The Chemical Revolution
Lavoisier, Davy and Faraday

Scientific Revolution

The Scientific Revolution is a term commonly referring to the transformation of thought about nature through which the Aristotelian tradition was replaced by so-called "modern" science.

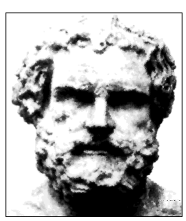
Chemical Revolution

The Greek Philosopher Democritus

- The Greek philosopher Democritus began the search for a description of matter more than 2400 years ago.
- He asked: Could matter be divided into smaller and smaller pieces forever, or was there a limit to the number of times a piece of matter could be divided?

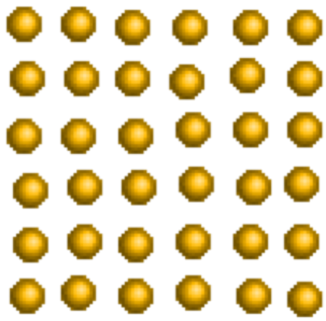
460-370 BC

Atomos



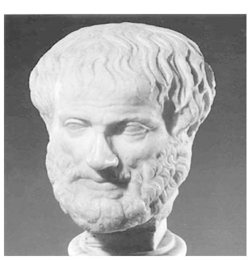
- His theory: Matter could not be divided into smaller and smaller pieces forever, eventually the smallest possible piece would be obtained.
- This piece would be indivisible.
- He named the smallest piece of matter "atomos," meaning "can not be cut."

Atomos



- To Democritus, atoms were small, hard particles that were all made of the same material but were different shapes and sizes.
- Atoms were infinite in number, always moving and capable of joining together.

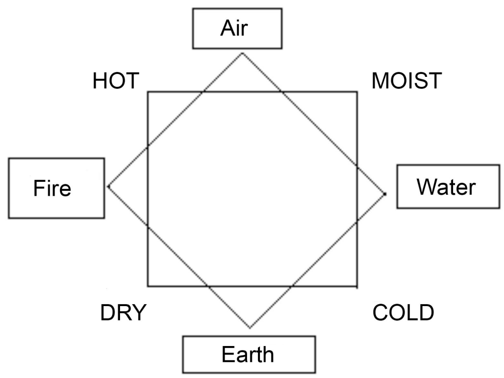
The Greek Philosopher Aristotle



384-322 BC

- Aristotle did not like the idea of matter containing so much empty space.
- Believed that matter could be continuously divided without end (the "continuous" idea of matter).
- There is no need for empty space.
- There are no atoms. All matter is made of the natural elements (**earth, water, air and fire** (and aether).

The four elements of ancient times.



- All matter is made up of these four elements
- The above four elements are transmutable

The Asiain View (*Taittirīya Upanishad* and *Aitareya Upanishad*, 6th century BC Even before Aristotle)

Four (five) interconvertible elements make up the earth

Pancha Bhoota (Sanskrit: पञ्चभूत), five great elements, which, according to Hinduism, is the basis of all cosmic creation.

- **Prithvi** (Sanskrit: पृथ्वी:, Earth),
- **Jal** (Sanskrit: अप:, Water),
- **Agni** (Sanskrit: अग्नि, Fire),
- **Vayu** (Sanskrit: वायु:, Air),
- **Akasha** (Sanskrit: आकाश, Space).

Ancient Indian Atomistic Thoughts

Kashyap (Acharya Kanada)

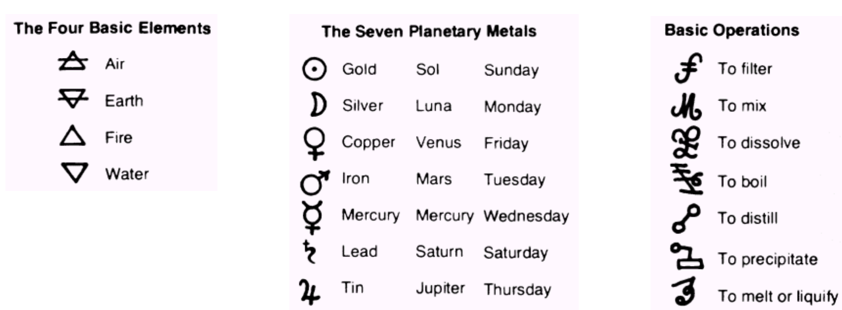
- Vaisheshika school of philosophy
- *Vaisheshika Sutras*
- 6th century BC

Every object of creation is made of atoms (paramāṇu) which in turn connect with each other to form molecules (aṇu). Atoms are eternal, and their combinations constitute the empirical material world.

The similarity of the early Indian views of matter with the Greek models have led historians to wonder if communication occurred between the philosophers in these early civilizations.

Alchemy (next 1500 years)

- Mixture of science and mysticism.
- Lab procedures were developed, but alchemists did not perform controlled experiments like true scientists.



Alchemists
300 BC to 17th century
Arabian origin but was prevalent world over

- **Transmutation of metals**
- **Philosophers stone**
- **Elixir of life**
- **Interconversion of minerals**
- **Looking for medicines**

Alchemists attempted to transmute cheap metals to gold. The substance used for this conversion was called the *Philosopher's Stone*.

The Aristotelian tradition and medieval alchemy eventually gave rise to modern chemistry

European and Asian philosophers

Alchemists

Phlogistonists

Modern chemists

History of the Atom Timeline

Democritus 460 BC and Dalton 1803 AD | Thomson 1897 | Rutherford 1912 | Bohr 1913 | Modern Quantum Cloud Model post 1930

The Atomos theory of Democristus was ignored and forgotten for more than *2000* years in favor of Aristotle's four element theory!

May be philosophers were great thinkers, but not true scientists.

Status of chemistry during the lifetime of Lavoisier (1743–1794)

- Four element theory is accepted for want of a better one.
- Boyle's definition of element did not get accepted; so water, air and earth are still elements.
- The phlogiston theory dominated chemical philosophy.
- The composition of air and water unknown.
- Hydrogen and oxygen are yet to be discovered.
- The mechanism of respiration and metabolism understood in the context of phlogiston.

Lavoisier recognized the opportunity

"The importance of the end in view prompted me to undertake all this work, which seemed to me destined to bring about a revolution in . . . chemistry. An immense series of experiments remains to be made."

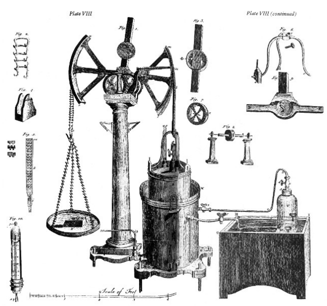
Lavoisier, Lab Notebook entry dated Feb. 20, 1773

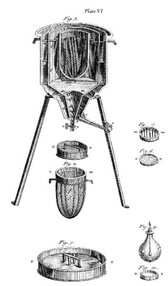
30 yrs old

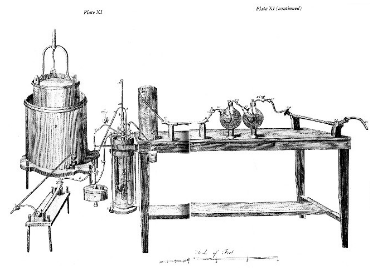
Lavoisier exploited the opportunity

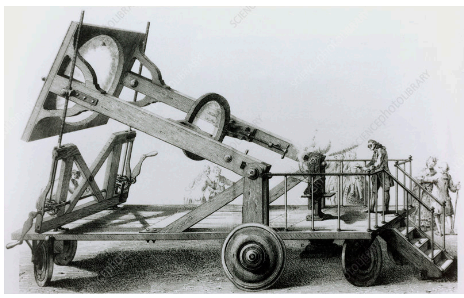
- Built a self-financed well-equipped laboratory.
- Invented and invested on new instruments: a burner that used 'amplified Sunlight' (heater), calorimeter, analytical balances, etc.
- Performed quantitative experiments to study chemical reactions, including combustion process.
- Established concepts as needed.

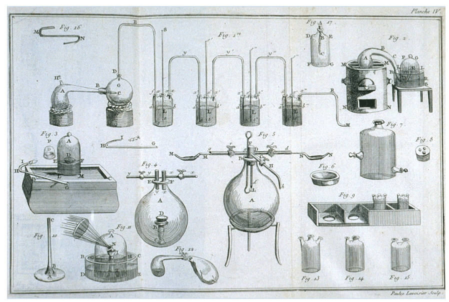
Home built laboratory equipments



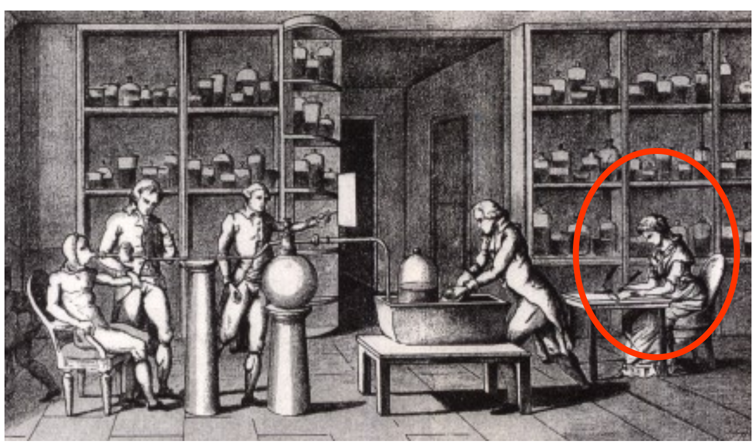








Married Marie-Anne in 1771



Helped to make sketches and take notes. She has drawn herself taking notes at the right hand table.

