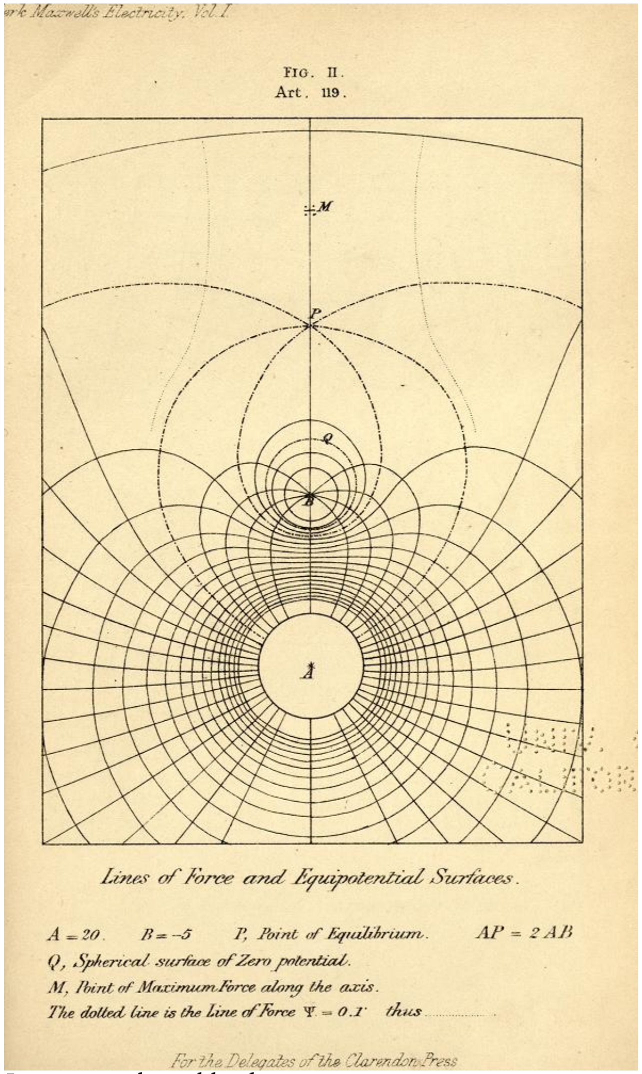


Faraday, Thomson, Maxwell:

Lines of Force in the Ether

8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 9 September 2020

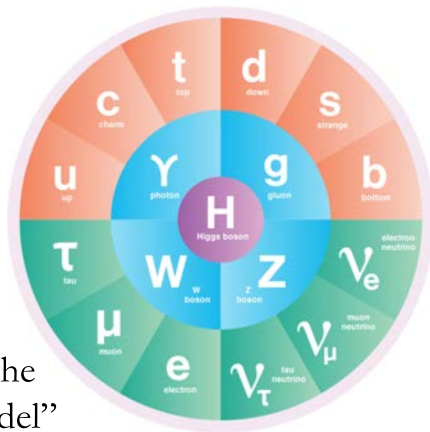
1. Physics, Then and Now

2. Faraday: Lines of Force in the Ether

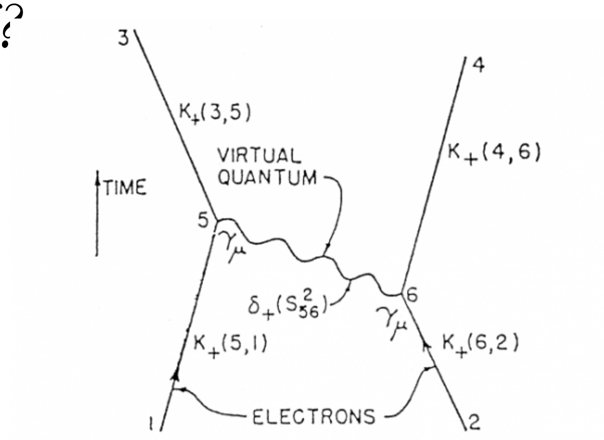
3. Thomson and Maxwell: Math and Mechanics

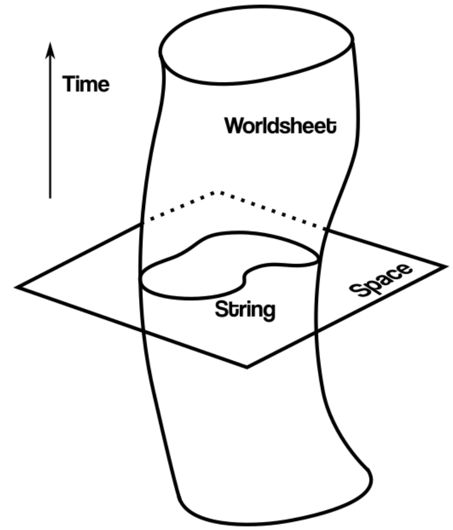
Physics, Then and Now

What is the world made of?



Particles of the "Standard Model"





Today: Particles exchanging particles in the vacuum. (Or maybe strings?)

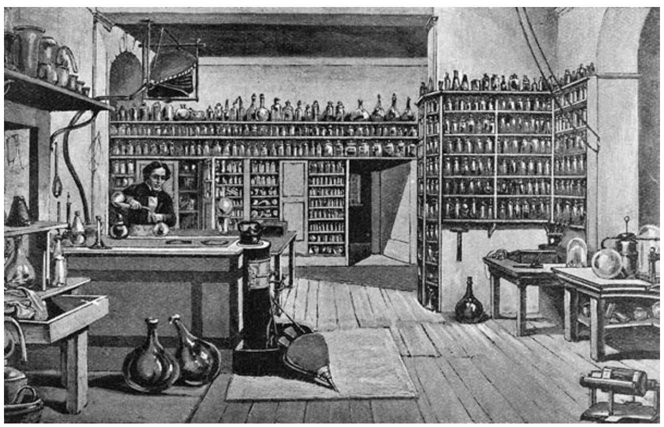
19th Century British Physicist: Bollocks! Wrong, wrong, and wrong...

Different ideas about the *fundamental entities* that make up the world — and yet we still use "their" equations!

Physics, Then and Now

Who pursues physics, and where?

