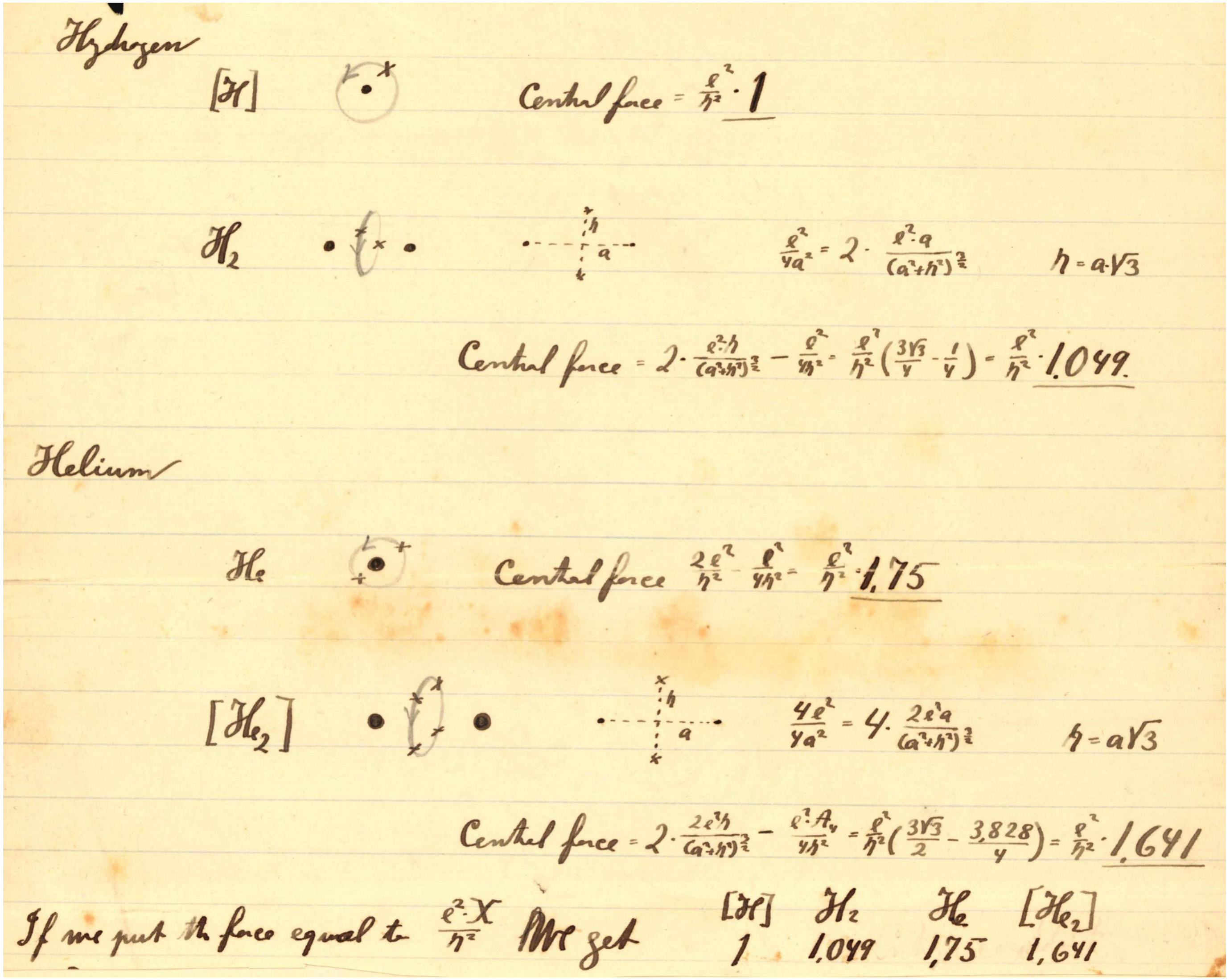
Some lessons from Clausius' 6-step cycle

- Motivation (raison d'être) to conceptualize entropy

- *Äquivalenzwert*: Entropy is a mathematical quantity to express the relation between heat *transmission* (from T_1 to T_2) e *conversion* of heat into work (and vice-versa).

- In reversible cycles to the total sum (of equivalence-values) is zero. Otherwise, the sum is positive (more natural than unnatural)

Rutherford (aka Manchester) memorandum 1912



Hydrogen

[H] Central force $= \frac{e^2}{r^2} \cdot 1$

H_2 $\frac{e^2}{4a^2} = 2 \cdot \frac{e^2 \cdot a}{(a^2+r^2)^{\frac{3}{2}}}$ $r = a\sqrt{3}$

Central force $= 2 \cdot \frac{e^2 \cdot r}{(a^2+r^2)^{\frac{3}{2}}} - \frac{e^2}{4r^2} = \frac{e^2}{r^2}\left(\frac{3\sqrt{3}}{4} - \frac{1}{4}\right) = \frac{e^2}{r^2} \cdot 1.049$

Helium

He Central force $\frac{2e^2}{r^2} - \frac{e^2}{4r^2} = \frac{e^2}{r^2} \cdot 1.75$

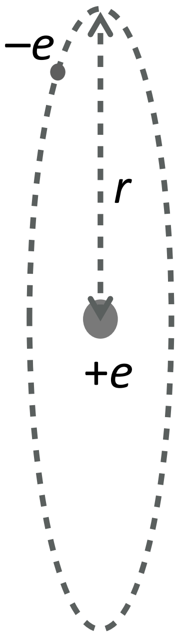
$[He_2]$ $\frac{4e^2}{4a^2} = 4 \cdot \frac{2e^2a}{(a^2+r^2)^{\frac{3}{2}}}$ $r = a\sqrt{3}$

Central force $= 2 \cdot \frac{2e^2r}{(a^2+r^2)^{\frac{3}{2}}} - \frac{e^2 \cdot A_4}{4r^2} = \frac{e^2}{r^2}\left(\frac{3\sqrt{3}}{2} - \frac{3.828}{4}\right) = \frac{e^2}{r^2} \cdot 1.641$

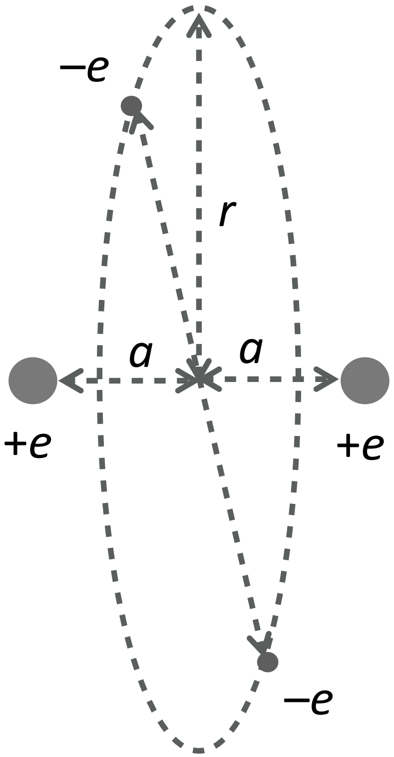
If we put the force equal to $\frac{e^2 X}{r^2}$ we get

