19th-Century Electrodynamics:

Current Electricity and Electromagnetic Theory

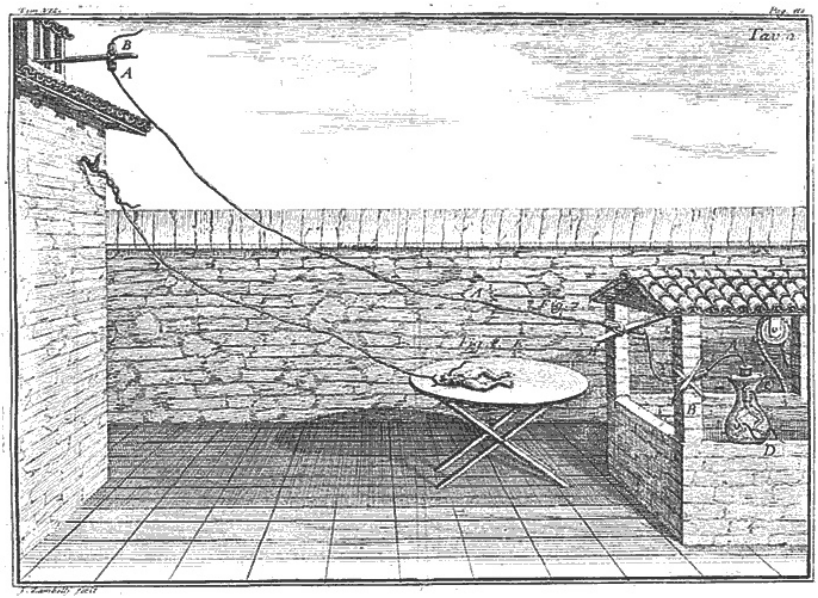
Waseda University, SILS,
History of Modern Physical Sciences

Galvani's Frogs

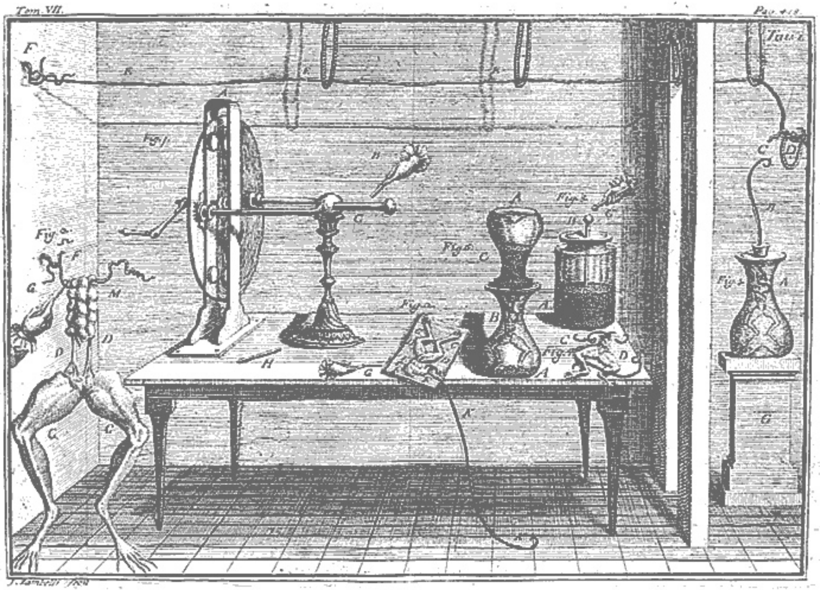
In the 1780s, Luigi Galvani (1737–1798) showed that frogs legs would twitch when sparked. He set up an experiment to test B. Franklin's theory of lightning. He hung frog's legs on a grounded metal trellis when there was a storm. But he noticed that the legs moved even when there was no storm. They moved whenever the organic tissues were in contact with *two different metals at the same time*. He attributed the motion to a *vital fluid* – that is, some kind of special life-giving fluid – called *animal electricity*.

In Galvani's theory, this special electricity was the source of life and motive power in animals. The living organism was a kind of Leyden jar. Galvani gave an account of voluntary motion based on the charged state of the muscle surfaces and nerves.

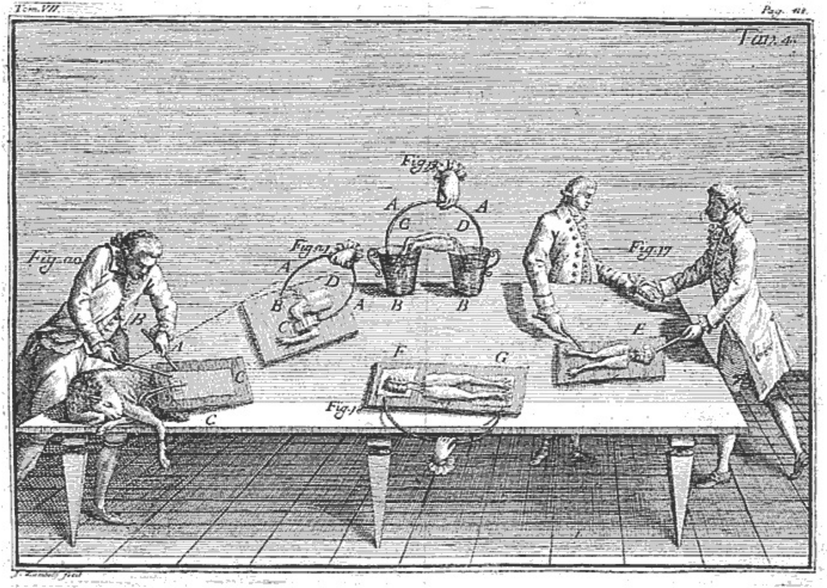
Galvani's work had a strong influence on the Romantic philosophers and writers – for example, M. Shelly's (née Wollstonecraft) *Frankenstein* (1818).