Theory of Combustion

- In early 18th Century, an attempt was made to understand combustion.
- Why do some materials burn, while others don't?

Observation:

❖ When a piece of wood burned, it turned into ash with much less mass than the original wood.

Question:

❖ What happens to the rest of the wood mass?

Johann Joachim Becher
1635 – 1682

Phlogiston Theory

17 & 18th centuries

Georg Ernst Stahl
1659-1734

According to the phlogiston theory a colorless, odorless and weightless substance called phlogiston, present in every material was released while it burnt and the 'ash' that remained was considered as 'dephlogisticated' material.

Phlogiston's properties

- Phlogiston is released when:
  - Wood burns.
  - Metals calcify or rust.
- Escaping phlogiston stirs up particles and thereby produces heat.
- Phlogiston is found in great quantities in organic matter.

Confirming phenomena-1

- Metal calces are powders, like ash, resulting from heating metals in a fire.
  - Stahl's idea was that phlogiston was driven out of the metal when the calx was produced.
  - If calx is reheated in an oven filled with charcoal (which is believed to be very rich in phlogiston), the calx turned back into the original metal.

Confirming phenomena-2

- Plants, are believed to absorb phlogiston from the atmosphere.
- They burned readily because they had much phlogiston to release.
- Combustion was found to be impossible in a vacuum.
  - Explanation: There was no air present to carry off the phlogiston.

Minor hitch in the theory

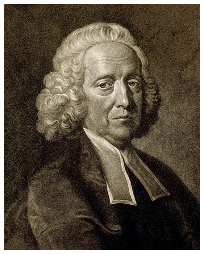
- Typically, metal calces weighed more than the original metal.
  - How can this be if the calcification process drives off the phlogiston in the metal?
  - Answer: Phlogiston possesses levity; *i.e.,* it is lighter than nothing.

Levity is an ancient idea.

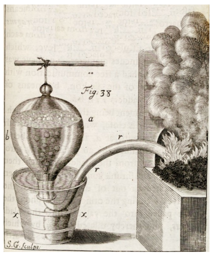
- Levity, or inherent lightness, is an idea found in Aristotle.
  - Air and fire rise because they possess levity, while earth and water fall because they possess heaviness.
  - These are qualitative notions. They do not fit in quantitative, mechanist explanations.

All air are not the same

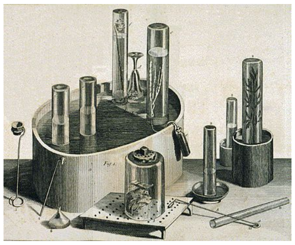
Parallel to phlogiston theory, another concept entered chemistry about the same time: the notion of “air” and that “air” is not just one thing, but that there are <u>different</u> <u>kinds</u> of air (many many air?)”



Stephen Hales
(1677 –1761)



Hales’s

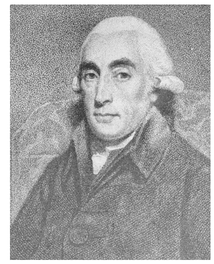


Priestly’s

Pneumatic troughs

New air(s)

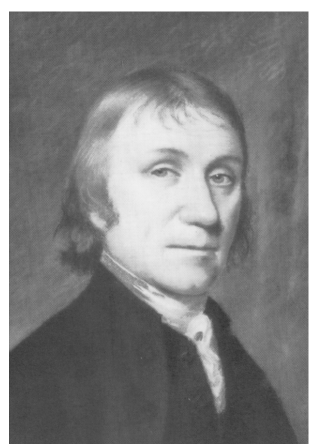
- Joseph Black identified several new gases, giving them names consistent with phlogiston theory.
  - e.g., “fixed air,” what we now call carbon dioxide.
- Other researchers identified other new “airs.”
  - e.g., “inflammable air” (hydrogen).



Joseph Black
1728-1799

Dephlogisticated air

- Joseph Priestley produced different gases by performing chemical reactions and collecting the gases produced with a pneumatic trough.
- He produced a new gas by heating mercuric calx by concentrating the sun’s rays on it.



Joseph Priestley
1733 – 1804

Dephlogisticated air-2

- According to phlogiston theory, he was re-impregnating the mercury with phlogiston, taken from the surrounding air.
- Hence, the air that remained was deficient in phlogiston. He called it “dephlogisticated air.

Dephlogisticated air-3

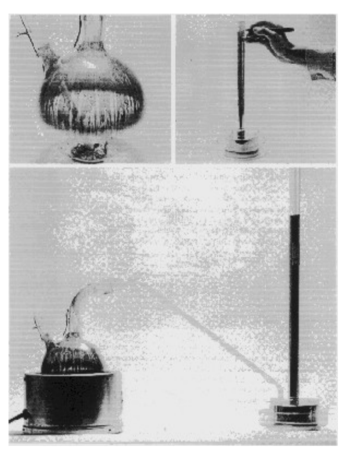
- Experimenting with his new air, Priestley found that:
  - A candle burned brighter in it.
  - A mouse put in a closed flask of the air lived longer than one in a flask with ordinary air.
  - He tried breathing it himself, and it made him feel great.

Lavoisier's ideas

- Lavoisier viewed heat as one of the elements, "caloric."
- Air he thought was a compound of different substances.
- He thought that Priestley's "dephlogisticated air" was actually an element.

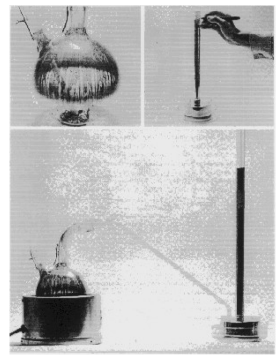
Lavoisier's classic experiment

- Lavoisier took mercury and a measured volume of air and heated them together.
- This produced a mercuric calx and reduced the volume of the air.



Lavoisier's classic experiment, 2

- He then reheated the mercuric calx by itself at a lower temperature and saw it go back to mercury.
- In the process it produced a gas, equal in volume to the amount lost from the first procedure.



Lavoisier's classic experiment-3

- Lavoisier concluded that instead of the original heating driving off phlogiston from the mercury, the mercury was combining with some element in the air to form a compound, which was the mercuric calx.
- He called that element "oxygen," meaning "acid maker."
- He classified all acids to contain oxygen; (wrong generalization).

Oxygen displaces phlogiston

- Phlogiston theory had everything upside down.
- Instead of driving off phlogiston during combustion, burning causes a compound to combine with the gas oxygen.
  - In the case of a metal, the compound is the calx produced (weight increases).
  - In the case of something rich in carbon, e.g., wood, the compound is a gas, carbon dioxide (weight decreases)

Oxygen vs Phlogiston

"All the facts of combustion and calcination are explained in a much simpler and much easier way without phlogiston than with it.

I do not expect that my ideas will be adopted at once; the human mind inclines to one way of thinking and those who have looked at Nature from a certain point of view during a part of their lives adopt new ideas only with difficulty - - -."

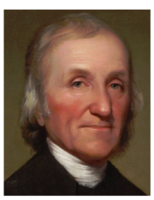
Lavoisier

Discovery of Oxygen

Lavoisier announced in 1775 that he has discovered a new gas resulting upon decomposition of Hg and Pb calx. He named it oxygen (meaning 'acid maker').

Lavoisier demonstrated (1779) its importance in respiration and glowing of candles and the left over part of air being toxic to animal. Thus he established for the first time that air is made up of two elements (one essential and another toxic for life).

Priority dispute: Who discovered oxygen?



Joseph Priestley
1733 – 1804

He mentioned to Lavoisier in **1774** about the discovery during a visit to Paris. Published the results in **1775**.

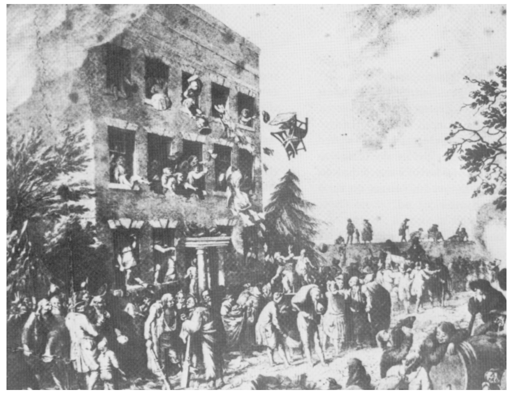
Carl Scheele
1742 - 1786

Swedish chemist **Scheele**, identified it **several years before** Priestley (1770-1773). Unfortunately, his scientific report sat in a printer's office for two years and got published in **1777**.