[H]	H_2	He	$[He_2]$
1	1.049	1.75	1.641

Stability and formation of H_2 and He_2



hydrogen atom



hydrogen molecule

hydrogen atom

Centripetal force = Coulomb force

$$m\omega^2 r = \frac{e^2}{r^2} \longrightarrow m\omega^2 r^3 = e^2$$

hydrogen molecule

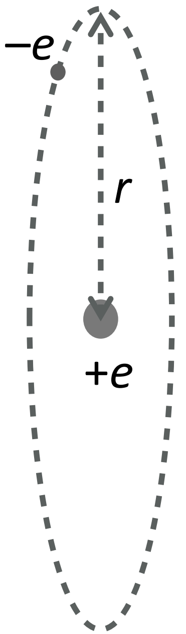
Condition for nuclear stability

$$\frac{e^2}{4a^2} = 2 \cdot \frac{e^2}{a^2+r^2} \cdot \frac{a}{\sqrt{a^2+r^2}} = \frac{2e^2 a}{(a^2+r^2)^{3/2}}$$

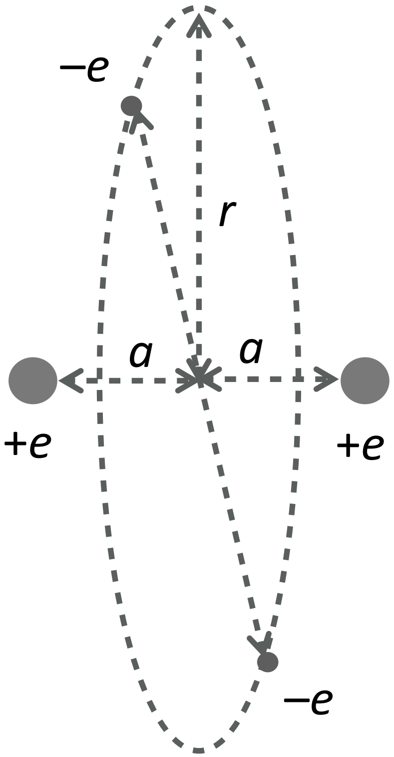
$$(a^2+r^2)^{3/2} = 8a^3 \longrightarrow a^2 + r^2 = 8^{2/3}a^2 = 4a^2$$

$$a^2 = r^2/3 \qquad r = a\sqrt{3}$$

Stability and formation of H_2 and He_2



hydrogen atom



hydrogen molecule

hydrogen atom

Centripetal force = Coulomb force

$$m\omega^2 r = \frac{e^2}{r^2} \longrightarrow \boxed{m\omega^2 r^3 = e^2}$$

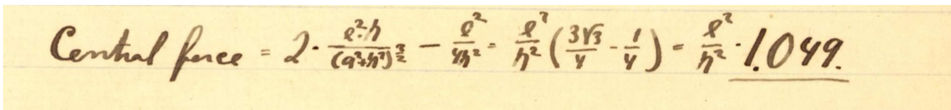
hydrogen molecule

Centripetal force

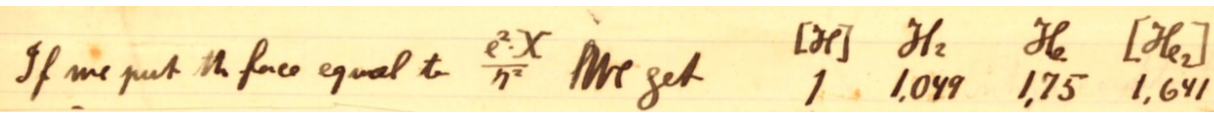
(per electron)

$$m\omega^2 r = 2 \cdot \frac{e^2}{a^2 + r^2} \cdot \frac{r}{\sqrt{a^2 + r^2}} - \frac{e^2}{4r^2}$$

$$m\omega^2 r = X \cdot \frac{e^2}{r^2} \text{ with } X = \frac{3\sqrt{3}-1}{4} \cong 1.049$$

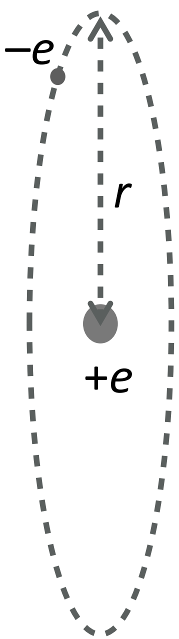

Central force $= 2\cdot\frac{e^2 r}{(a^2+r^2)^{\frac{3}{2}}} - \frac{e^2}{4r^2} = \frac{e^2}{r^2}\left(\frac{3\sqrt{3}}{4} - \frac{1}{4}\right) = \frac{e^2}{r^2}\cdot 1.049$

Similar procedure to Helium

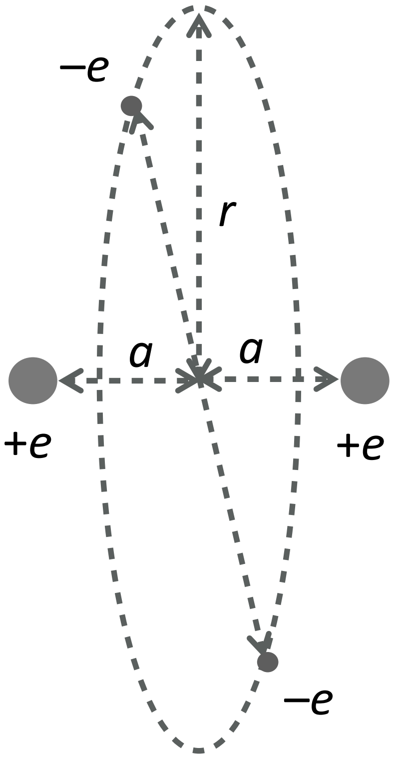

If we put the force equal to $\frac{e^2 X}{r^2}$ we get

[H]	H_2	He	[He_2]
1	1,049	1,75	1,641

Planck's constant enters Bohr's model



hydrogen atom



hydrogen molecule

In general $m\omega^2 r^3 = Xe^2$

Hydrogen atom: $X = 1$

Hydrogen molecule: $X = 1.049$

How to fix ω and r?