During the first half of the 19th century, people who worked on physics *also* worked on chemistry, mathematics, astronomy, physiology, all grouped under the term, "natural philosophy."



Michael Faraday in his laboratory at the Royal Institution, London, 1830s

Much of this research was *not* done in universities, but in separate "institutes" or "academies," separated from teaching. Not only were most natural philosophers not "professors," some prominent ones had not even attended university themselves!

Big shift toward research conducted in universities beginning around 1850.

Physics, Then and Now

Who pursues physics, and where?

During the first half of the 19th century, people who worked on physics *also* worked on chemistry, mathematics, astronomy, physiology, all grouped up … term, "natural philosophy."

We shouldn't assume that either physics or physicists of earlier times were like what we might expect today!

Michael Faraday in his laboratory at the Royal Institution, London, 1830s

… as *not* done in universities, but in separate "institutes" or "academies," separated from teaching. Not only were most natural philosophers not "professors," some prominent ones had not even attended university themselves!

Big shift toward research conducted in universities beginning around 1850.

Questions?

Faraday: Lines of Force in the Ether

Michael Faraday, 1791-1867

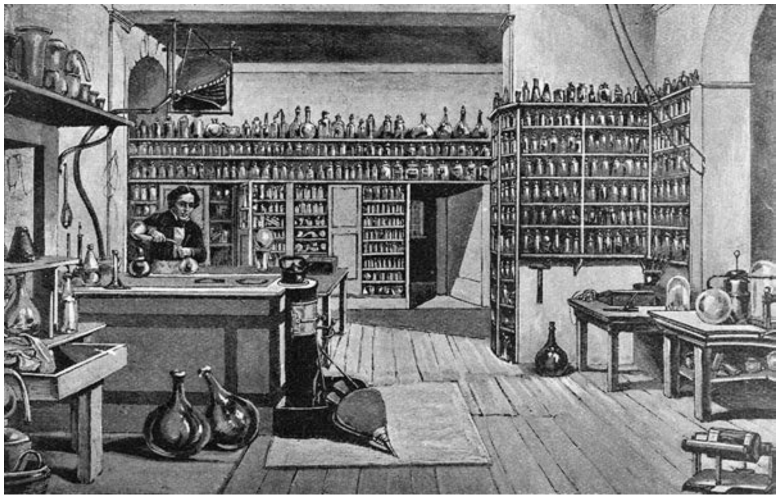
Michael Faraday became one of the most successful and famous natural philosophers of the 19th century: a remarkable "rags to riches" story. He was born into a poor family and never attended high school (let alone college).

Apprenticed to a *bookbinder* at age 13.

He met the famous chemist Humphrey Davy when Davy gave a series of public lectures on natural philosophy at the *Royal Institution* in London.

Faraday took careful notes on Davy's lectures, bound them into a fancy book, and presented the book to Davy as a gift. (*Hint: good way to get a UROP...*) Davy took Faraday on as an assistant — another manual-skills apprenticeship.

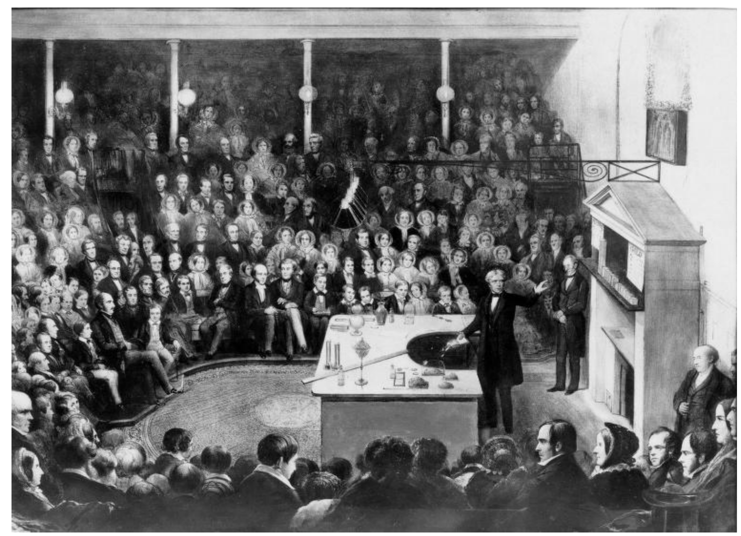
Faraday: Lines of Force in the Ether



Faraday in his Royal Institution laboratory, 1840s

Eventually Davy stepped down and Faraday became director of the Royal Institution. He worked on chemistry, optics, electricity, magnetism, electrolysis ... To Faraday, these were all elements of a *single, unified* approach to nature. He was fascinated by the *interconvertibility* of forces.

Partly inspired by his *religious background*: he belonged to a small Protestant sect called the *Sandemanians*, who emphasized an underlying unity to all of nature — all people and things are (somehow) connected to all others.

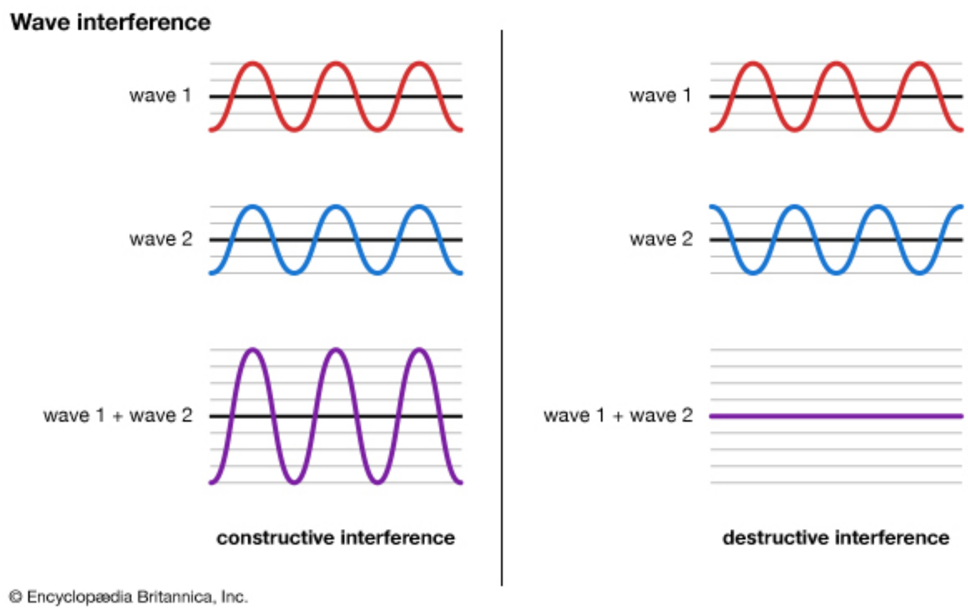


Faraday delivering Royal Institution “Christmas Lecture,” 1855

Luminiferous Ether

Much of Faraday's work centered around the *ether*: an all-pervasive medium filling space, which enabled distinct physical processes to affect one another (interconvertibility of forces). What was the ether?