Antoine Lavoisier
1743—1794

In **1775 Lavoisier** announced to the Academy of Science in Paris that he had isolated a component of air that he called "eminently breathable air" by decomposition of mercuric oxide.

Priestley fled to the U.S.

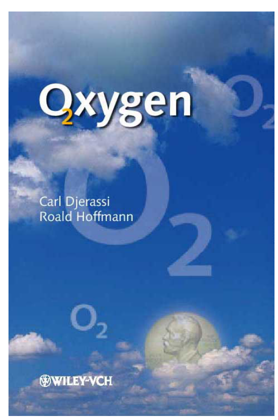


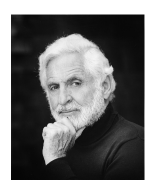
- Priestley was an enthusiastic supporter of the American and French revolutions. His outspoken radical views enraged a mob that burned down his house and library. Priestley escaped to the United States where he lived for the remainder of his life.

A popular Broadway play

On an evening in October 1774, **Antoine Lavoisier**, the architect of the chemical revolution, learned that the Unitarian English minister, **Joseph Priestley**, had made a new gas. Within a week, a letter came to Lavoisier from the Swedish apothecary, **Carl Wilhelm Scheele**, instructing the French scientist how one might synthesize this key element in Lavoisier's developing theory, the life-giver oxygen.

Scheele's work was carried out years before, but remained unpublished until 1777. Scheele and Priestley fit their discovery into an entirely wrong logical framework—the phlogiston theory—that Lavoisier is about to demolish. How does Lavoisier deal with the Priestley and Scheele discoveries? Does he give the discoverers their due credit? And what is discovery after all? Does it matter if you do not fully understand what you have found? Or if you do not let the world know?

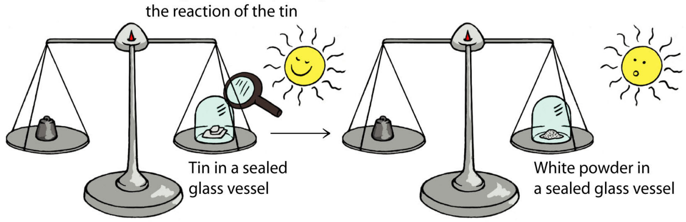




The Law of Conservation of Matter

By paying close attention to the weights of his experimental ingredients, Lavoisier made the Conservation of Matter a fundamental principle of chemistry.

The Law of Conservation of Mass



From *Conceptual Chemistry*, Second Edition by John Suchocki. Copyright © 2004 Benjamin Cummings, a division of Pearson Education.

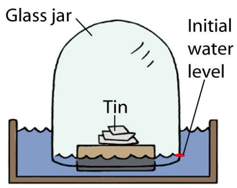
magnesium oxide = Magnesium + oxygen

(Reactants) (Products)

Total mass is the same

Air is not an element but a mixture.

- Lavoisier was sure that air contained more than one element.
- Determined the amount of the "reacting component" in the air. He named this reacting component oxygen.



① Lavoisier placed a piece of tin on a block of wood floating in water and covered it with a glass jar.

What is an element?

Robert Boyle's (1627-1691) definition of element
"An element is a substance that cannot be decomposed into anything simpler"

Cavendish: **"**When inflammable and common air are exploded in a proper proportion, almost all the inflammable air, and near one-filth of the common air, lose their elasticity, and are condensed into dew (water)." (Done in 1781 and *Published in 1784)*.

Water is not an element. It is a mixture.

Lavoisier (1783)

- Combustion of inflammable air with oxygen carried out in a closed vessel yielded water in a very pure state.
- Water can be decomposed to inflammable air (hydrogen) and oxygen. Iron filings in water rusted and released inflammable air. Rusting occurred through the reaction of released oxygen with iron filings.
- Thus water can be decomposed to two elements and can also be formed from the same two elements. **Water is not an element, it is a compound.**

Water and air are not elements: Four element theory is not valid

Priority disputes and Lavoisier's reaction

Cavendish's experiments were done in 1781 and published in 1784. In the meantime his assistant Blagden visited Paris in 1783 and mentioned about Cavendish's results to Lavoisier. The latter published the water results in 1783. There was some feeling that Lavoisier might have used the information given to him by Blagden to anticipate the publication of a discovery made by Cavendish.

Lavoisier: "There was no principle of scientific conduct that forbade him to give better explanations of other men's discoveries than those they could provide themselves, an attitude to which no man of science could take exception.

This theory is not, as I hear it called, the theory of the French chemists. It is mine. It is a right that I claim by the Judgment of my contemporaries and at the bar of history."

Order in chaos

Law of the conservation of Mass

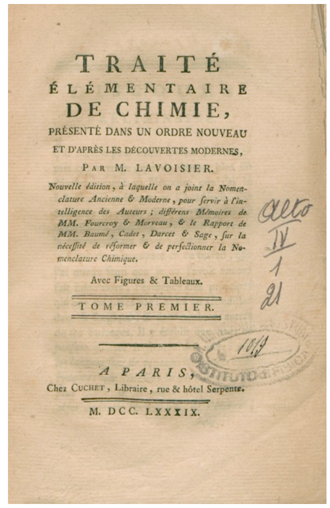
Law of the indestructibility of matter applied to chemical change

In every operation an equal quantity of matter exists both before and after operation.

Established the field of thermochemistry

Established a system of nomenclature

Conceived oxygen based acid principle



TRAITÉ
ÉLÉMENTAIRE
DE CHIMIE,
PRÉSENTÉ DANS UN ORDRE NOUVEAU
ET D'APRÈS LES DÉCOUVERTES MODERNES,
PAR M. LAVOISIER.

Nouvelle édition, à laquelle on a joint la Nomenclature Ancienne & Moderne, pour servir à l'intelligence des Auteurs ; différens Mémoires de MM. Fourcroy & Morveau, & le Rapport de MM. Baumé, Cadet, Darcet & Sage, sur la nécessité de réformer & de perfectionner la Nomenclature Chimique.

Avec Figures & Tableaux.

TOME PREMIER.

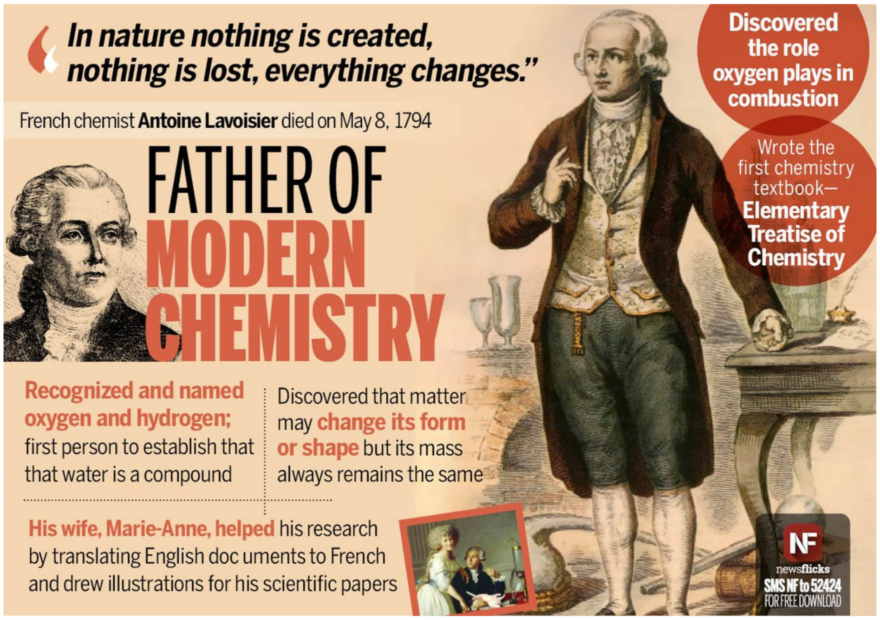
A PARIS,
Chez CUCHET, Libraire, rue & hôtel Serpente.
M. DCC. LXXXIX.

Antoine Lavoisier
1789

Antoine Lavoisier – Sad Ending

Despite his eminence and his services to science and France, he came under attack as a former farmer-general of taxes and was guillotined in 1794 (51 yrs old).

"It took them only an instant to cut off that head, and a hundred years may not produce another like it."
Joseph-Louis Lagrange



Readings

Antoine Lavoisier, Douglas McKie, 1952

An International Historic Chemical Landmark, The Chemical Revolution, ACS, pamphlet, 1999

Antoine Lavoisier, H. Hartley, Proc. Royal Soc. A, 189, 427-454, 1947

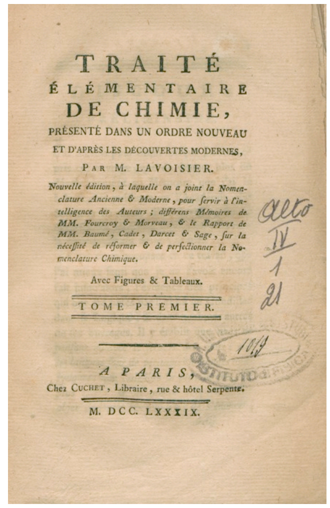
http://mysteryofmatter.net/Lavoisier.html

"Well, certainly, Lavoisier was one of the great, great masters of all time."