$$E_{kin} = K\nu \qquad \frac{1}{2}m\omega^2 r^2 = K\frac{\omega}{2\pi}$$

$$m\omega r^2 = \frac{K}{\pi}$$

$$m\omega^2 r^4 = \frac{K^2}{m\pi^2}$$

$$r = \frac{K^2}{\pi^2 X m e^2}$$

$$\omega = \frac{m\pi^3 e^4 X^2}{K^3} \qquad \nu = \frac{m\pi^2 e^4 X^2}{2K^3}$$

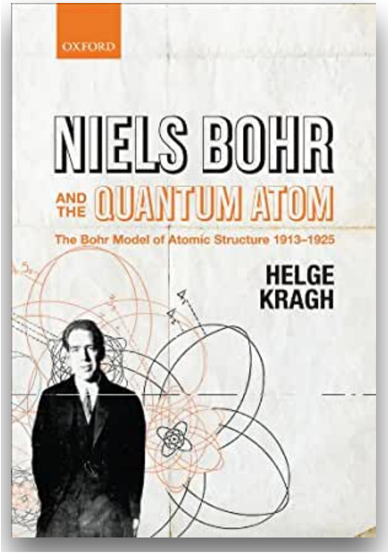
Pause for reflection…

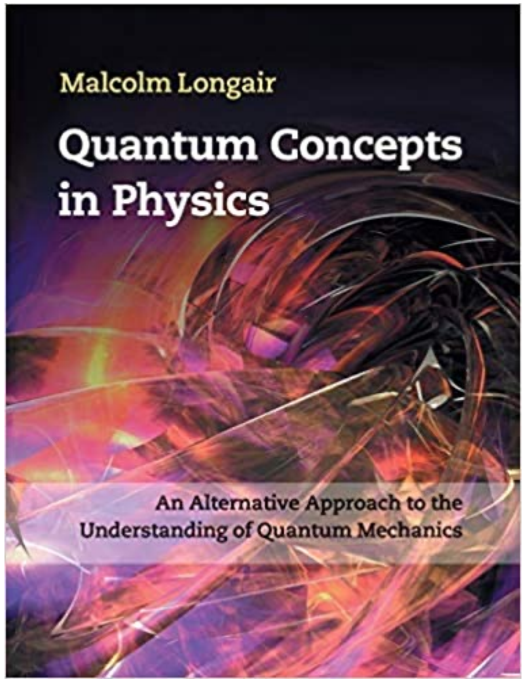
- Is there anything being quantized?
- Where are the spectral lines?
- What is the value of Planck's constant?
- Are there quantum jumps?

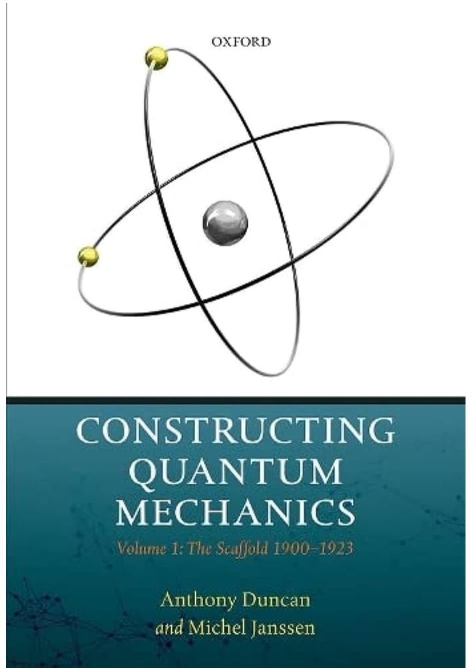
Useful references

The Genesis of the Bohr Atom

BY JOHN L. HEILBRON* AND THOMAS S. KUHN**







Historical research

Didactic reconstruction

Some lessons from the Manchester memorandum

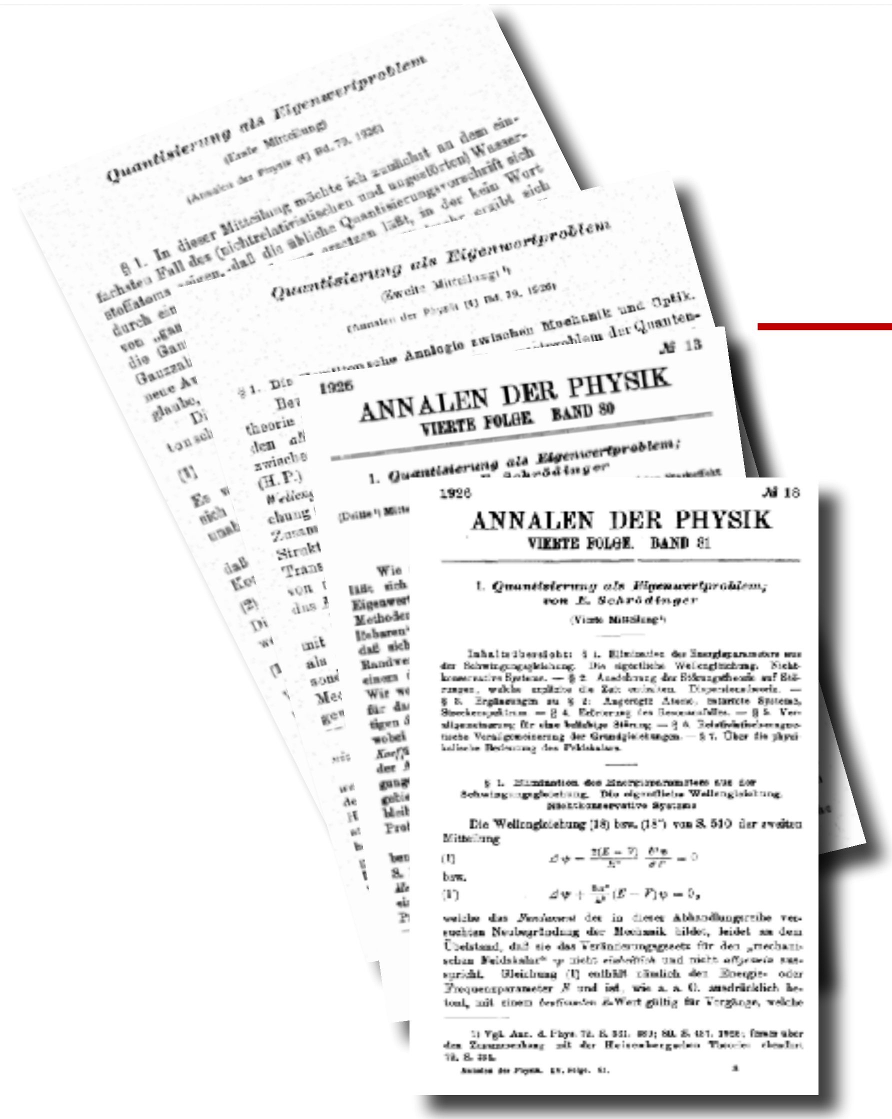
- At first, Bohr was **not** interested in explaining the hydrogen spectrum (otherwise considered his key achievement); he was way **more ambitious** than textbooks would have him appear (explain **all molecules**).

- The (in)famous electron jumps were inferred from the structure of Balmer's formula;

- Bohr had problems explaining a ½ factor theoretically, although its need was clear from the experimental value of R

- Orbital frequency $\neq$ radiation frequency: MAJOR controversy!