Galvani's apparatus for experimenting with "natural electricity"



Galvani's apparatus for experimenting with "artificial (static) electricity"



Galvani's experiments with "animal electricity"

Volta's Doubts

Alessandro Volta (1745–1827) was not convinced that the *galvanic force* was a new explanatory principle. He believed that the motion of the frogs was caused by the same kind of electricity as was found in *other natural processes*.

He set up new dissections which removed the analogy with the Leyden jar and showed that the motion was a direct result of contact with the nerves on two *different* metals. He was struck by the necessary role of the metals. He began to investigate the behavior of metals in his mouth. He found he could produce a sour taste and tingling sensation as long as two different metals were used (silver and tin or copper, and so on).

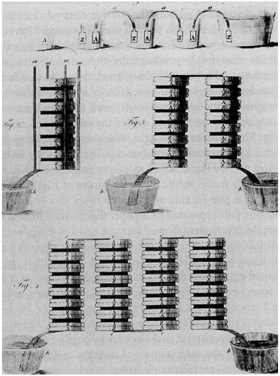
He found that similar effects could be produced when one metal touched two different fluids. He concluded that the cause of these effects was the very same electrical force found in other natural processes.

Volta's Pile

Volta noticed that if the components were joined in a circuit from one end of the apparatus to the other, a new kind of electrical effect could be produced – a continuous charge, as though from a Leyden jar which never "ran dry."

Volta discovered that the strength of the continuous charge could be increased by alternating metals and fluids. This lead to the first *Voltaic Pile* (wet cell battery).

It was quickly discovered that the effect could be increased by joining multiple piles in series. The pile was very easy to reproduce and spread rapidly through Europe. Volta became famous and toured Europe demonstrating his pile.



The voltaic pile

Volta demonstrating his pile to Napoleon (by G. Bertini)

The Debate about Causes

The invention of the battery turned research away from questions of animal physiology. The focus now became on increasing the strength of the battery and exploring its properties.

The battery appeared to be a source of electrical fluid, and the question of *how* the fluid was produced became key. Volta and Galvani held that metallic contact was the source. Most English natural philosophers, however, claimed that the electrical fluid was produced by a chemical reaction.

They began to study the chemical aspects of the process.

Humphry Davy (1778–1829)

Humphry's father was a wood carver. The boy was apprenticed to an apothecary (pharmacist), and taught himself chemistry from books and carried out his own experiments.

He was apprenticed to Beddoes at the *Pneumatic Institution*. Here, he came into contact with the radical politics and philosophy of the English dissenters. He also developed close ties with the Romantic writers. Their philosophy had a lasting effect on his work.

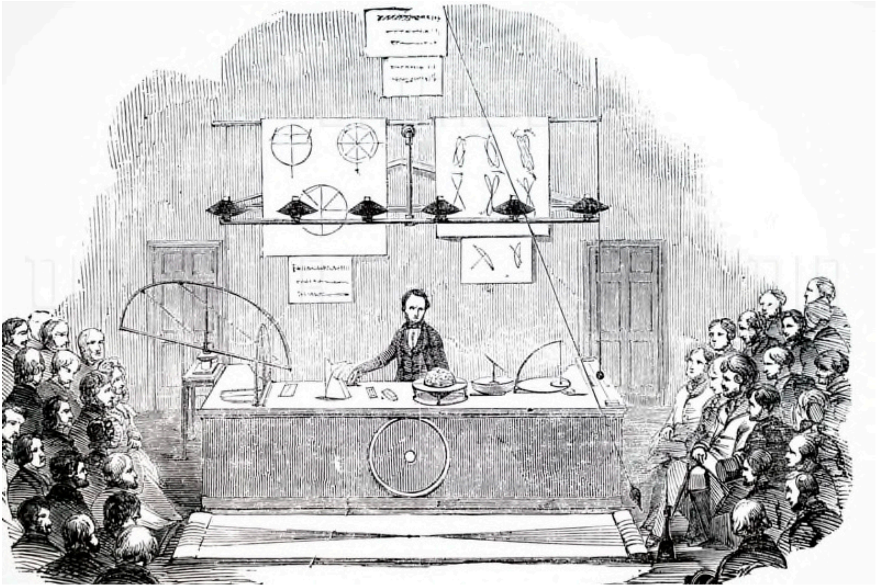
He worked at, and headed, the Royal Institution. He brought Micheal Faraday into science but had a hard time appreciating his skills. He became very famous and successful.