Humphry Davy

Humphry Davy: Chemistry's First Showman

Humphry Davy
1778-1829



TRAITÉ
ÉLÉMENTAIRE
DE CHIMIE,
PRÉSENTÉ DANS UN ORDRE NOUVEAU
ET D'APRÈS LES DÉCOUVERTES MODERNES,
PAR M. LAVOISIER.

Nouvelle édition, à laquelle on a joint la Nomenclature Ancienne & Moderne, pour servir à l'intelligence des Auteurs; différens Mémoires de MM. Fourcroy & Morveau, & le Rapport de MM. Baumé, Cadet, Darcet & Sage, sur la nécessité de réformer & de perfectionner la Nomenclature Chimique.

Avec Figures & Tableaux.

TOME PREMIER.

A PARIS,
Chez CUCHET, Libraire, rue & hôtel Serpente.
M. DCC. LXXXIX.

Antoine Lavoisier
1789

Beginning

"I have neither riches, nor power, nor birth to recommend me. Yet if I live, I trust I shall not be of less service to mankind and my friends, than had I been born with these advantages"

Notebook entry at age 17

End

"Fortune had smiled on Davy, perhaps too kindly in his younger years, and left him eager for praise, jealous of rivals and anxious to shine in every field. Those were his failings, but withal his romantic genius made an enduring mark."

H. Hartley,

Humphry Davy, Nelson, London, 1966

A land of promise

"There is now before us a boundless prospect of novelty in science; a country unexplored, but noble and fertile in aspect; a land of promise in philosophy."

When Davy started his exploration electricity was popularly regarded as an invisible and volatile fluid stored in glass Leyden jars, ever ready to leap out with a bang.

Davy Makes Science Fashionable

- The first preparation of nitrous oxide in a pure form; Davy was also the first to recognize its anesthetic properties.
- The isolation of metallic potassium, sodium, barium, strontium, calcium, magnesium, and boron.
- Davy was the first to argue that if electricity could be generated by chemical action then, conversely, electricity could decompose compounds into their fundamental elements (birth of electrochemistry)
- The realization that chemical forces were, fundamentally, electrical in nature (birth of the Nature of a chemical bond)
- The invention of the Miner's Safety Lamp (the Davy Lamp)

The Age of Wonder, Ch 6 & 8, R. Holmes, 2010

Born in Penzance on Dec 17 1778

John Tonkin, Family benefactor

John B. Borlase, Local doctor

Thomas Beddoes opens, The Pneumatic Institute in Bristol, Appoints Davy (19 yrs old) as Laboratory Operator in 1798

- Gas research 1978 – 1801

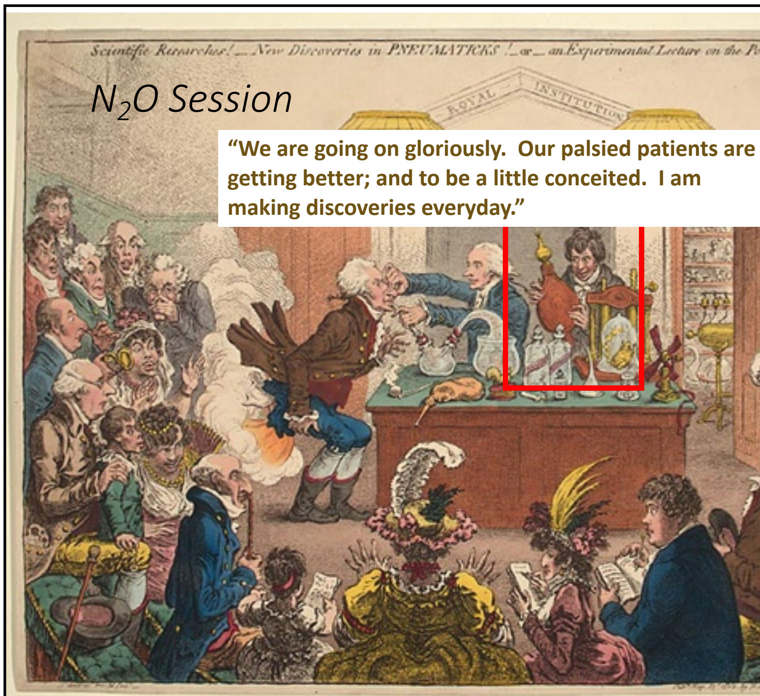
Royal Institution, London, 1801-1825, Director

- Electrochemistry, Isolation of elements, Davy Lamp invention

The Pneumatic Institute

Thomas Beddoes

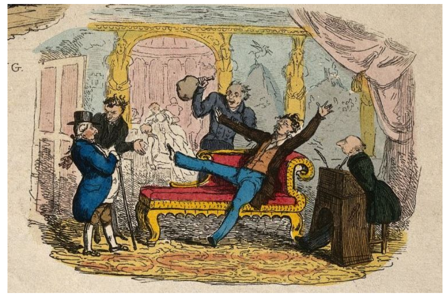
N_2O Session

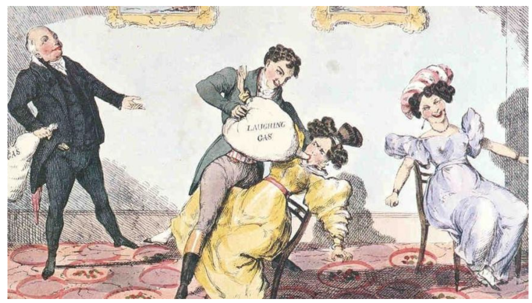


"We are going on gloriously. Our palsied patients are getting better; and to be a little conceited. I am making discoveries everyday."

Humphry Davy

Nitrous oxide parties, early 18th century

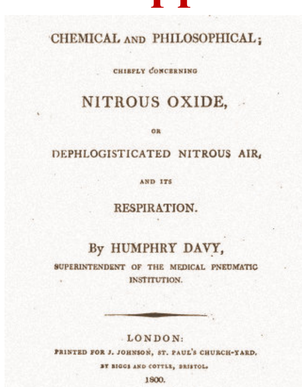




Humphry Davy invited friends to try laughing gas so he could observe their responses.

"Give me more, give me more; this is the most pleasurable thing I've ever experienced."

Missed opportunity



CHEMICAL AND PHILOSOPHICAL;

CHIEFLY CONCERNING

NITROUS OXIDE,

OR

DEPHLOGISTICATED NITROUS AIR,

AND ITS

RESPIRATION.

By HUMPHRY DAVY,

SUPERINTENDENT OF THE MEDICAL PNEUMATIC INSTITUTION.

LONDON:

PRINTED FOR J. JOHNSON, ST. PAUL'S CHURCH-YARD,

BY BIGGS AND COTTLE, BRISTOL.

1800.

"As nitrous oxide in its extensive operation appears capable of destroying physical pain, it may probably be used with advantage during surgical operations in whichno great effusion of blood takes place."

Davy's failure to capitalize on his discovery of anesthesia doomed thousands to needless surgical pain.

Davy never followed up on the idea that nitrous oxide could be a anesthesia, his attention was diverted by Volta's discovery of the battery.

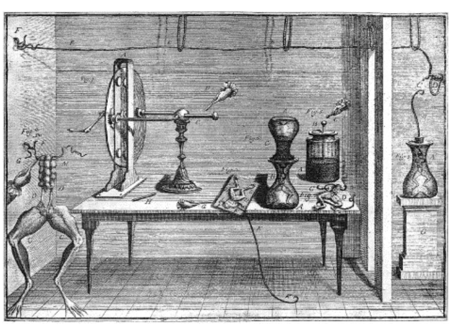
Humphrey Davy

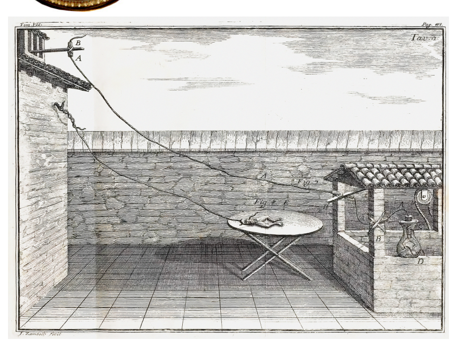
Moves on from nitrous oxide to carbon monoxide

Galvani and animal electricity

Luigi Galvani
1737-1798

Lucia Galeazzi (Galvani)