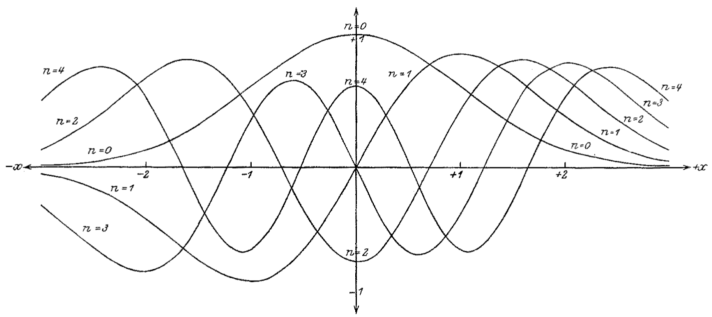
From micro to macromechanics (Schrödinger, 1926)

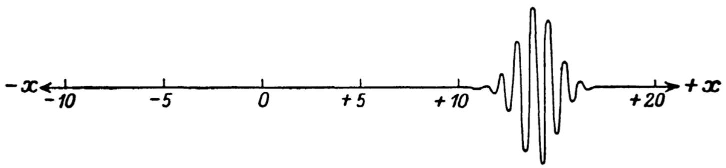


Schrödinger's four communications
(1926)

The Continuous Transition from Micro- to Macro-Mechanics

(*Die Naturwissenschaften*, 28, pp. 664-666, 1926)

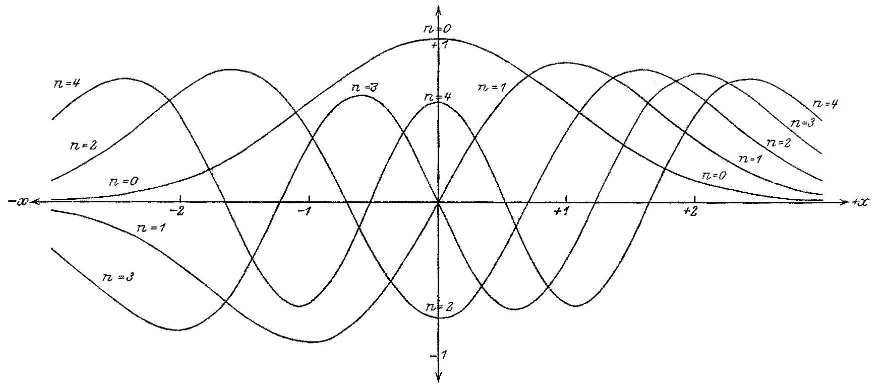




From micro to macromechanics (Schrödinger, 1926)

The Continuous Transition from Micro- to Macro-Mechanics

(*Die Naturwissenschaften*, 28, pp. 664-666, 1926)



Harmonic oscillator

$$\begin{cases} \psi_n = e^{-\frac{x^2}{2}} H_n(x) e^{2\pi i \nu_n t} \\ \left(\nu_n = \frac{2n+1}{2}\nu_0 \;;\; n = 0, 1, 2, 3 \ldots\right) \end{cases}$$

"A group of proper vibrations may represent a particle"

$$\psi = \sum_{n=0}^{\infty} \left(\frac{A}{2}\right)^n \frac{\psi_n}{n!} \qquad \psi = e^{\pi i \nu_0 t - \frac{A^2}{4} e^{4\pi i \nu_0 t} + A x e^{2\pi i \nu_0 t} - \frac{x^2}{2}}$$

Now we take, as is provided for, the real part of the right-hand side

[5] i means $\sqrt{-1}$. On the right-hand side the real part is to be taken, as usual.

$$\psi = e^{\frac{A^2}{4} - \frac{1}{2}(x - A\cos 2\pi\nu_0 t)^2} \cos\left[\pi\nu_0 t + (A \sin 2\pi\nu_0 t) \cdot \left(x - \frac{A}{2}\cos 2\pi\nu_0 t\right)\right]$$

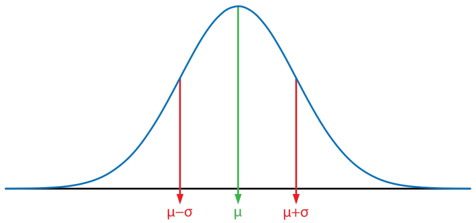
From micro to macromechanics (Schrödinger, 1926)

$$\psi = e^{\frac{A^2}{4}-\frac{1}{2}(x-A\cos 2\pi\nu_0 t)^2} \cos\left[\pi\nu_0 t + (A\sin 2\pi\nu_0 t).\left(x - \frac{A}{2}\cos 2\pi\nu_0 t\right)\right]$$

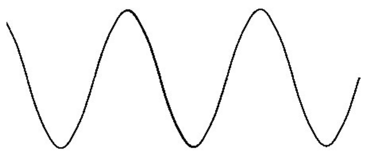
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