The Royal Institution, founded by Count Rumford and leading scientists such as Cavendish, received its charter from George III in 1800. Its goals were

> "… the general diffusion of the knowledge of all new improvements, in whatever quarter of the world they may originate; and teaching the application of scientific discoveries to the improvement of arts and manufactures in this country, and to the increase of domestic comfort and convenience."

Its functions were to retain research scientists provided with research facilities, and to bring new scientific developments to the public attention. It disseminated knowledge through publications and especially lectures, with an emphasis on practical science, of benefit to everyone. The presence of Davy, and later Faraday, made the Royal Institution one of the most important research facilities in Great Britain in the 19th century.

The Royal Institution, cartoon by James Gillray, 1802



A Friday Evening Discourse at the Royal Institution,
Baden Powell, mathematics, first half of the 19th century

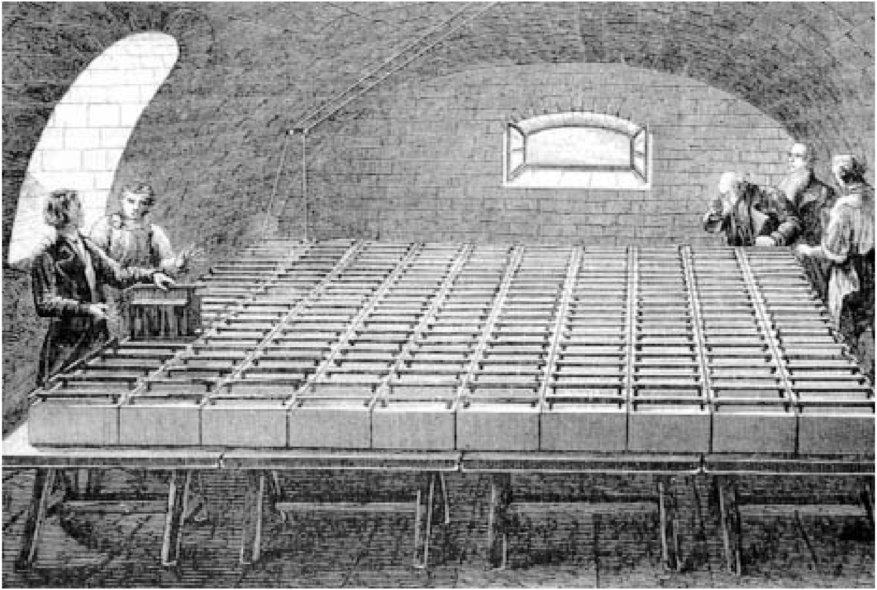
A Friday Evening Discourse at the Royal Institution, 1904

Davy at the Royal Institution

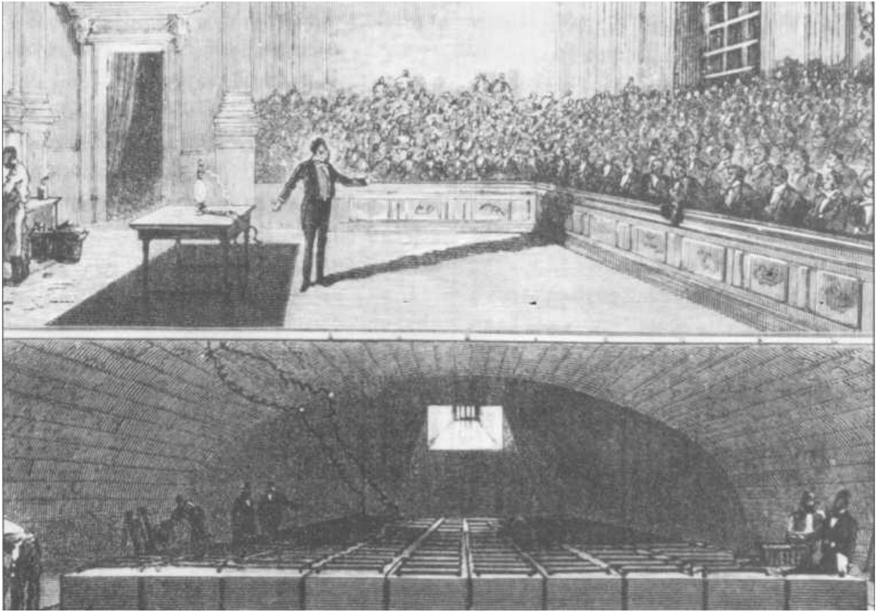
Davy's appointment was key to the early success of the Royal Institution. He was appointed as an assistant and eventually became the head of the Institution.

He was a wildly popular lecturer with a showman's flair. When he gave a Friday Evening Discourse, the lecture halls would be packed, while people who could not get in waited outside on the streets to hear secondhand reports about what had happened.

He produced ever more extravagant demonstrations of the power of the electro-chemical effect using bigger and bigger batteries.