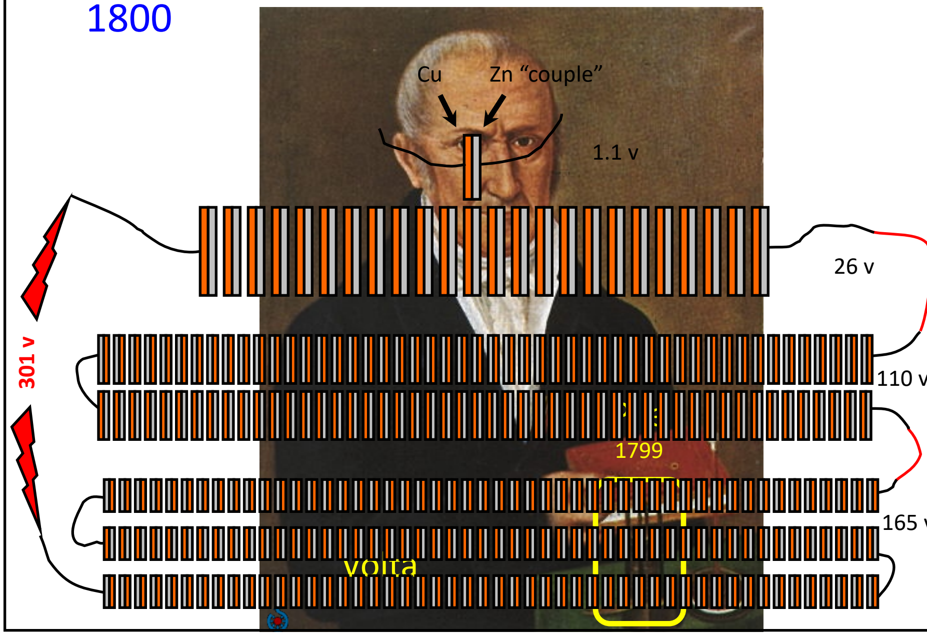




Luigi Galvani, discovered "animal electricity" when two different metals were connected in series with a frog's leg and to one another.

Electrolysis

Volta's pile
1800



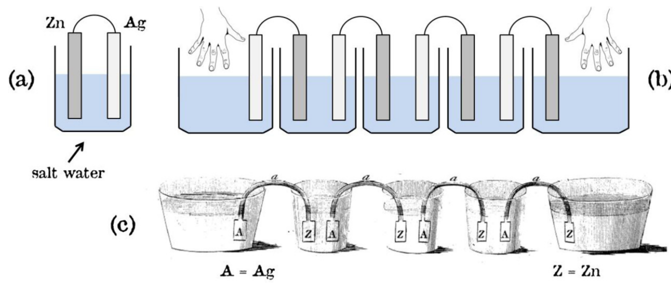
Volta's pile, the first battery

In 1800 A. Volta invented the voltaic pile, which was one of the first electric batteries. It was essentially a stack of alternating metal discs separated by brine-soaked material that helped make them more conductive.

Volta demonstrated his battery for the French leader Napolean and promptly earned a nice gold medal, -----

Humphry Davy built his own Voltaic pile and experimented

Davy used electricity to split up compounds to form elements

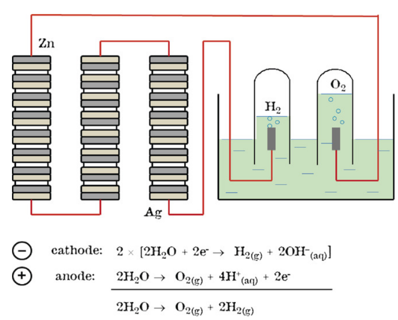


Davy (1807-08)

"I acted upon aqueous solutions of potash and soda, saturated at common temperatures, by the highest electrical power I could command, and which was produced by a combination of Voltaic batteries belonging to the Royal Institution, ----

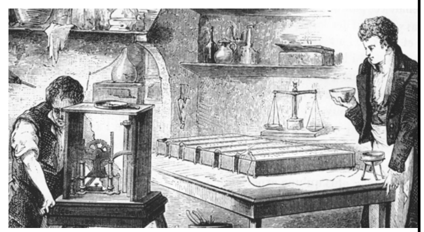
"…though there was a high intensity of action, the water of the solutions alone was affected, and hydrogen and oxygen disengaged with the production of much heat and violent effervescence."

(*electrolysis of water*)



Davy (1807-08)

A small piece of pure potash, which had been exposed for a few seconds to the atmosphere, so as to give conducting power to the surface, was placed ------

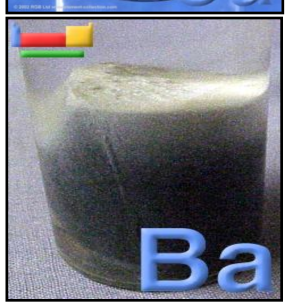


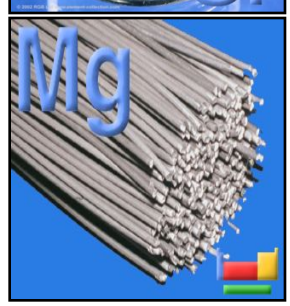
…small globules having a high metallic luster, and being precisely similar in visible characters to quick-silver, appeared, some of which burnt with explosion and bright flame, as soon as they were formed, and others remained, and were merely tarnished, and finally covered by a white film which formed on their surfaces.

Davy's Elemental Discoveries

1807

1808





Davy's excitement on elemental discoveries

Li	Be	**B**
Na	**Mg**	Al
K	**Ca**	Ga
Rb	Sr	In
Cs	**Ba**	Te

"... when he saw the minute globules of potassium burst through the crust of potash, and take fire as they entered the atmosphere, he could not contain his joy– he actually bounded about the room in ecstatic delight; and . . . some little time was required for him to compose himself sufficiently to continue the experiment"

Edmund Davy, Cousin who watched the expt.

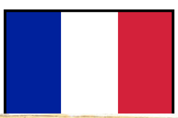
1807-8

Humphry Davy

Big Science

a

Roy



Napo

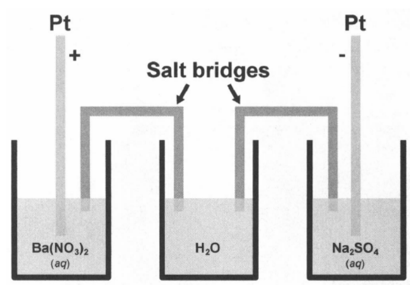
(via Ga

tes

tes

al

The ions make a bond

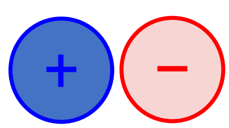


Using this set-up, Davy showed that a precipitate of BaS04 was formed in the middle compartment, thus proving that barium ions migrated towards the negative electrode and sulphate ions towards the positive one.

Electricity supplied more than new elements...

Davy's view of chemical bonding

----that the elements of bodies are capable of being separated from each other by certain electrical attractions and repulsions."



Davy Makes Science Fashionable

- The first preparation of nitrous oxide in a pure form; Davy was also the first to recognize its anesthetic properties.
- The isolation of metallic potassium, sodium, barium, strontium, calcium, magnesium, and boron.
- Davy was the first to argue that if electricity could be generated by chemical action then, conversely, electricity could decompose compounds into their fundamental elements (birth of electrochemistry)
- The realization that chemical forces were, fundamentally, electrical in nature (birth of the Nature of a chemical bond)
- The invention of the Miner's Safety Lamp (the Davy Lamp)

The Age of Wonder, Ch 6 & 8, R. Holmes, 2010

Forgotten Davy lamp

- Enormous coal mine explosions in England during 1800s.
- Each miner carried a wax candle stub on his helmet or in his hand.
- The open flame ignited the gases (methane) killing a large number of miners every year.
- The miners approach Davy at the Royal Institute

Davy's life holds some lessons for ethics and science today.

August 3rd, 1815.

SIR,

I had the honour of receiving the letter which you addressed to me in London at this place, and I am much obliged to you for calling my attention to so important a subject.

It will give me great satisfaction if my chemical knowledge can be of any use in an inquiry so interesting to humanity, and I beg you will assure the Committee of my readiness to co-operate with them in any experiments or investigations on the subject.

I shall be here ten days longer, and on my return south will visit any place you will be kind enough to point out to me where I may be able to acquire information on the subject of the coal-gas.

Your obedient, humble servant,
H. DAVY.

Chief Mining Engineer John Buddle Approaches Davy at the behest of miners

John Buddle
1773-1843

'After a great deal of conversation with Sir Humphry Davy, and he making himself perfectly acquainted with the nature of our mines and what was wanted,------ he said " **Do not despair, I think I can do something for you in a very short time**".'

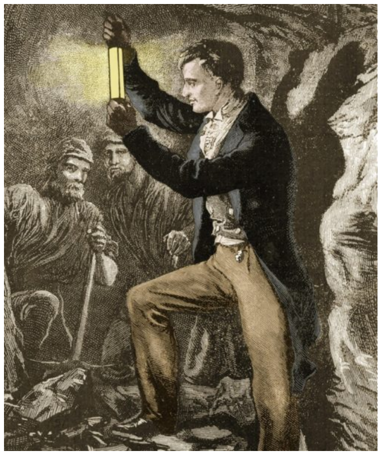
Invention of Davy lamp

- Studied the problem for three weeks in Durham, visiting mines and talking to miners;
- Went back to the lab for three months.
- Built a working prototype lamp what would be known as the Davy Lamp.
- Returned to the mines. He spent hours underground, teaching safety techniques, refining the design.