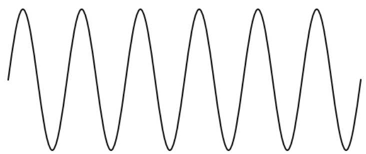
Gaussian

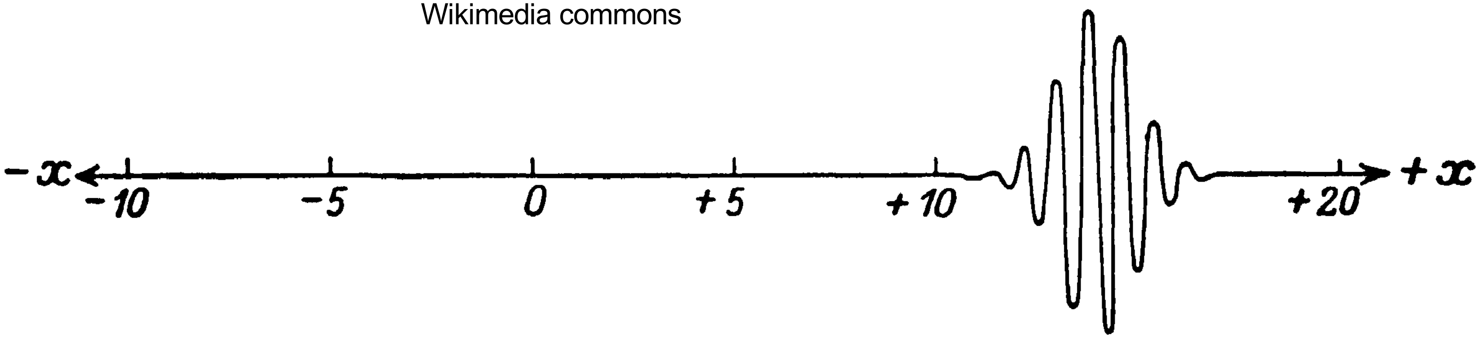
cosine wave with varying period



Wikimedia commons



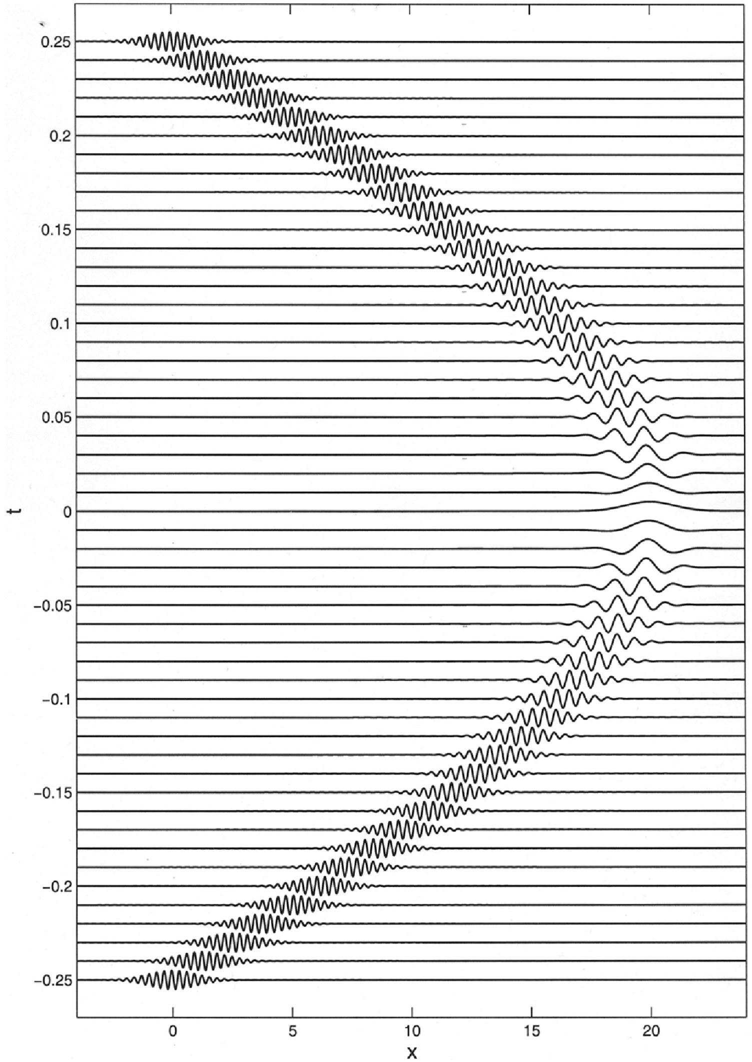




Oscillating wave group as the representation of a particle in wave mechanics

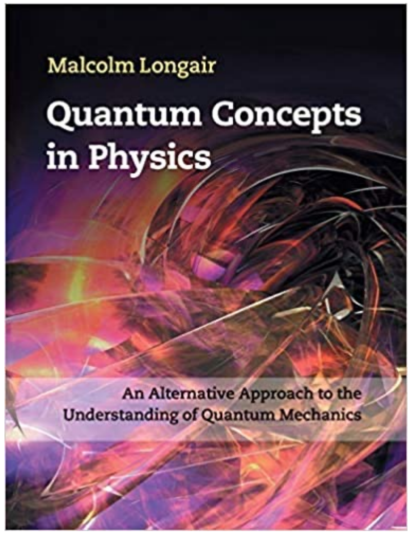
From micro to macromechanics (Schrödinger, 1926)

$$\psi = e^{\frac{A^2}{4} - \frac{1}{2}(x - A\cos 2\pi\nu_0 t)^2} \cos\left[\pi\nu_0 t + (A\sin 2\pi\nu_0 t).\left(x - \frac{A}{2}\cos 2\pi\nu_0 t\right)\right]$$

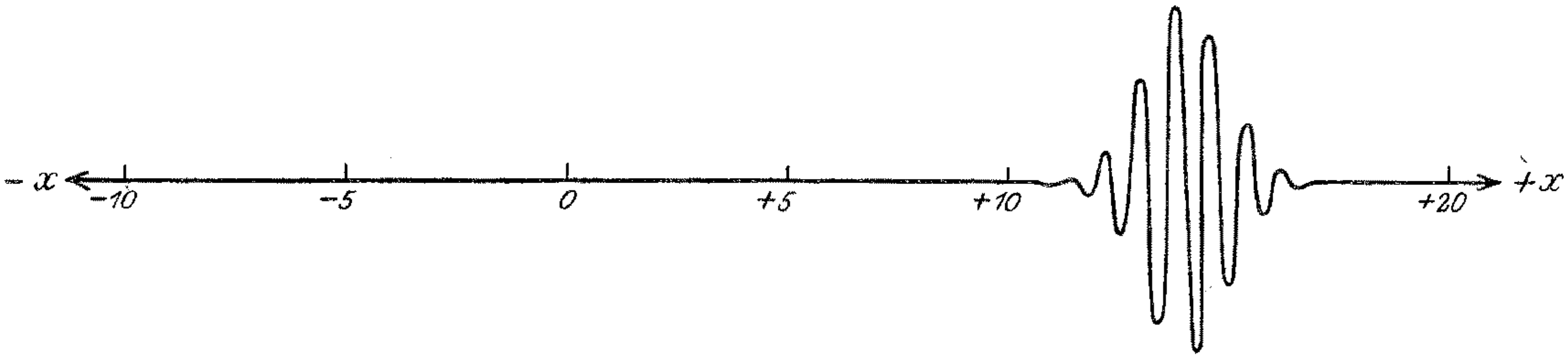


The evolution of wave-packet with A =20 (Diagram created by Dr. David Green)

Source: Chapter 14.6



From micro to macromechanics (Schrödinger, 1926)