A wet cell battery in the basement of the Royal Institution

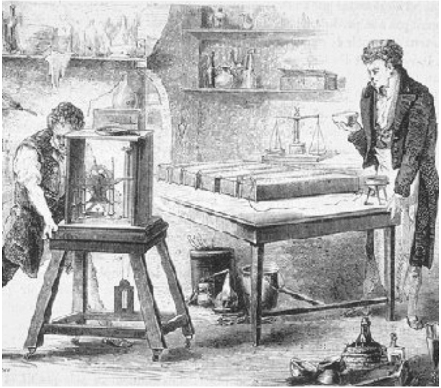


Davy demonstrating an arc light bulb at the Royal Institution

Electrical Analysis

Davy was one of the most successful chemical *analysts* of his time. He used Lavoisier's ideas about simple substances and *laboratory analysis* to greatly expand the list of known elements.

Whereas most chemists relied on heat to break up compounds, Davy used the currents generated by his batteries. He produced a series of every larger and more powerful batteries, applying the current to a variety of substances and observed how the substances reacted to the charge.



Electro-Chemistry

Davy was able to show that different elements or compounds react in chemically different ways to electrical charge: some chemicals go to one pole (electrode), some to the other; some would decompose with little current, some required much more. This made it possible to rank substances (or radicals) according to their *charge* (positive or negative) and *affinity* (intensity of charge).

Davy used these methods isolate a large number of new simple substances – such as sodium, potassium, barium, strontium, calcium, magnesium, and so on.

He also analyzed and named the substances chlorine, fluorine and iodine. He showed that they had closely related chemical properties. They formed a natural group, the *halogens* – they are highly reactive, form salts with metals, and so on.

The Unity of Nature

Davy was deeply impressed by the relationship between electricity and chemical affinity. He believed that there must be a *single force* underlying all nature, and that it was the natural philosopher's task to investigate this force *empirically*, just as the poet did so *intuitively*. He did not believe that his simple substances were elements, but that matter was simply the manifestation of this single unifying force.

In this, he was influenced by the idealist philosophy of Immanuel Kant and German *Naturphilosophie*. Kant, in his *Critique of Pure Reason* (1781), had argued that we have no access to things as they are in and of themselves, and hence have no warrant for supposing that sub-sensible bodies are like sensible ones. In *Metaphysical Foundations of Natural Science* (1786), he asserted that all matter may simply be the manifestation of force – a unity of all force. (Kant's works were translated into English by S.T. Coleridge, the romantic poet.)

Electricity and Magnetism

During the 1820s, Hans Christian Ørsted (1777–1851) demonstrated the relationship between electricity and magnetism. Ørsted was educated in Germany and became strongly influenced by German *Naturphilosophie*. When he returned to Denmark he established a tradition of experimental physics at Copenhagen University.

H.C. Ørsted, 1813

"One has always been tempted to compare magnetic forces with electrical forces… An attempt should be made to see if electricity, in its most latent stage, has any action on the magnet as such."

In 1820, during the course of a lecture on electrical phenomena, he set a compass needle parallel to a platinum wire carrying current. The needle was deflected at right angles to the wire. When Ørsted changed the direction of the current, the needle deflected in the other direction.

The Electromagnetic Effect

Ørsted's discovery of the effect had far reaching results. The French (that is, the Laplacians) could no longer maintain the independence of magnetic and electric fluids. No one knew what to do with the fact that the force appeared to be *circular*.

André-Marie Ampère (1775–1836) and François Arago (1786–1853), who were anti-Laplacians, like most electrical experimenters in Europe, began to investigate the interaction of these forces. They found that current could be passed through a wire wrapped around an iron core to produce an electromagnet.

- Ampère showed that two wires carrying current produced a magnetic effect on one another.
- Parallel wires will attract one another if the current is in the same direction; repel, if in the opposite direction.

A New Kind of Force

In the Newtonian research programs of the 18th and early 19th centuries, forces were always described as acting from one body to another *in straight lines*. Laplace had held this to be a basic principle of physical science.

The electromagnetic effect, however, appeared to defy this model.

An electrical force moving in one direction appears to be *wrapped in a circular magnetic force*. The magnetic poles have no absolute position, only direction. The direction of the poles is always the same relative to the direction of the current.

Some theorists attempted to reduce these forces to Newtonian action at a distance. Micheal Faraday, however, took these features as fundamental properties.

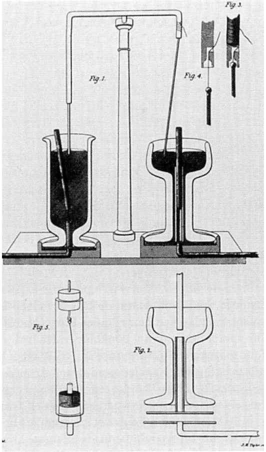
Michael Faraday (1791–1867)

Faraday was born to the family of a blacksmith. He was apprenticed to a bookseller, during which time he heard Davy lecture. He was a member of a strict Protestant sect and never sought material advancement. He came to work at the Royal Institute as an assistant and slowly worked his way up. He was associated with the Institute his whole life. He took over the lectures and started new series for broader audiences.