Invention of miners lamp, Davy Lamp



Training miners with Davy Lamp



John Buddle: "We have at last subdued this monster".

Davy lamp is still popular world over

In September 1816 '*we, the undersigned miners at the Whitehaven Collieries'* *thanked Davy for his 'invaluable discovery of the safe lamps, which are to us life preservers*'.

Priority Dispute: Davy lamp

Buddle urged Davy to take out a patent, pointing out that he could not only make his fortune but control the quality of the lamps issued to miners. Davy consistently refused, although he knew his colleague Wollaston had made a fortune with a patent on processing platinum. Yet Davy was hugely proud of his achievement, and was never modest about it.

Davy's high-minded claims produced a bitter priority dispute. In the spring of 1816 the engineer at the Killingworth mine, just north of Newcastle, George Stephenson, challenged Davy's precedence, and accused him of plagiarising of his own 'Geordie Lamp'.

Priority Dispute: Iodine

Priority dispute on the discovery of iodine with the gifted young chemist Joseph Gay-Lussac. Gay-Lu sac, Davy's exact contemporary.

Two not-so-well-known chemists, N. Clément and C. B. Desormes had reported that a strange new substance had been discovered in seaweed. Gay-Lussac was assigned to review their experiments and repeat them to make sure the results were correct. Six days before the announcement of the results by Gay-Lussac, Ampère, Clément, and Desormes paid a visit to Davy and showed him the sample. Davy immediately isolated and identified the element as iodine.

Gay-Lussac's short paper was actually presented and published first, on 12 December. Davy, taken by surprise, presented his to the Academie on 13 December, but antedated it to 11 December, and had it published as such in the Journal de Physique. He claimed, perhaps justly, that he had previously shared his key ideas with Gay-Lussac.

Davy's surprising sharpness in a 'priority' controversy was noticed by Faraday.

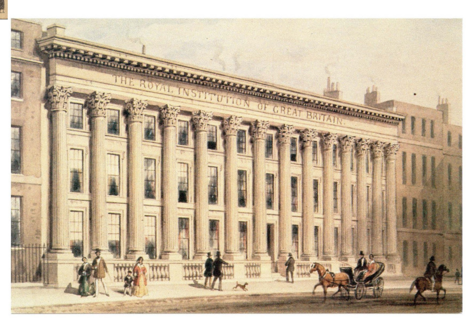
ChemMatters, December 2006, p. 18

Faraday’s words made the difference

"I was witness in our laboratory to the gradual and beautiful development of the train of thought and the experiments which produced it. The honour is Sir H. Davy's, and I do not think that this beautiful gem in the rich crown of fame which belongs to him will ever again be sullied with the unworthy breath of suspicion."

The Age of Wonder: Communication with the public

Outstanding Lecturer & Performer



The first one-way street in the world

Davy's advice on giving on lectures

"I was made to write out the first lecture entirely, and Davy took me into the lecture hall the evening before I was to talk and made me read it all out while Davy sat in the furthest corner and listened; and them Davy read the lecture while I listened. Next day I read it to an audience of about 150 to 200 people and they gave me a very generous plaudit at the conclusion."

John Dalton on his first lecture at Royal Institution in 1803

Davy's advice on doing research
To err is human

"I was perhaps wrong in publishing, in such haste, a new theory of chemistry. My mind was ardent and enthusiastic. I believed that I had discovered the truth. Since that time my knowledge of facts is increased since that time I have become more skeptical."

"Hypotheses . . . should be the instruments of thought, the secret amusements of the mind; but truth only should be brought to light."

"When we begin the study of any science... We ought to form no idea but what is a necessary consequence, and immediate effect, of an experiment or observation ... We should proceed from the known facts to the unknown."

Davy trusted the experiments more than his brain

"One good experiment is worth more than the ingenuity of a brain like Newton's."

Recipe for Research
"Observation, Experiment and Analogy"

- Observe to formulate a problem
- Experiment to gain an understanding
- Compare the results with known to generate a hypothesis

Readings

http://mysteryofmatter.net/Davy.html

https://www.rigb.org/whats-on

***The Age of Wonder*, R. Holmes, 2008, Ch 6 and 8**

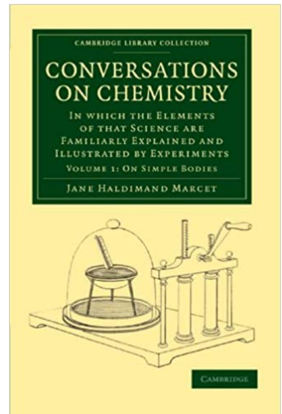
Sir Humphry Davy: Boundless Chemist, Physicist, Poet and Man of Action, JM. Thomas, PP. Edwards, and VL. Kuznetsov, *ChemPhysChem*, **2008**, *9*, 59

Sir Humphry Davy: natural philosopher, inventor, discoverer, poet, man of action. JM. Thomas, *Proc. Am. Phil. Soc.* **2013**, *157*, 143.

Sir Humphry Davy and the coal miners of the world: a commentary on Davy (1816) 'An account of an invention for giving light in explosive mixtures of fire-damp in coal mines', JM Thomas, *Phil. Trans. R. Soc.* A **2014**, *373*: 20140288.

The Greatest Discovery of Davy: Michael Faraday

Michael Faraday
1791-1867



Jane Marcet, 1805

Einstein kept a picture of Faraday (alongside those of Newton and Maxwell) for inspiration

***The Electric Life of Michael Faraday*, A. Hirshfield, 2006**

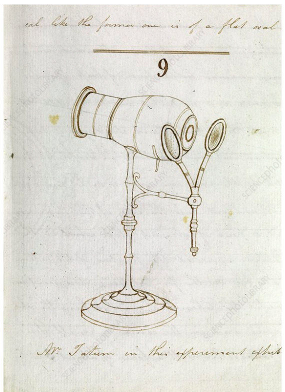
Davy's lectures at RI recorded

Jane Marcet, 1769-1858

"the most wonderful and the most interesting phenomenon of nature are almost all of them produced by chemical powers"

Conversations on Chemistry, 1817

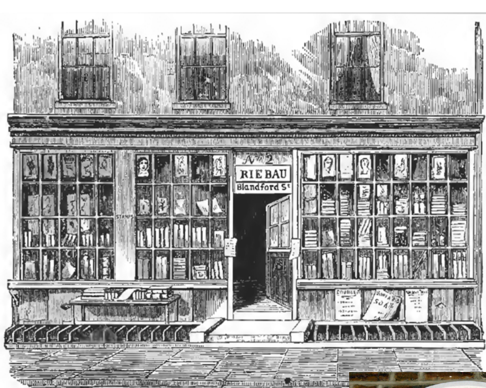
John Tatum's lectures (1772-1858) exposed Faraday to science



Faraday, a bookbinder's apprentice at the time, lacked a formal education and studied by reading books and attending lectures. He attended around 13 lectures by silversmith John Tatum (1772-1858) between February 1810 and September 1811. The notes Faraday made from these lectures formed four volumes and 300 pages and helped him start his career in science. An example of Faraday's notes taking ability.

Tatum was the founder, in 1808, of the City Philosophical Society where Faraday and other scientists received inspiration.

- *The Encyclopedia Britannica* – his source for electrical knowledge and much more
- *Conversations on Chemistry* – 600 pages of chemistry for ordinary people written by Jane Marcet based on Davy's lectures at the Royal Institution



Building Confidence

"When I questioned Mrs. Marcet's book (Conversations on Chemistry) by such little experiments as I could perform, and found it true----, I felt I got hold of an anchor of chemical knowledge---."

Michael Faraday

Getting Started

Faraday wrote about the experience later in life after Davy's death to J.A. Paris. (1829)

> "My desire to escape from trade, which I thought vicious and selfish, and to enter into the service of Science, which I imagined made its pursuers amiable and liberal, induced me at last to take the bold and simple step of writing to Sir H. Davy, expressing my wishes, and a hope that if an opportunity came in his way he would favor my views; at the same time, I sent the notes I had taken of his lectures." (1812)

Davy's encouraging reply to Faraday

"Sir,– I am far from displeased with the proof you have given me of your confidence, and which displays great zeal, power of memory, and attention. I am obliged to go out of town, and shall not be settled in town till the end of January; I will then see you at any time you wish. It would gratify me to be of any service to you; I wish it may be in my power.

I am, Sir, your obedient humble servant,
H. Davy."

Faraday was grateful to Davy till the end of his life
A revealing letter where Davy cautions

"At the same time that he thus gratified my desires as to scientific employment, *he still advised me not to give up the prospects I had before me, telling me that Science was a harsh mistress, and in a pecuniary point of view but poorly rewarding those who devoted themselves to her service.* He smiled at my notion of the superior moral feelings of philosophic men, and said he would leave me to the experience of a few years to set me right on that matter."