Thomas Young, ca. 1800: *wave theory of light*



If light consisted of waves, *what were these waves made of? What were they waves in?*

They must have been waves in the

$$\underbrace{\textit{lumini}}_{\text{light}}\underbrace{\textit{ferous}}_{\text{carrying}}\ \textit{ether}\,,$$

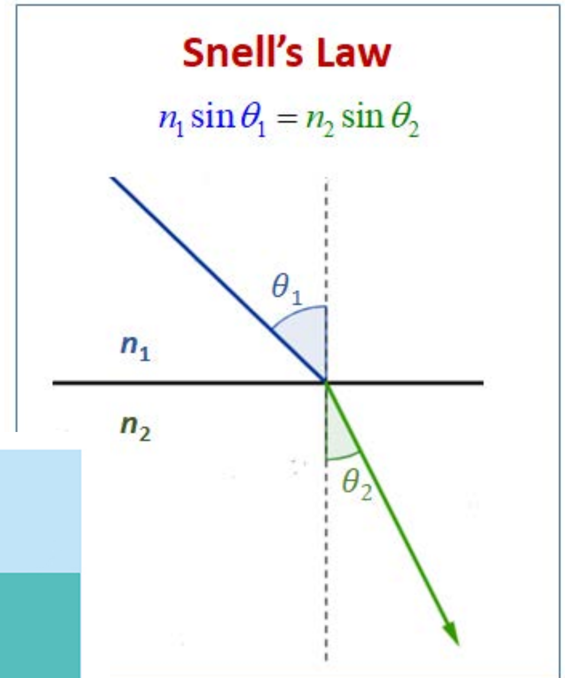
the *medium* in which light traveled.

Luminiferous Ether

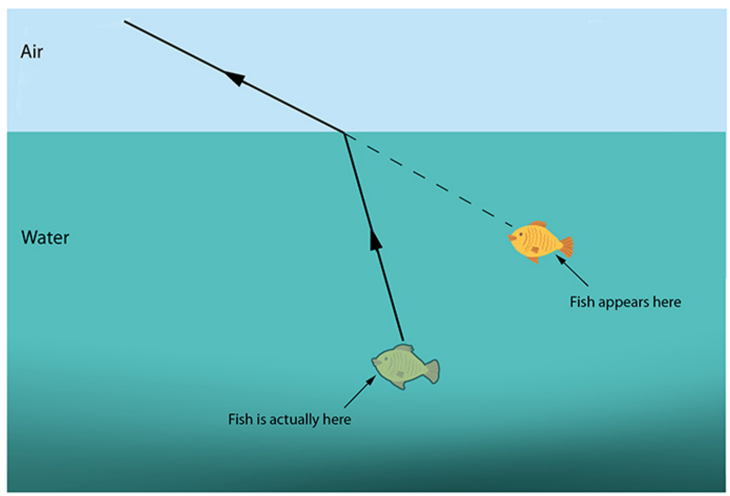
Why should light need a *medium*?

French physicists had found ca. 1800 that the *speed* of light depends on the medium in which it travels (slower in water than air).

n: index of refraction

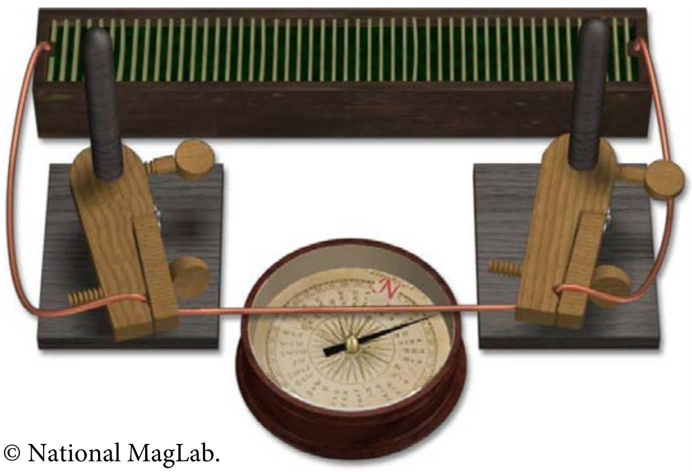


The ether must be the reference medium, with respect to which any local changes are measured: n_0.



Induction

So much for light. What about electricity and magnetism?

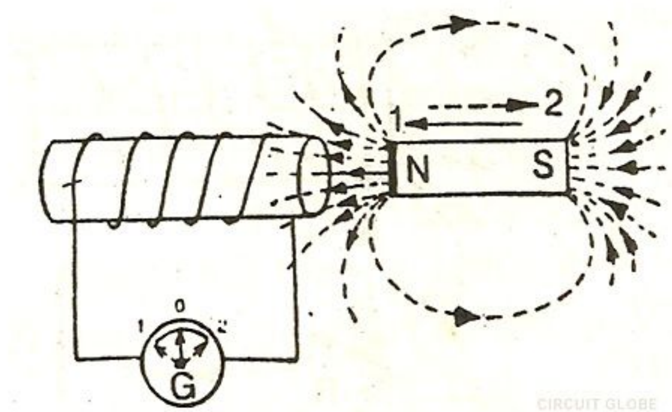


© National MagLab.

In 1820, while giving a public lecture, the Danish natural philosopher *Hans Christian Oersted* accidentally discovered that electric current flowing near a magnetic compass will deflect the compass needle.