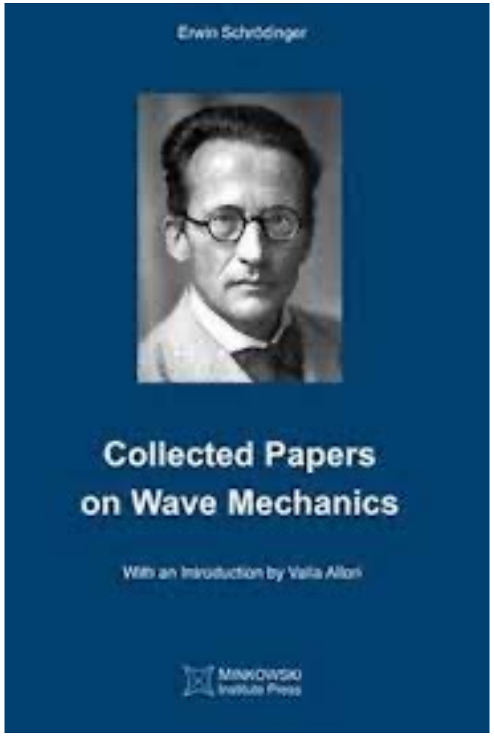


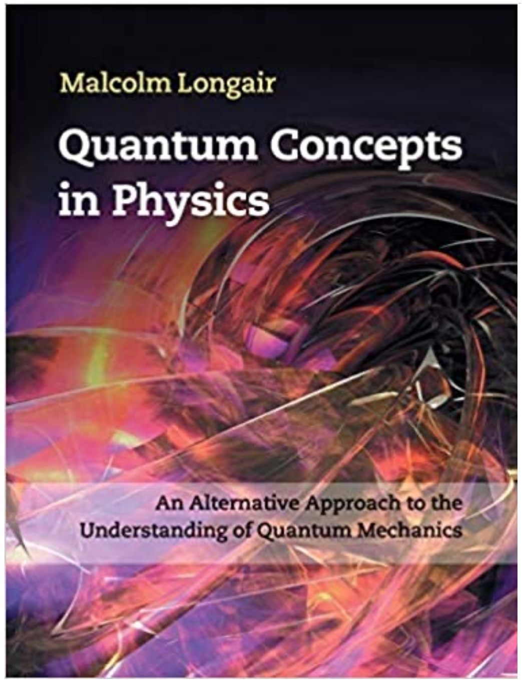
Unsere Wellengruppe hält dauernd zusammen, breitet sich nicht im Laufe der Zeit auf ein immer größeres Gebiet aus, wie man es sonst, z. B. in der Optik, gewohnt ist.

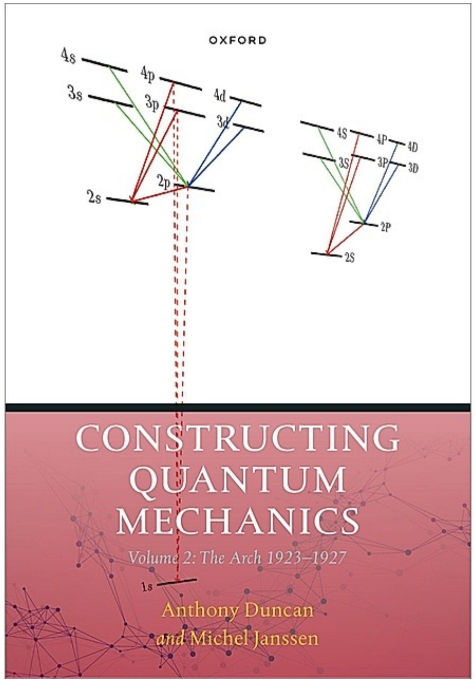
Eine mutige Voraussage:

Es läßt sich mit Bestimmtheit voraussehen, daß man auf ganz ähnliche Weise auch die Wellen-gruppen konstruieren kann, welche auf hoch-quantigen Keplerellipsen umlaufen und das undulationsmechanische Bild des Wasserstoff-elektrons sind; nur sind da die rechentechnischen Schwierigkeiten größer als in dem hier behandelten, ganz besonders einfachen Schulbeispiel.

Useful references







Original papers

Didactic reconstruction

The classical roots of wave mechanics: Schrödinger's transformations of the optical-mechanical analogy

Christian Joas, Christoph Lehner *

Max Planck Institute for the History of Science, Boltzmannstr. 22, 14195 Berlin, Germany

Studies in History and Philosophy of Modern Physics 40 (2009) 338–351

Historical research

Some lessons from Schrödinger's micro-macro

- Schrödinger was initially seeking physical meaning in the *real* component of his wave function and struggled to accept a complex wave function.

- For him, fundamental entities are waves; particles are wave groups.

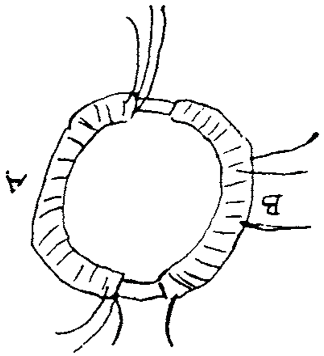
- Schrödinger's prophecy/vision was not fulfilled (wave packets almost always disperse), but this did not prevent him from arguing for “spatio-temporal“ interpretations of QM.

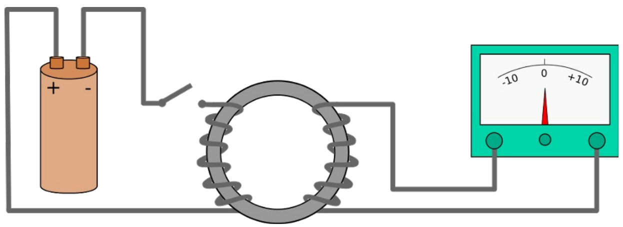
Discovery of induction

Faraday's diary (1822)

Convert magnetism into electricity

Induction ring





29.8.1831

3. [...] Then connected the ends of one of the pieces on A side with battery; immediately a sensible effect on needle. It oscillated and settled at last in original position. On *breaking* connection of A side with battery again a disturbance of the needle.

4. Made all the wires on A side one coil and sent current from battery through the whole. Effect on needle much stronger than before.

8. Hence effect evident but transient; but its recurrence on breaking the connection shows an equilibrium somewhere that must be capable of being rendered.

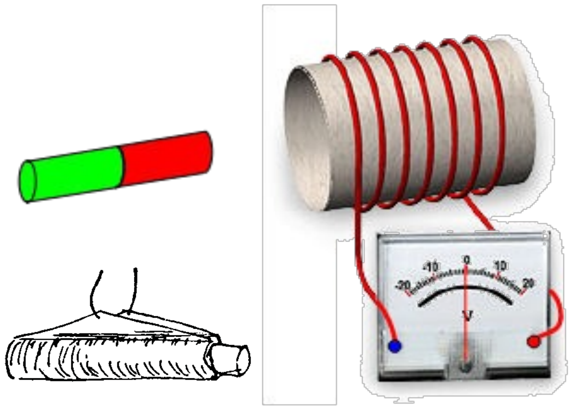
Discovery of induction

Faraday's diary (1822)

Convert magnetism into electricity

17.10.1831

Moving a magnet through a coil



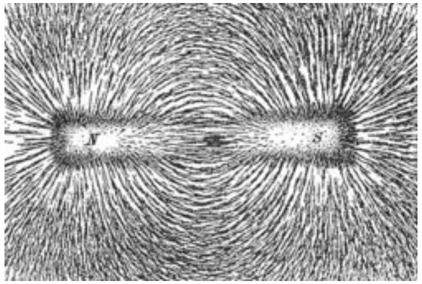
57. The 8 ends of the helices at one end of the cylinder were cleaned and fastened together as a bundle. These compound ends were then connected with the Galvanometer by long copper wires then a cylindrical bar magnet 3/4 inch in diameter and 81⁄2 inches in length had one end just inserted into the end of the helix cylinder—then it was quickly thrust in the whole length and the galvanometer needle moved—then pulled out and again the needle moved but in the opposite direction. This effect was repeated every time the magnet was put in or out and therefore a wave of Electricity was so produced from mere approximation of a magnet and not from its formation *in situ*.