A letter written to a friend by Faraday in 1829

Getting the foot in the hole, Apprentice as a chemist

Faraday's tough time with Lady Jane Davy

Lady Davy in front of guests *ordered Faraday to take his meal in the kitchen with the servants*.

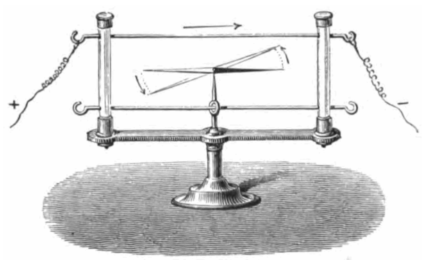
Faraday to his hometown friend,

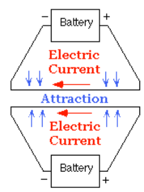
"Alas!, how *foolish perhaps was I to leave home, to leave those whom I loved and who loved me* ----. And what are the boasted advantage to be gained? Knowledge. ---- *What a result is obtained from knowledge and how much must the virtuous human mind be humiliated* --- Ah Ben, I am not sure that I have acted wisely in leaving a pure and certain enjoyment for such a pursuit."

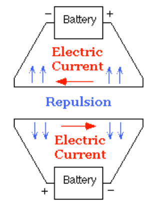
Early observations on the connection between magnetism and electricity

Hans Christian Ørsted, 1777-1851
First to establish a connection between electricity and magnetism

André-Marie Ampère
1775-1836

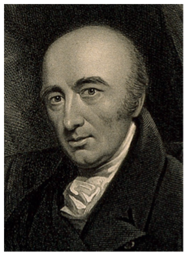




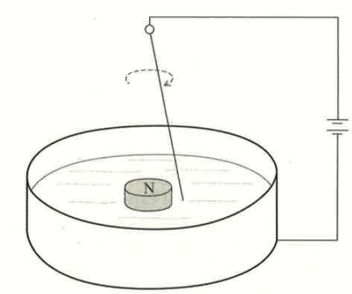


Orsted experiment
https://www.youtube.com/watch?v=qS361iadCPA

Ampere experiment
https://www.youtube.com/watch?v=GW7PvSR9VUo



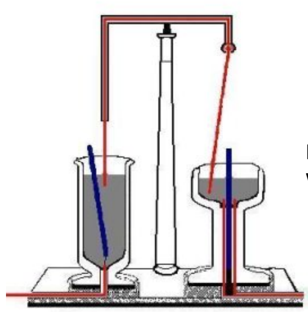
William Hyde Wollaston
1766 –1828



Davy was trying to re-create a famous electromagnetism experiment with fellow chemist William Wollaston, wondering why applying an electric current to a wire caused that wire to behave like a magnet. He could not make the experiment work. He teasingly told Faraday to try his hand at it after he was done cleaning the lab. *Faraday figured it out, and the result was the* ***first induction motor****, which converts electrical current into continuous mechanical motion*.

World's First Electric Motor-1821

Wire fixed
Magnet free



Magnet fixed
Wire free

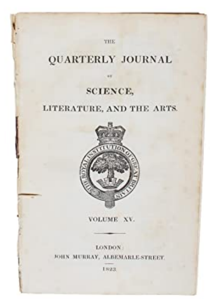
Electromagnetic rotation experiment of Faraday

Faraday's electric motor on You-tube

https://www.youtube.com/watch?v=8LTP49d7KF8

The publication that created excitement and problems

On Some New Electromagnetic Motions and the Theory of Electromagnetism M. Faraday, *Quarterly Journal of Science*, **1821-23 (three articles)**



(US$ 4,060.35)

Faraday published without acknowledging Davy and Wollaston.

Davy and Wollaston accused Faraday of plagiarizing their idea.

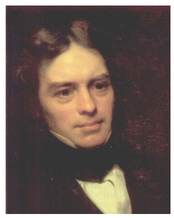
Public liked the little motor and pocket-sized motor were gifted and sold.

But, Faraday was out of favor with the old guards of British scientific establishments. They were unsure of his knowledge to make such an important discovery.

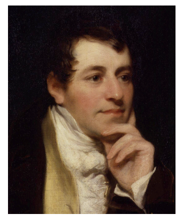
Public and old guards were not aware that Faraday is the author of an authoritative review on electromagnetism published in Annals of Philosophy under a pseudo-name.

Mentor and mentee relationship was complex

Science is a human endeavor, driven by hopes, dreams and aspirations. They may be brilliant, even geniuses. But as human beings they may also be seriously flawed.



Michael Faraday
1791-1867



Sir Humphry Davy
1778-1829

Occasionally, science can take on personal, almost vindictive quality.

Complex relationship between Davy and Faraday

Compliments

Davy to Faraday, "I think you are a better chemist than Donovan."

---- believe me there is *no one more interested in your success & welfare than your sincere well wisher & friend, H. Davy*."

Complex relationship

Davy tried to block his own protege from "rising to the light."

Faraday's nomination to the Royal Society was announced at ten successive Royal Society meetings and, at the eleventh, on January 8, 1824, secret ballots were cast. *Faraday was elected-with one dissenting vote by Davy.*

Recommended Faraday to be the Director of RI and assigned him on an uninteresting project on glass (1825-1831).

Humphry Davy dies in 1829.

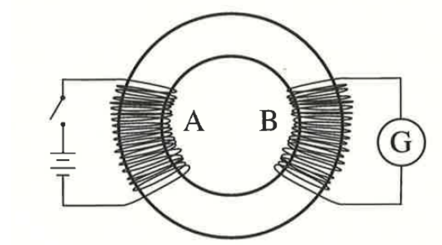
Faraday finds a trusted friend in Ampere

To Ampere, Faraday privately complained

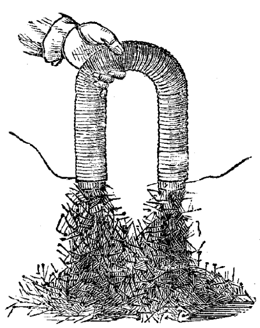
"*I am compelled to say I have not found that kindness, candor and liberality at home* which I have now on several occasions uniformly experienced from the Parisian men of Science ... *Considering the very subordinate position I hold here and the little encouragement which circumstances hold out to me I have been more than once tempted to resign scientific pursuits altogether* ... I struggle on in hopes of getting results at one time or another that shall by their novelty or interest raise me into a more liberal and active sphere."

Series of pioneering discoveries 1831-

First Electromagnetic Induction



Electricity to Magnetism

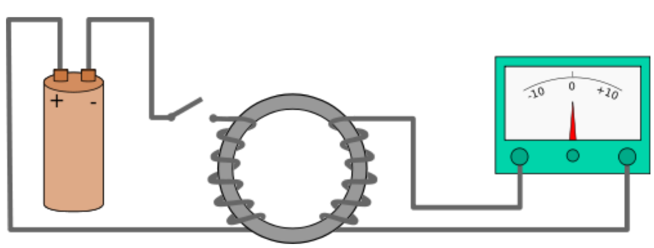


Chemical energy

Electrical energy

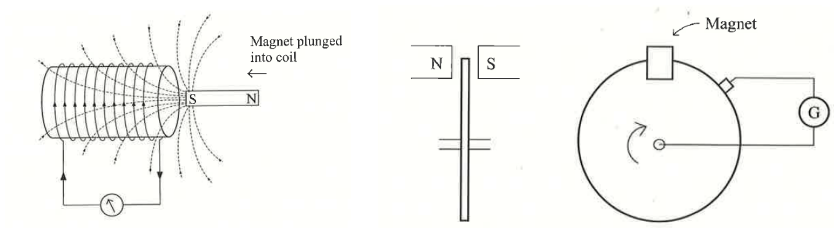
Magnetic energy

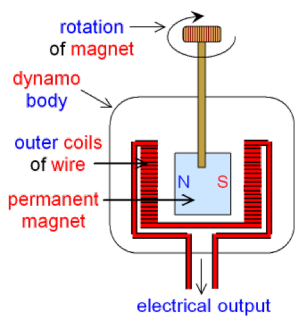
Mechanical energy



The First Electrical Generator & Dynamo

A device which converts mechanical energy to electrical energy





Magnetism to electricity

Faraday electromagnetic induction

https://nationalmaglab.org/customsearchresultmaglab?q=Michael+Faraday&cx=004099242236933193842%3A9shljmjve7a&cof=FORID%3A11&sa=SEARCH&x=0&y=0

The future of electromagnetism

Basic *vs* Applied Science

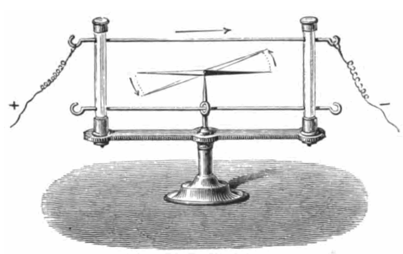
Prime Minister Robert Peel: **What is the practical value of this new device (electromagnetically driven transformer)?**

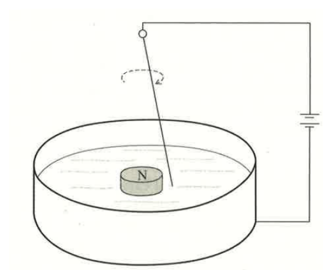
Michael Faraday**: I know not, but I wager that one day your government will tax it.**

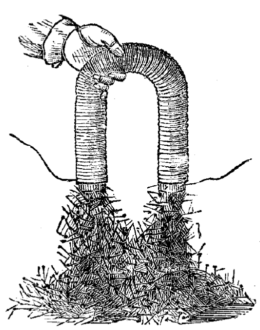
Conversation recorded in 1831

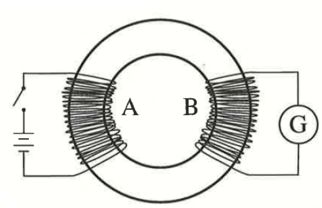
The first industry to be built on the invention made in a laboratory rather than in a workshop

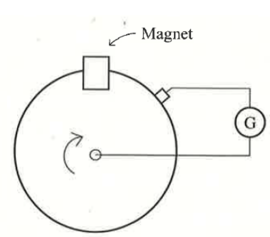
How electricity and magnetism communicate?