Electric currents could induce *magnetic* effects!

This became headline news throughout Europe.* To Faraday, this seemed to be exactly the kind of *interconversion of forces* that he was so interested in. Within months, Faraday had replicated Oersted's finding, and also discovered the *inverse*: Moving *magnets* could induce an *electric* current.



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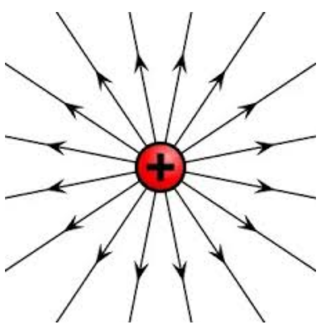
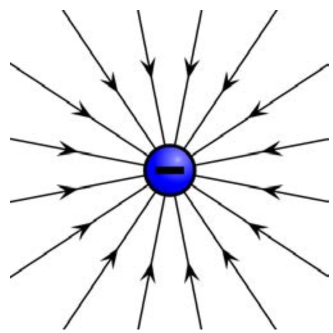
* trending: #TheNeedleMoved

Lines of Force

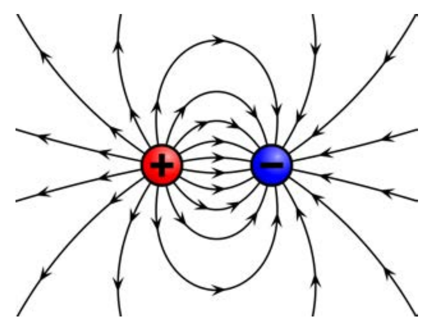
While investigating induction, Faraday began to sketch helpful doodles: *lines of force*, which he thought represented states of *tension* in the underlying *ether*.





The *number* of lines N radiating outward from a positive charge (or inward toward a negative charge) was proportional to the magnitude of the charge.

The *density* of field lines would fall off as $1/r^2$: N field lines would intersect a sphere at any given radius r, so the *number density* would scale like N/A, with $A = 4\pi r^2$.



Reproduced *Coulomb's law* from electrostatics:

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1\, q_2}{r^2}$$

Lines of Force

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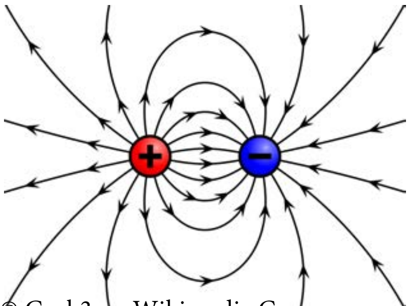

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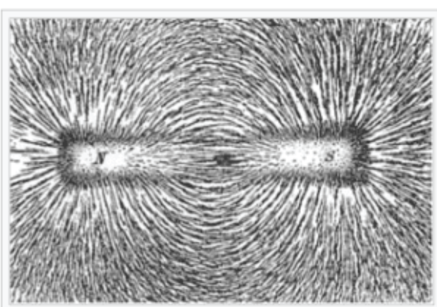
$$F \propto \frac{1}{r^2}$$



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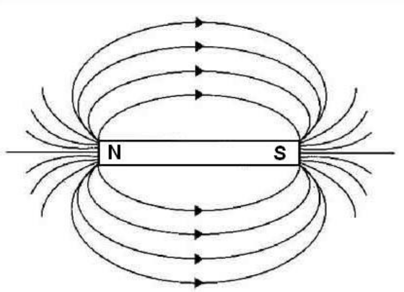

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Magnetic lines of force would diverge from a North pole and converge at a South pole. A further break from Newton: forces did *not* always act along shortest-distance lines between two points.

Lines of Force

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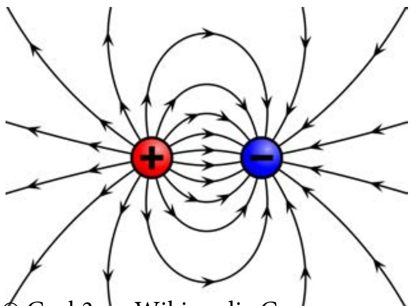

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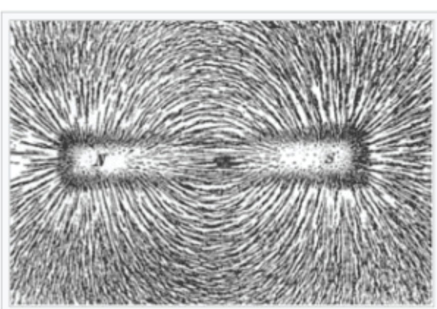
$$F \propto \frac{1}{r^2}$$

Faraday introduced the idea of a *field*. The electric and magnetic fields described the *state of the ether*, as represented by local lines of force: what were the *stresses* and *tensions* in the ether at a particular location, and how did those change over time?



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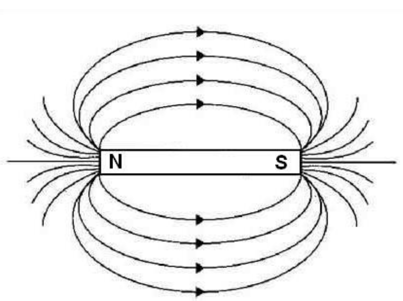