He became a meticulous experimenter, working on electromagnetism and chemical affinity. His work was more profound than Davy's and this produced friction between them. Although Faraday had no advanced mathematics, he laid the foundations for the theory of electromagnetism.

Faraday at work in the laboratory of the Royal Institution

Faraday lecturing at the Royal Institution



Shortly after Ørsted discovered the electromagnetic effect, Faraday was asked to write a report on the "history" of electromagnetism. So much had been done that Faraday found it difficult to sort out who had done what, so he repeated all of the experiments himself. He set up an experiment to physically demonstrate that the electromagnetic force was a *rotational force*.

He used an electrical current to produce mechanical motion. On the left hand side, a free magnet (set into a ball and socket joint) can rotate around a fixed wire. On the right hand side, a rigid wire is free to rotate around a fixed magnet. The cups are filled with mercury. When the current is turned on, the magnet and the wire rotate.

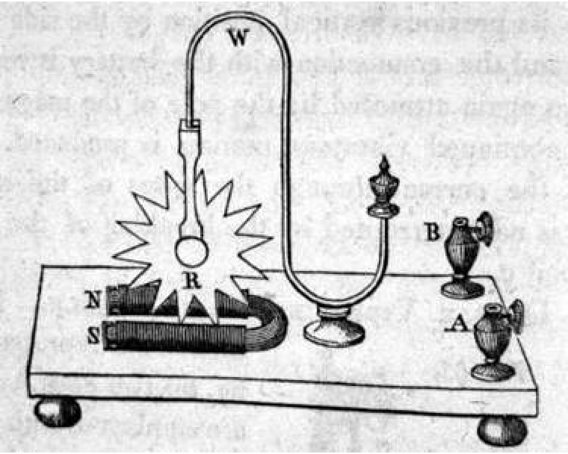
The Impact of the *Rotations*

Faraday's rotations were a huge success. They made his reputation in Europe. They demonstrated that electricity could be used to produce *motion* – that it was equivalent to *mechanical work*.

In the next year, Barlow made the first *philosophical motor* (electrical motor).

Davy was upset, he believed Faraday had stolen the idea from a conversation he overheard. This hardly mattered, however, because Faraday was just getting started.

Barlow's Wheel



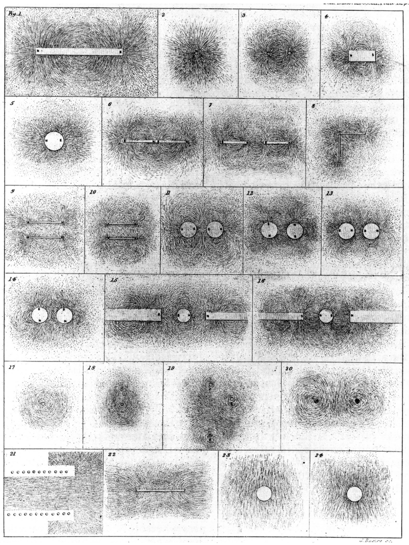
Current comes in at A, goes under the board to W, through axis of the wheel, R, and into a grove filled with mercury. Then it goes through the two coils of the electromagnet and under the board to B, and out.

Revealing Hidden Forces

Faraday set about to try to produce an electric current with a magnetic effect. He wound two separate coils around opposite sides of an iron ring. He attached one coil to a battery and the other to a galvanometer. He was surprised by the result: when he closed the circuit the needle jumped, but only for moment. It, then, settled down and only jumped again when he opened the circuit. There was no steady current in the secondary coil. Current was only produced by change in the first current; hence, change in the magnetic field.

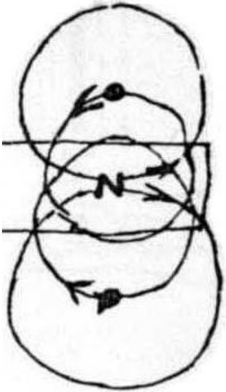
He developed a new model to explain the phenomena. He pointed out that iron filings, scattered on a paper held over a magnet, will arrange themselves in distinct patters along what he called the *magnetic lines of force*. He argued that when he closed the circuit on his coil new lines of force were created which moved across the other coil. When he opened the circuit they moved in the opposite direction.

Iron filings on paper above a magnet



Faraday's illustrations of iron filings

The Electromagnetic Field



He demonstrated the same effect in a different way, by winding a coil around a ring and attaching it to a galvanometer. When he moved a magnet inside the coil the needle moved. When the magnet was still, the needle was still. *Relative movement was necessary to produce a current.*

Current, in fact, could be understood as movement within an *electromagnetic field* – a term Faraday introduced in 1845.

He developed the idea that all of space is filled with electromagnetic *lines of force*, forming a continuous field. Magnetic poles, static electrical charges, and moving currents cause the lines to deflect. The field is characterized by the displacement of a theoretical point-charge.