Lines of force

IMAGInation: Continuous curved patterns

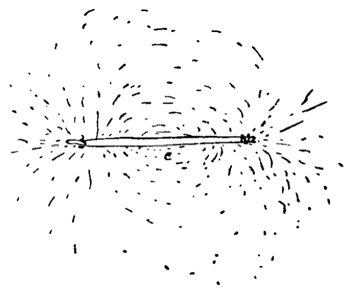
- Place a bar magnet beneath a sheet of paper

- Spread iron fillings



- Continuous curves from pole to pole

Diary (1851)



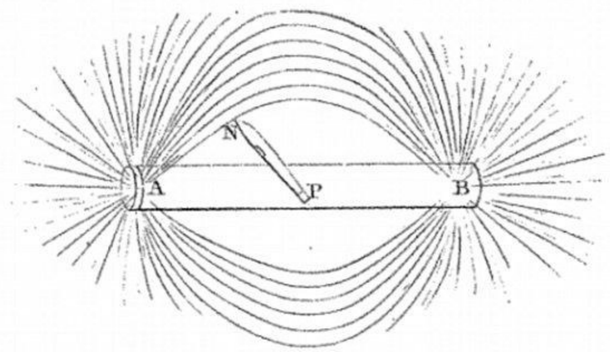
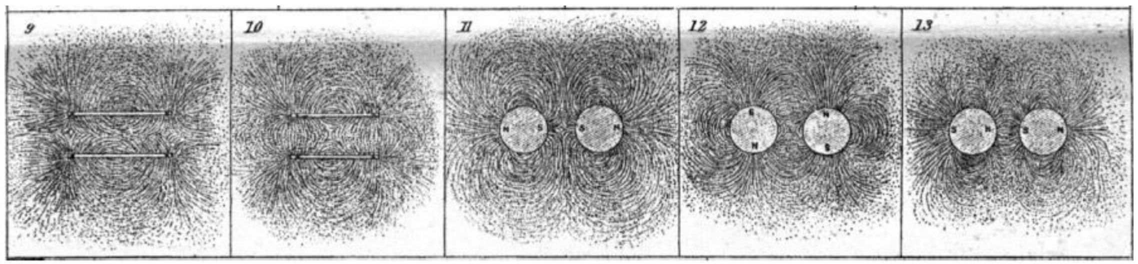


Fig. 25.

1st series (1831)

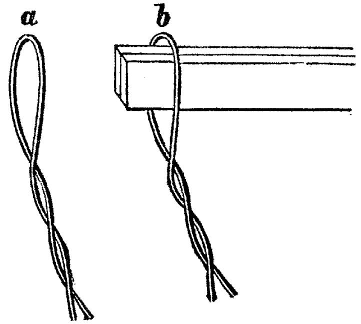


29^{th} series (1852)

Moving wire

28th series (1852)

Fig. 2.

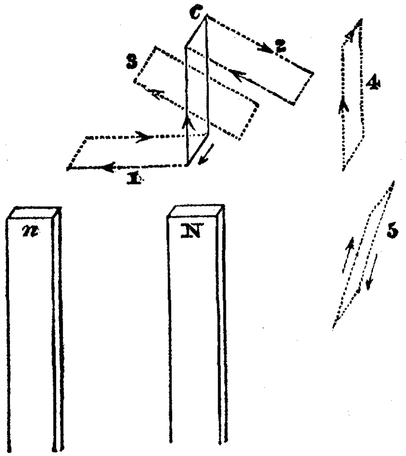


When the bend of the wires was formed into a loop and carried from *a* to *b*, the galvanometer needle was deflected two degrees or more. The vibration of the needle was slow, and it was easy to reiterate this action five or six times, breaking and making contact with the galvanometer at right intervals, so as to combine the effect of induced currents; and then a deflection of 10° or 15° could be readily obtained.

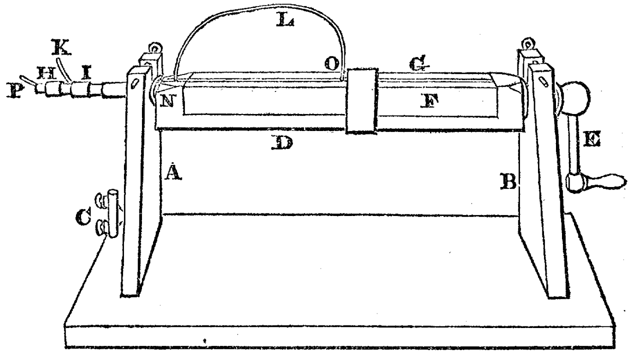
- Deflection is proportional to number of times, i.e. “number of lines of force that cut/cross the loop” (Counting principle)
- The “moving wire” undergoes a profound transformation: from a *phenomenon* to a [reasoning?] *instrument* to interpret other phenomena (Fisher, 2001)

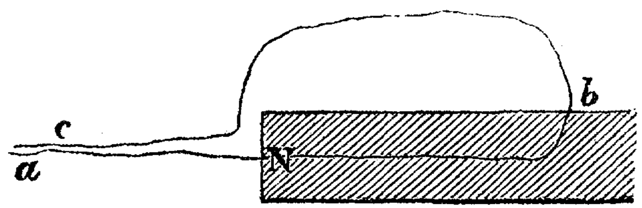
Moving/revolving circuits/magnets

28th series (1852)



If Fig. 3 represent a magnetic pole *N*, and over it a circuit, formed of metal, which may be of any shape, and which is at first in position *c*; then if that ciruit be moved in one direction into position 1, 2, 3, 4 or 5; or any position in between; or if the pole moves to position *n,* then, an electric current will be produced in the circuit.

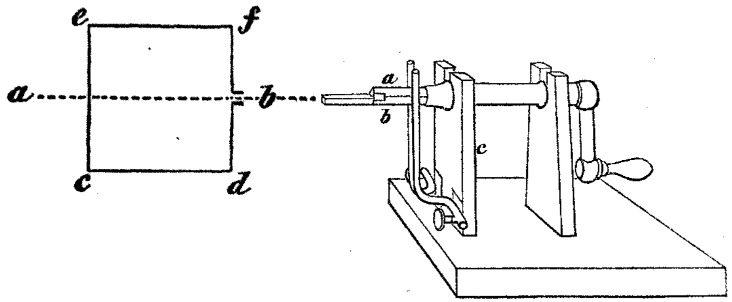




Inside the magnet!

Revolving rectangles

29th series (1852)



One revolution	gave 7°	equal to 7°	per revolution.
Two revolutions	gave 13·875	equal to 6·937	per revolution.
Three revolutions	gave 21·075	equal to 7·025	per revolution.
Four revolutions	gave 28·637	equal to 7·159	per revolution.
Five revolutions	gave 37·637	equal to 7·527	per revolution.