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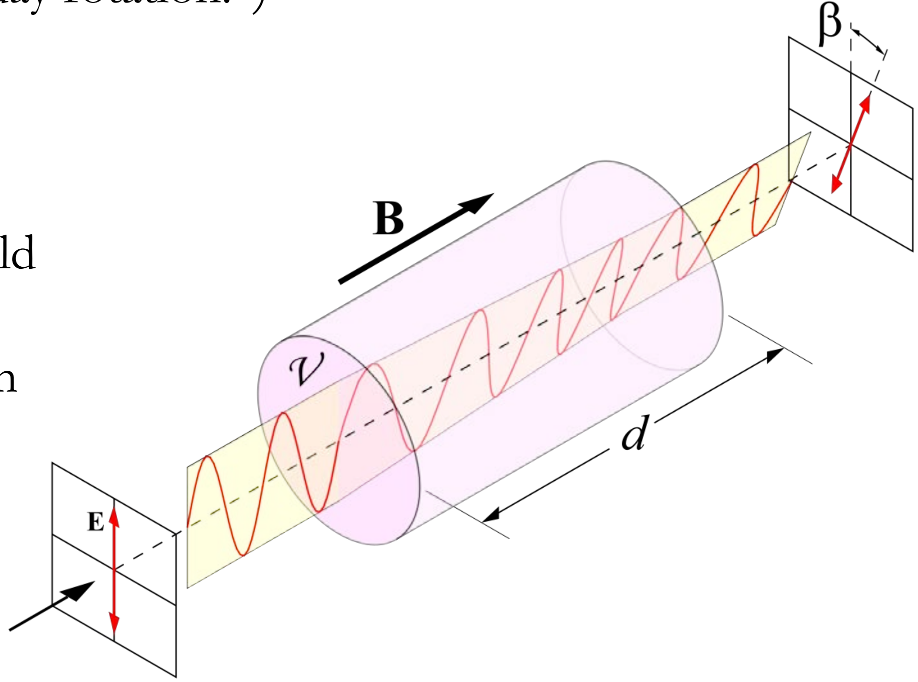
But Was It Real?

In 1845, Faraday thought of a way to demonstrate that the ether was a real, physical substance: he found that a magnetic field will *rotate* the plane of polarization of light. (Now known as the "Faraday effect" or "Faraday rotation.")

To Faraday and his peers, this was striking evidence that the ether must be real: the **B** field was a *twisting strain* in the ether (a kind of torsion), and it deformed the material medium within which light traveled.



Cf. Daschner, Kaiser, and Formaggio, "Exploiting Faraday rotation to jam quantum key distribution via polarized photons," *Quantum Information and Computation* 19 (2019): 1313-1324, arXiv:1905.01359.

Faraday Summary

Michael Faraday worked on a variety of natural phenomena (chemistry, optics, electrolysis, electricity, magnetism ...) with a special interest in the *interconvertibility of forces* — as his Sandemanian religion emphasized, there was an essential *unity of nature*.

He was never trained in mathematics, but was an apprenticed tinkerer who became a leading experimentalist, eventually working at the Royal Institution (rather than at a university).

He introduced *lines of force* and then *fields* as ways to characterize the state of the all-pervasive *ether*, the medium within which natural forces unfolded, and the reason for an underlying unity.

In place of Newtonian "action at a distance," Faraday aimed to explain all physical phenomena in terms of local *fields*, which could convey effects point-by-point throughout the ether.

Questions?

Thomson and Maxwell: Math and Mechanics

Cambridge University, King's Parade, ca. 1870

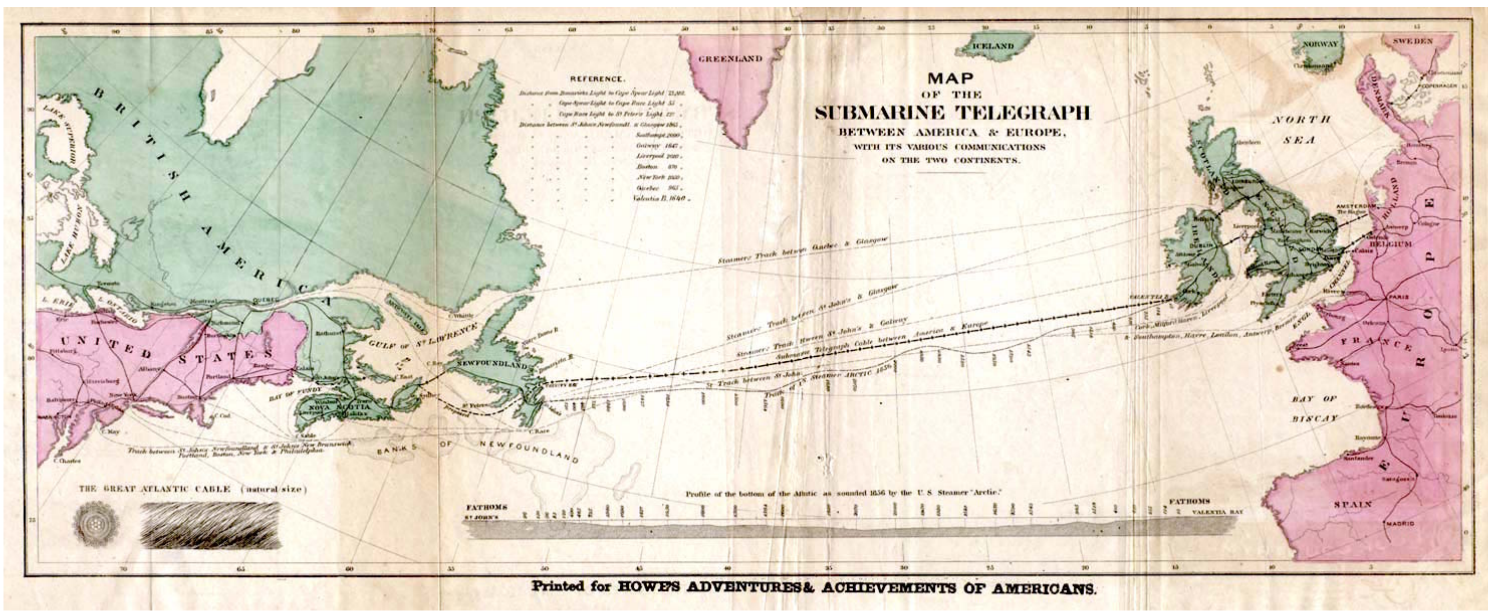
Faraday used very little formal mathematics in his studies — not surprising, since he never studied math beyond elementary geometry. A tremendous shift began in the mid-19th century: a new culture of research centered around intense mathematical training (especially at Cambridge University).

Two products of that new training — *William Thomson* (later *Lord Kelvin*) and *James Clerk Maxwell* — picked up Faraday's pictorial work and translated it into a powerful mathematical formalism. Both were Scottish born and educated at Cambridge in the 1840s and 1850s.

Thomson and Maxwell: Math and Mechanics

Both Thomson and Maxwell became deeply involved with practical engineering applications of the physics of the ether, even as they pursued fancy mathematical approaches.