A New Role for Ether

Faraday proposed that the lines of electromagnetic force were acting in some kind of underlying medium, which he took to be the same *ether* that was invoked in the wave theory of light. He sought to link the phenomena of light and electromagnetic induction, and found that polarized light could be affected by magnetic lines of force. (Later, Faraday began to move away from the ether model.)

Despite the brilliance of Faraday's work, it included no higher mathematics – and hence, no way of predicting the phenomena, and no way of precisely testing the model.

The French school, especially the Laplacians, attempted to model electrical phenomena by point charges and rectilinear forces, and to reduced Faraday's curved lines of force to some underlying rectilinear model. The Germans modeled the behavior of assumed particles of electricity.

Thomson' Analogy: Electrostatic Force and Heat Flow

In 1842, at 18, William Thomson gave an analytical theory of electrostatic phenomena, by making an analogy between an electrostatic field and heat flow in a solid body and modeling them both with the equations of fluid dynamics.

The field	=	An unequally heated body
A dielectric medium	=	A body conducting heat
A conductor	=	A *perfectly* conductive body
(+) particles move from from higher to lower potential	=	Heat flows from higher to lower temperature
(-) surface of conductor	=	Surface where heat enters
(+) surface of conductor	=	Surface where heat leaves
(+) charged body	=	Heat sink

Thomson's Work on Electrodynamics

Next, in 1846, Thomson published a paper on electrodynamics that introduced a mathematical method of modeling the way that a magnetic force wraps itself around a current – the *curl operator*. Thomson's style of theorizing was strongly physical. He tried to reduce the *ether* to explanations drawn from known phenomena: jellies, waxes, pulleys, "wigglers," pumps, gears, and so on.

Thomson's theories of electrodynamics, and his style of doing theoretical physics became increasingly marginalized as the 19th century progressed. Following Maxwell, and the "Maxwellians," the younger generation of physicists preferred to allow the mathematical model to act as a description of an *unknown reality*.

James Clerk Maxwell (1831–1879)

Maxwell came from a noble Scottish family, son of a lawyer and Laird of Glenlair. He was educated at Edinburgh and Cambridge (2nd Wrangler), worked as a professor and first director of the Cavendish Laboratory, but died young of intestinal cancer.

He made a new theory of colors which incorporated the work of Newton, Goethe and Helmholtz and linked the physics of color perception to the physiology of the eye. He worked on the theory of thermodynamics. He developed a full theory of the electromagnetic field which predicted the relationship between light and electromagnetism.

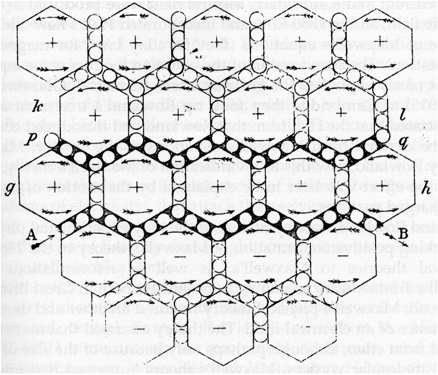
J.C. Maxwell at 23

Maxwell's 1st Theory of the Electromagnetic Field

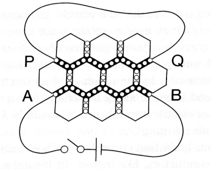
In 1861, Maxwell put out a new theory which predicted novel, potentially testable, experimental results. The first of these was *displacement current*, the effect already produced by Faraday, but unexplained in current theories. The second was the prediction of self-propagating transverse waves of electromagnetic force moving in the ether at the *speed of light*. It did away with the idea of an electrical fluid. Instead, all electromagnetic phenomena would be determined by the state of the medium, the ether.

The basis of Maxwell's 1st theory were spherical cells made up of the matter of ether and packed into space. The tendency of the cells to either spin in a stationary position or to move from place to place depended on their placement in a conductor or dielectric. All of space was packed with large *vortex cells* between which were packed smaller *idle wheels*. When the rotational velocity of the vortex cells changes, the idle wheels are moved causing current.

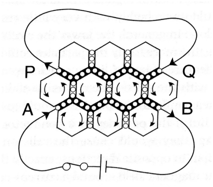
Maxwell's 1st Theory



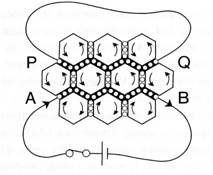
Maxwell's diagram



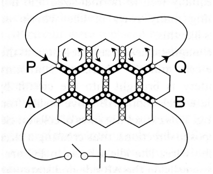
1: current off



2: turning on



3: current on



4: turning off

Maxwell's Treatise, and his 2nd Theory

In 1873, when he was at the Cavendish, Maxwell published *A Treatise on Electricity and Magnetism*. The style of presentation was almost personal, presenting a chronological and experimental account of his investigations and theorizing since the 1850s. It struck many readers as badly organized. He advised his readers to approach the four sections in parallel readings, not in sequence. Nevertheless, it contained a new and highly abstract theory of electromagnetism.