Now 144 square inches is to 128 square inches as 2,61° is to 2,32° proving that the electric current induced is directly as the lines of magnetic force intersected by the moving wire [...] no alterations are caused by changing the velocity of motion, provided the amount of lines of force intersected remains the same. […] "thrice as advantageous to intersect the lines within nine square feet once, as to intersect those of one square foot three times"

Fig. 6.

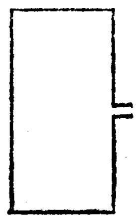
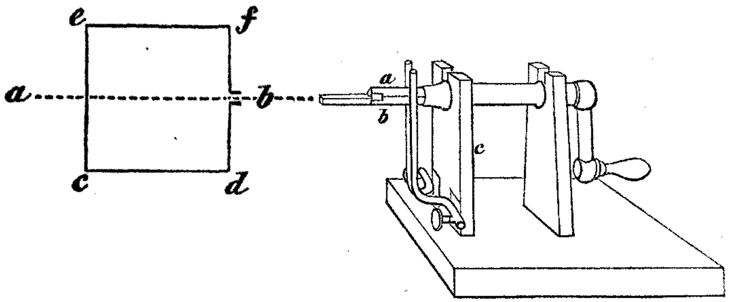


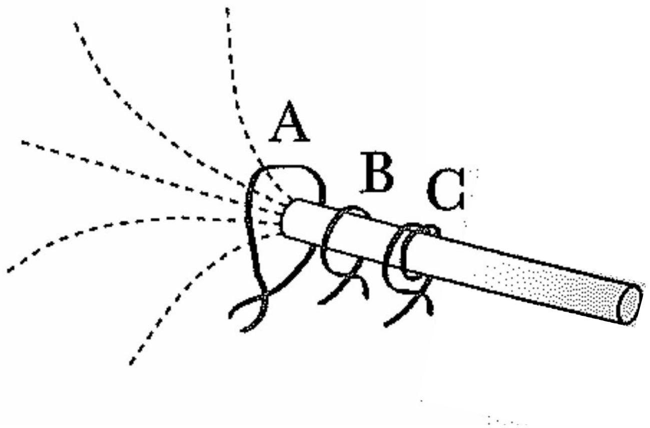
Fig. 7.

Revolving rectangles

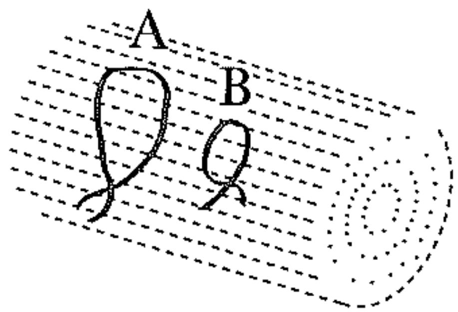
29th series (1852)



3195. When a given length of wire is to be disposed of in the form best suited to produce the maximum effect, then the circumstances to be considered are contrary for the case of a loop to be employed with a small magnet (39. 3184.), and a rectangle or other formed loop to be employed with the lines of terrestrial force. In the case of the small magnet, *all* the lines of force belonging to it are inclosed by the loop; and if the wire is so long that it can be formed into a loop of two or more convolutions, and yet pass over the pole, then twice or many times the electricity will be evolved that a single loop can produce (36.). In the case of the earth's force, the contrary result is true; for as in circles, squares, similar rectangles, &c. the areas inclosed are as the squares of the periphery, and the lines of force intersected are as the areas, it is much better to arrange a given wire in one simple circuit than in two or more convolutions. Twelve feet of wire in one square inter-



Loop in a small magnet



Loop in "lines of terrestrial force"

Lessons from quantifying induction

- 20 years (!) from discovery to concept/quantification!
- Deep insight into arduous scientific discovery
- Moving wire, revolving magnets/rectangles: from experiments to reasoning instruments
- Change in number of lines of force crossing
- From concrete to abstract $$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$

Using history of physics to teach physics?

Why?

- No intermediates: you too can read the original!
- Original motivation of theories, concepts…
- New (usually less abstract) ways to explain things
- (Erratic) processes *vs.* (rational) products
- Reflect critically about the didactical transposition
- Deeper appreciation for the difficulties encountered by learners

How?

- Selected (short!) excerpts; clearly formulated Int. Learning Outcomes
- Standard topics; originals provide new insights (a-ha moments)
- Usually better *a posteriori*, comparing with traditional way to teach

An old paper...

THE UNIVERSITY OF CHICAGO PRESS JOURNALS

JOURNAL ARTICLE

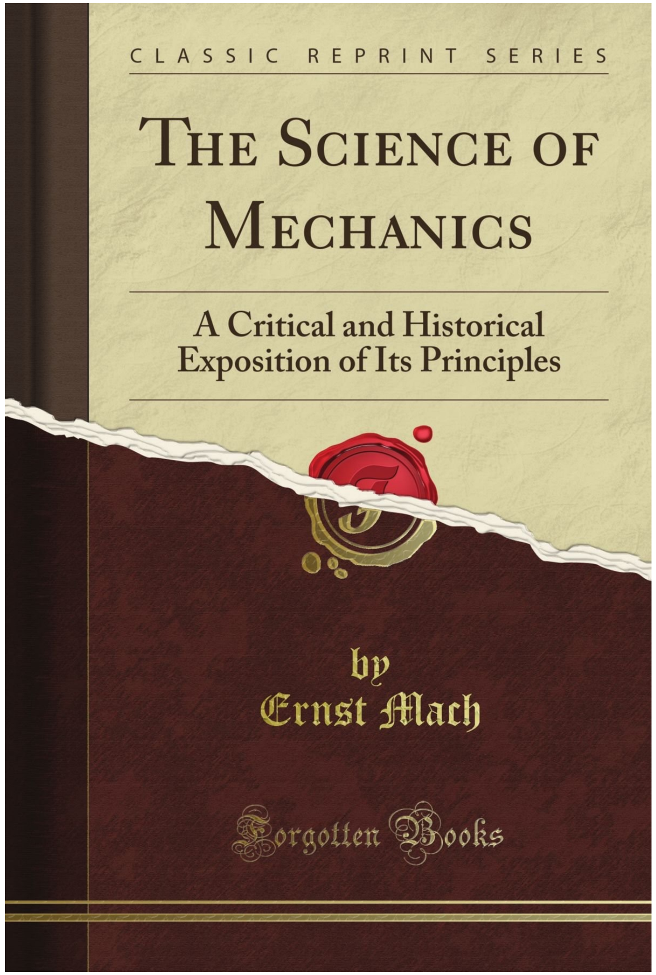
The Pedagogic Value of the History of Physics

Florian Cajori

The School Review
Vol. 7, No. 5 (May, 1899), pp. 278-285 (8 pages)

Published by: The University of Chicago Press

An old textbook...



Thanks!
ricardo.karam@ind.ku.dk