Most important application: *telegraphy*. Britain was an island with distant colonies; it also sought to strengthen global trading relationships.



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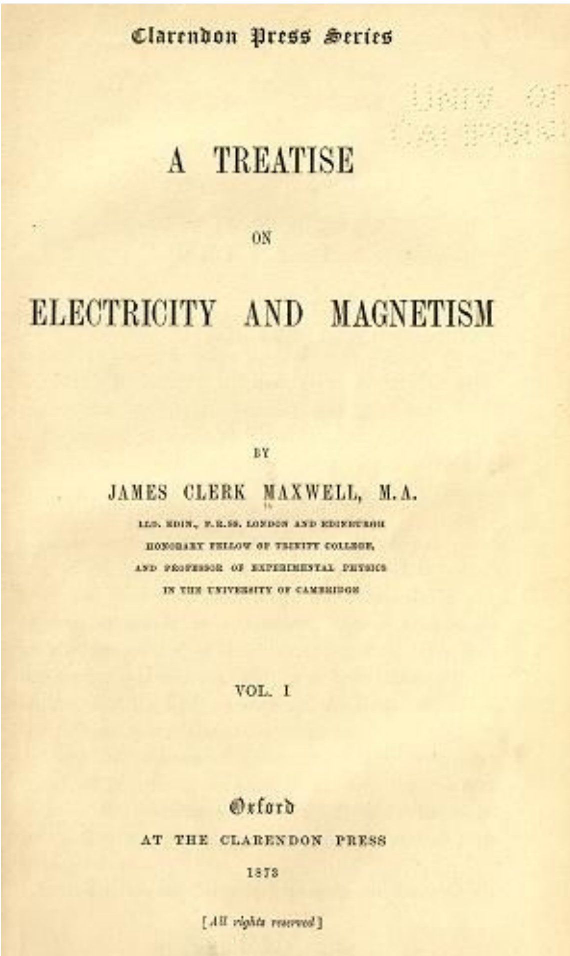
Thomson and Maxwell: Math and Mechanics


Clarendon Press Series

A TREATISE

ON

ELECTRICITY AND MAGNETISM

BY

JAMES CLERK MAXWELL, M.A.

LLD. EDIN., F.R.SS. LONDON AND EDINBURGH

HONORARY FELLOW OF TRINITY COLLEGE,

AND PROFESSOR OF EXPERIMENTAL PHYSICS

IN THE UNIVERSITY OF CAMBRIDGE

VOL. I

Oxford

AT THE CLARENDON PRESS

1873

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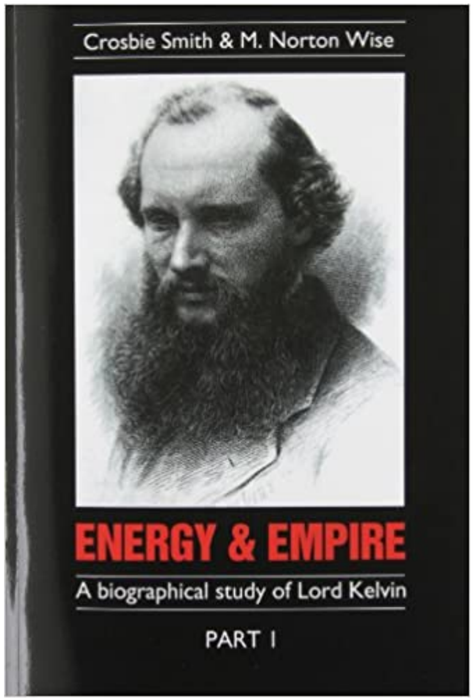
Maxwell, pp. vii-viii: "The important applications of electromagnetism to *telegraphy* have also reacted on pure science by giving a *commercial value* to accurate electrical measurements, and by affording to electricians the use of apparatus on a *scale* which greatly transcends that of any ordinary laboratory. The consequences of *this demand for electrical knowledge*, and of these experimental opportunities for acquiring it, have been already very great, both in stimulating the energies of advanced electricians, and in diffusing among practical men a degree of accurate knowledge which is likely to conduce to the general scientific progress of the whole engineering profession."

Thomson: Mathematical Analogies



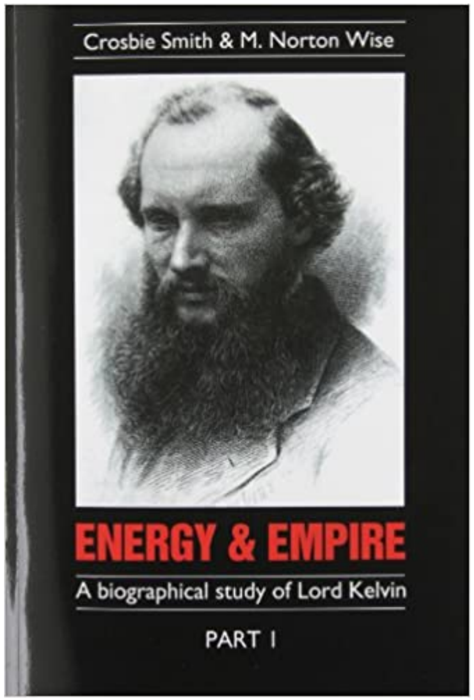
(... it's 892 pages!)

William Thomson read Faraday's papers as an undergraduate. He began to find that Faraday's work on electricity and magnetism and Newton's work on mechanics could be formulated within the *same mathematical structure*. The key was to introduce a *potential*, ϕ.

$$\boxed{\underbrace{\mathbf{F}}_{\textit{vector}} = -\underbrace{\nabla \underbrace{\phi}_{\textit{scalar}}}_{\textit{vector}}}$$

$$\nabla\phi = \left(\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, \frac{\partial\phi}{\partial z}\right)$$