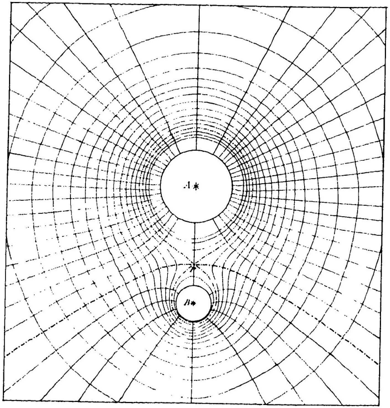
The new theory was built directly on a mathematical conception of the underlying dynamics. *There was no attempt to create a mechanical model*. The basic principles of Maxwell's theory are now expressed in *Maxwell's equations* – actually written up by Heaviside. Maxwell first expressed the basic laws of the electromagnetic field verbally *in a footnote*.

Maxwell's Laws of Electromagnetic Force

(1) Electric force at a point has no inward or outward tendency.
(2) Magnetic force at a point has no inward or outward tendency.
(3) Changing magnetic force wraps an equal circular electric force around itself.
(4) Changing electric force wraps an equal circular magnetic force around itself.

(1) and (2) imply that it is the field itself, not point charges in the field that create divergence, computable as the inverse square. In (3) and (4) there is a constant, computable to the speed of light, that links the change in space to the change in time.

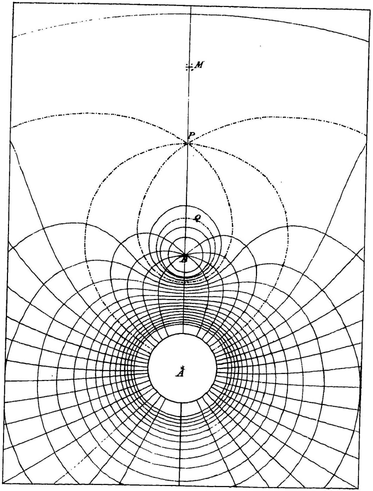
From these, Maxwell developed a system of equations which described all electromagnetic phenomena in terms of an abstract electromagnetic field – *thought to be situated in the ether*. The physical properties of the ether were simply assumed to be those expressed by the equations themselves.



Lines of Force and Equipotential Surfaces.

$A = 20$. $B = 5$ P. Point of Equilibrium. $AP = \frac{2}{3} AB$.

Lines of force around two (+) spheres



Lines of Force and Equipotential Surfaces.

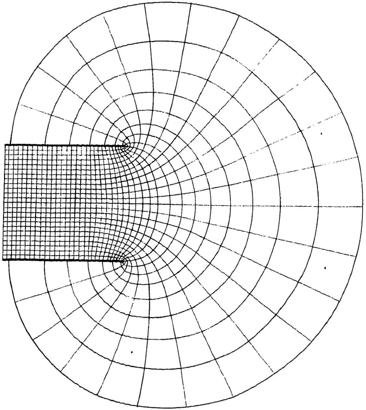
$A = 20$ $B = -5$ P, Point of Equilibrium. $AP = 2 AB$

Q, Spherical surface of Zero potential.

M, Point of Maximum Force along the axis.

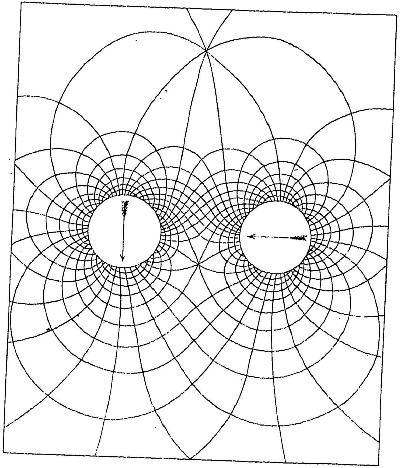
The dotted line is the line of Force $\Psi = 0.1$ thus.

Force around a (+) sphere and (-) point



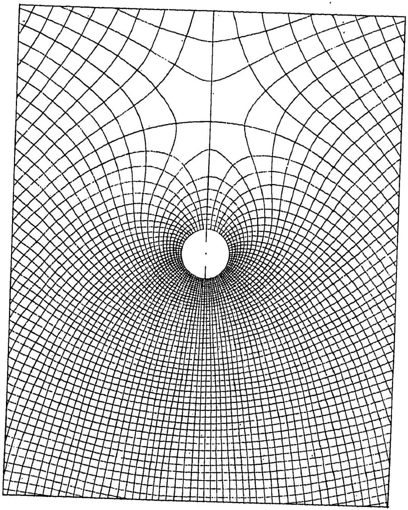
Lines of Force between two Plates.

Lines of force between charged plates



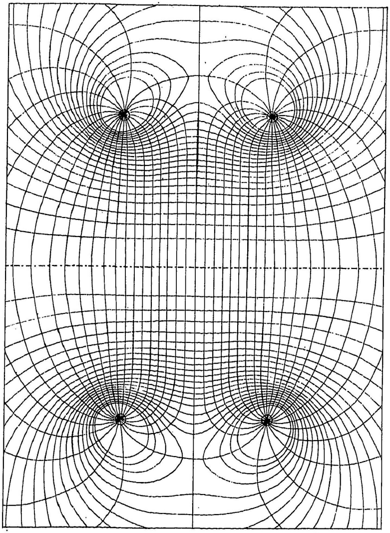
Two Cylinders magnetized transversely.