Thomson: Mathematical Analogies



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$$\mathbf{F}_{\text{grav}} = m\mathbf{g}\,,$$
$$\mathbf{g} = -\nabla\phi_{\text{grav}}\,,$$
$$\nabla\cdot\mathbf{g} = -\nabla^2\phi_{\text{grav}} = 4\pi\rho_m$$

mass density ρ_m was the source for diverging lines of the gravitational field

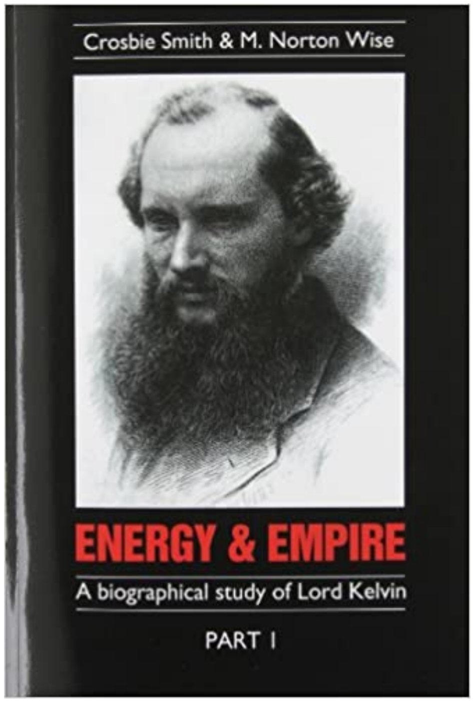
$$\mathbf{F}_{\text{electric}} = q\mathbf{E}\,,$$
$$\mathbf{E} = -\nabla\phi_{\text{electric}}\,,$$
$$\nabla\cdot\mathbf{E} = -\nabla^2\phi_{\text{electric}} = 4\pi\rho_c$$

charge density ρ_c was the source for diverging lines of the electric field

There was a precise mathematical analogy between electric phenomena and mechanics.

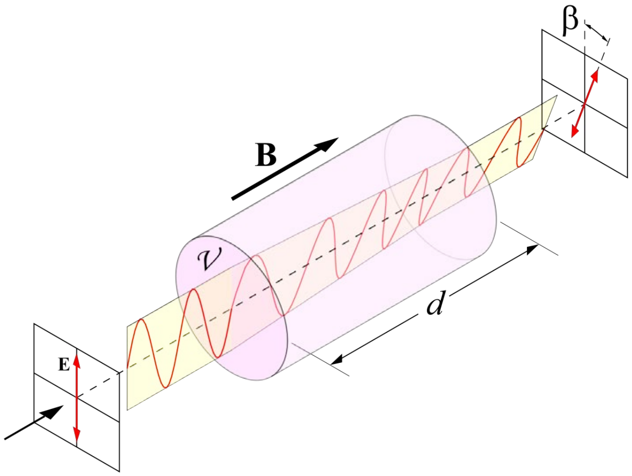
"Laplacian": $$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2}$$

Thomson: Mathematical Analogies



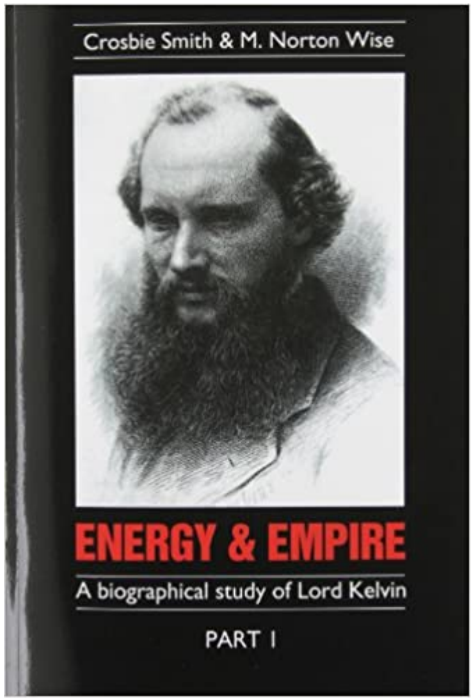
(… it's 892 pages!)

Within one year of Faraday's discovery of the "Faraday effect," Thomson had given *that* a more precise mathematical treatment as well (*while still an undergraduate!*). He introduced a *vector potential* **A** and a new operator, *curl*.



$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$= \hat{\mathbf{x}}\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right) + \hat{\mathbf{y}}\left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right) + \hat{\mathbf{z}}\left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)$$

Thomson: Mathematical Analogies



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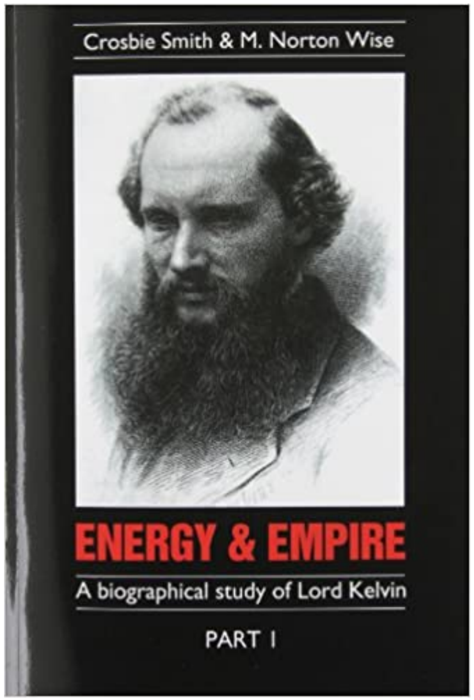
Following Faraday's lead, Thomson interpreted his mathematical result *mechanically*: the ether was an elastic medium which could be put under tension or strain. New mathematical techniques (like *curl*) could *quantify* the medium's response to pressures.

In a famous set of lectures in Baltimore, Thomson encouraged his listeners to get a *feel* for the new physics:

"Stick your hand in a bowl of jelly, and see how it wiggles and vibrates as you move your hand around."

That was what physics was all about!

Thomson: Mathematical Analogies



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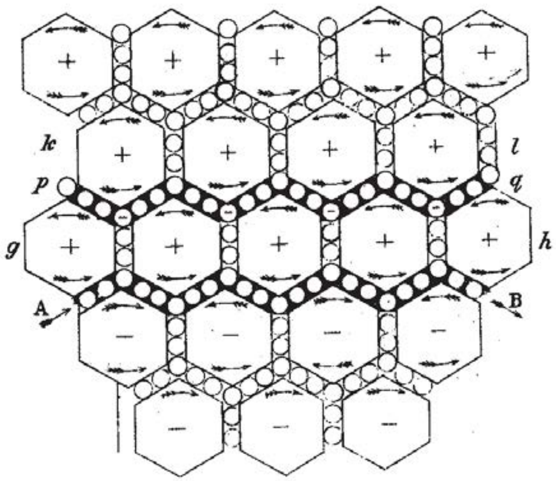
"Mechanical Worldview": If the *math* was the same, then one could model *electromagnetism* on *mechanical models*. And if those models reproduced all the relevant phenomena, then maybe they weren't *only* models. Maybe the ether really was just a mechanical system.