Two magnetized cylinders



Uniform magnetic field disturbed by an Electric Current in a straight conductor.

Magnetic field around one current



Two Circular Currents.

Around two circular currents

The "Maxwellians"

Because of Maxwell's early death, the defense of his work was taken up by younger men – F.S. FitzGerald, O. Lodge and O. Heaviside, and later H. Hertz – known as the "Maxwellians." They advocated the usefulness of Maxwell's theory to practical applications in the new electrical industries, and made a revised versions of the theory using vector calculus.

FitzGerald in a letter to Thomson

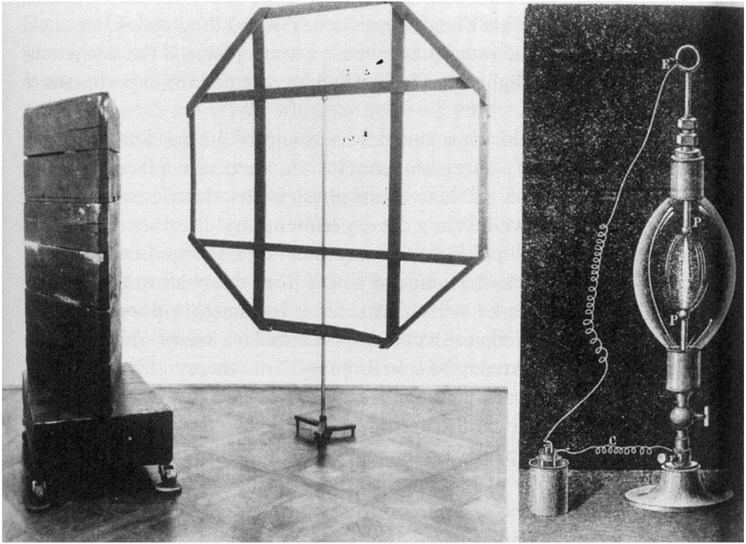
"You say… *We must imagine a luminiferous ether to be a substance which…moves as if it were an elastic solid*. Now this *we must* is entirely unjustifiable… I cannot see how you are justified in concluding that we must deal with the ether as if it were an elastic jelly. The electromagnetic properties of the ether are much better keys to its properties than light waves, and I cannot see, nor apparently can you, how it can be both electric and magnetic and at the same time an elastic solid."

Testing the Theory

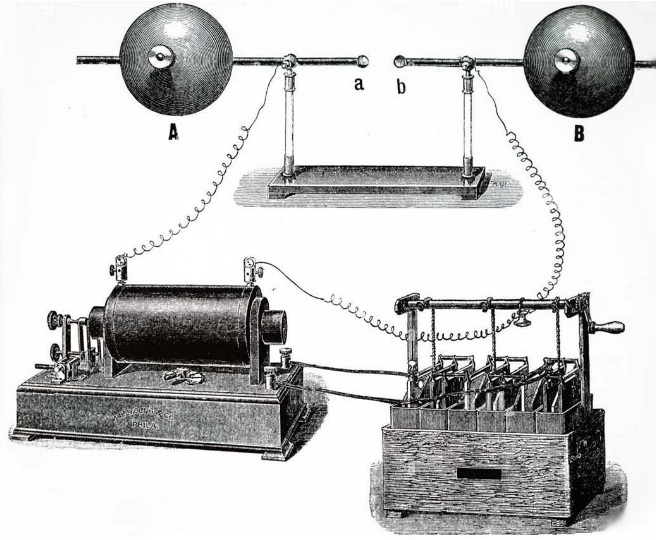
The theory was empirically tested by looking for evidence of the ether, as Michelson and Morely, and by trying to produce electromagnetic waves, as Hertz.

In 1886, while teaching as a Privatdozent at Kiel, Heinrich Hertz (1857–1894), who had been a student of Hermann von Helmholtz, was able to produce electromagnetic effects at a distance, which were propagated by electromagnetic waves with a large wave length – that is, radio waves. He was able to measure the speed of these waves in his lecture hall and found that they had the same velocity as light.

Helmholtz announced the discovery to the Berlin Physical society saying: "Gentleman! I have to communicate to you today the most important discovery of the century."



Hertz's first electromagnetic wave apparatus



Hertz's radio wave apparatus

Overview

- We saw an example of how a simple discovery can lead to an entirely new field of knowledge. In the modern sciences, theories are developed in conjunction with *new tools*. There is no such thing as sustained electrical current *in nature*.
- There is an interplay between cultural, philosophical and artistic ideas and the sciences. We see how philosophical commitments can direct scientific work and even effect what people *see*.
- We see the rise of an increasingly abstract and mathematical approach: the development of a predictive mathematical theory and the further claim that this is our best approach to the things *as they are*.
- We see the introduction of the concept of the *field*, a non-Newtonian, non-Laplacian concept – this leads to a solidification of the 19th-century worldview of ether.