Maxwell: Mechanical Models of the Ether



Maxwell, "On Faraday's Lines of Force," 1856

James Clerk Maxwell was a few years younger than Thomson. He also became steeped in the new Cambridge mathematical approach, and developed further analogies between electromagnetic and mechanical systems.

To model the effects of a magnetic field on the ether, he imagined that the **B** field lines were under tension, and were kept apart from each other by a kind of hydrostatic pressure in an incompressible fluid: "molecular vortices."

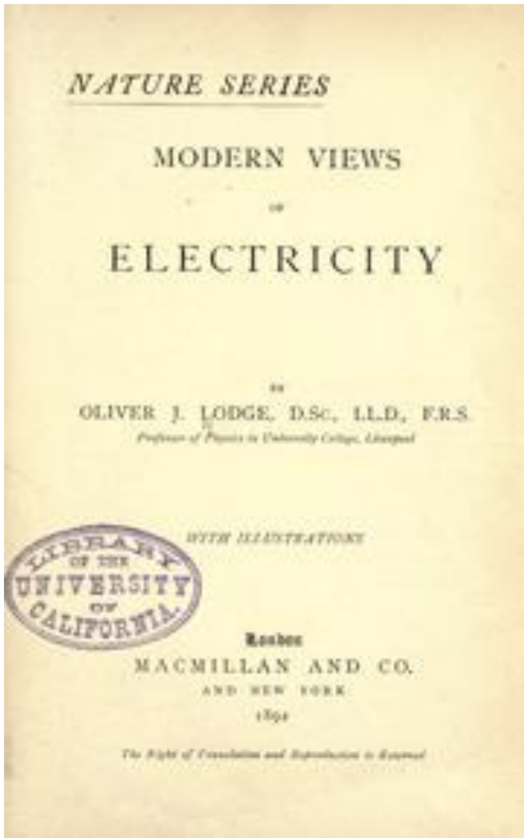
Between the vortices were "idle wheels," which stayed in place but could rotate at different speeds. If an external force changed the *rate* at which one vortex was spinning, that would change the rate of spin of its *nearest neighboring* idle wheels. Those, in turn, would change the rotation speed of *their* nearest neighbors (akin to conveyor belts). All *local* effects, by which a magnetic disturbance could *propagate through the medium*.

Maxwell: Mechanical Models of the Ether

Maxwell, p. 157: The action of one "electrical system" on another is "effected, not by direct action at a distance, but by means of a distribution of stress in a *medium* extending continuously [throughout space]."

Maxwell, p. 164: "The distribution of stress [in the elastic-medium ether] is precisely that to which Faraday was led in his investigation of induction [...]. At every point of the medium there is a state of stress such that there is tension along the lines of force and pressure in all directions at right angles to these lines."

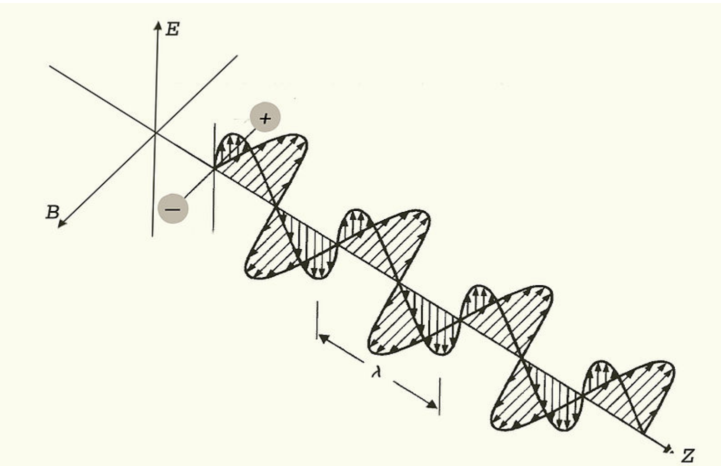
Maxwell: Mechanical Models of the Ether



In a review of Oliver Lodge's follow-up book, *Modern Views of Electricity* (1889), the French physicist Pierre Duhem exclaimed on the British style:

> "Here is a book intended to expound the modern theories of electricity [...]. In it there are nothing but strings which move around pulleys, which roll around drums, which go through pearl beads, which carry weights; and tubes which pump water while others swell and contract; toothed wheels are geared to one another and engage hooks. *We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.*"

Maxwell: Mechanical Models of the Ether



In 1865, Maxwell fixed some parameters in his model (akin to spring constants), based on experimental studies of how **E** and **B** fields behaved. Then he calculated *how quickly* a mechanical disturbance would propagate within his model of the ether, and he found that the fields propagated *at the speed of light:*

"The velocity of transverse undulations in our hypothetical medium [...] agrees so exactly with the velocity of light calculated from optical experiments [...] that we can scarcely avoid the inference that *light consists of the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.*"

Light was nothing other than the propagation of **E** and **B** fields within the luminiferous ether!

Summary

Leading natural philosophers in the 19th century were convinced that the world was made of *very different entities* than what present-day physicists believe: *not* elementary particles in a vacuum, but *mechanical disturbances* in an all-pervasive, elastic *medium*, the "ether."

Until the mid-19th century, leading natural philosophers could enter research careers based on an *apprenticeship model*, and worked in "institutes" or "academies" (with no formal teaching function), *not* at universities.

Faraday, Thomson, and Maxwell each pursued *analogies* between the luminiferous ether and mechanical systems: Faraday with rudimentary geometrical arguments and novel visual aids, Thomson and Maxwell with increasingly sophisticated mathematical tools. They became convinced of a "mechanical worldview": electromagnetic effects were *at root* mechanical. Moreover, local causes yielded local effects: no "action at a distance."