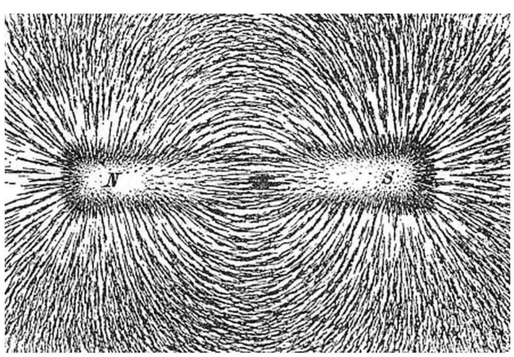




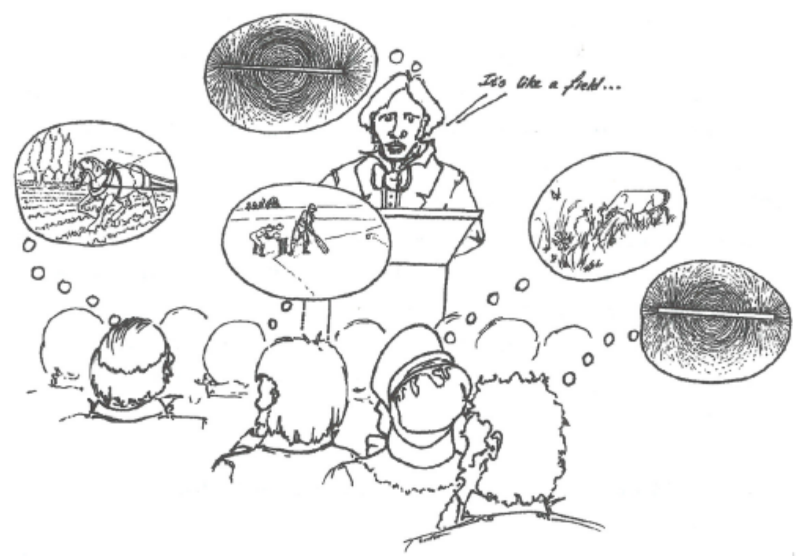
- Newtonian approach dominated the scene during Faraday's time.
- At the time of Faraday electricity, magnetism and gravity believed to follow Newtonian physics. Action at a distance along straight lines.
- Ampere saw straight line Newtonian attraction/repulsion between current in the two wires
- Faraday discovered that electricity and magnetism are interconnected.
- Faraday visualized electricity and magnetism in terms of 'lines of forces' and 'field theory'.

Magnetic lines of force

A struggle to conceptualize how forces could be transmitted across empty space.

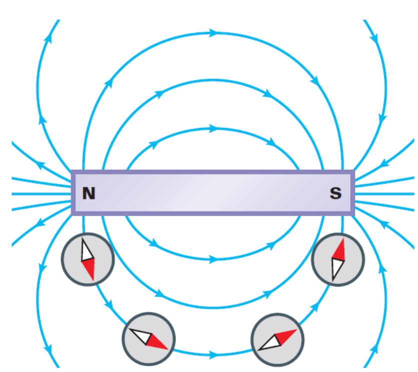


If iron filings are sprinkled around a magnet, they form discrete curves, originating at the poles and extending into the space surrounding the magnet.



Magnetic Field

- Magnetic field lines point from the north pole to the south pole of the magnet
  - The north pole of a compass needle always points in the direction of the field (from North to South)

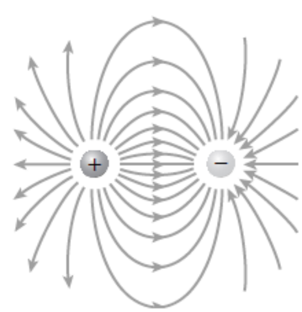


Electric Field

- Electric force, like gravitational force, is a field force
- Field forces can act through space even when there is no physical contact between the objects involved
- A charged object has an electric field in the space around it

Electric Field Lines

- This diagram shows the electric field lines for two equal and opposite point charges
  - Notice that the lines begin on the positive charge and end on the negative charge



Electric Field & Magnetic Field

- Electric forces through electric field.
- Vector field, **E**.
- Source: electric charge.
- Positive charge (+) and negative charge (-).
- Opposite charges attract, like charges repel.
- Electric field lines visualizing the direction and magnitude of **E**.

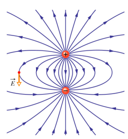
Magnetic forces through magnetic field.

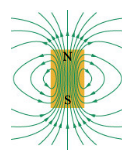
Vector field, **B**

Source: **moving** electric charge (current or magnetic substance, such as permanent magnet).

Opposite poles attract, like poles repel.

Magnetic field lines visualizing the direction and magnitude of **B**.





Establishing for the first time a link between magnetism and light

In March 1832, Faraday asked the secretary of the Royal Society to deposit a note in his safe.

"I am inclined to compare the diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water or those of air in the phenomenon of sound; i.e. I am inclined to think the vibratory theory will apply to these phenomena, as it does to sound and, most probably, to light."

To Ampere, Nov 1845

"I happen to have discovered a direct relation between magnetism and light also Electricity and Light---and the field it opens is so large & I think rich that I naturally wish to look at it first"

Much larger discovery: Light is an electromagnetic wave 1845

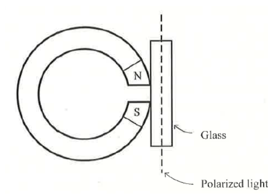
Faraday Effect: Magnetic field rotates plane polarized light

“Today worked with lines of magnetic force, passing them across different bodies (transparent in different directions) and at the same time passing a polarized ray of light through them (…) there was an effect produced on the polarized ray, and thus magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile and of great value in the investigation of both conditions of natural force. An excellent day’s work.” (notebook entry, Sep 18, 1845)

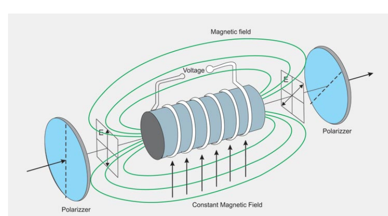
Thoughts on Ray Vibrations
Michael Faraday "Experimental Researches in Electricity", Vol III, 447
(Philosophical Magazine, S.3, Vol XXVIII, N188, **1846**)

Much larger discovery
Light is an electromagnetic wave

Faraday Effect: Magnetic field rotates plane polarized light



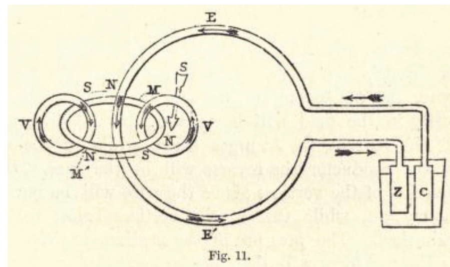
In 1845, Michael Faraday discovered that the plane of polarization of linearly polarized light is rotated when the light rays travel along the magnetic field direction in the presence of a transparent dielectric, an effect now known as **Faraday rotation**



Maxwell: Light is an electromagnetic wave

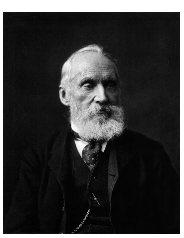
(1865 publication)

"The electromagnetic theory of light, as proposed by Faraday, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation. ---- Faraday discovered that when a plane polarized ray transverses a transparent diamagnetic medium in the direction of the lines of magnetic force produced by magnets or currents in the neighborhood, the plane of polarization is caused to rotate."



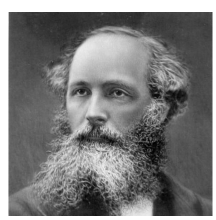
Maxwell's visualization of electromagnetic interaction. Electrical and magnetic forces are perpendicular to each other.

Electromagnetic waves travels at the speed of light
Light is an electromagnetic wave



William Thomson
Lord Kelvin

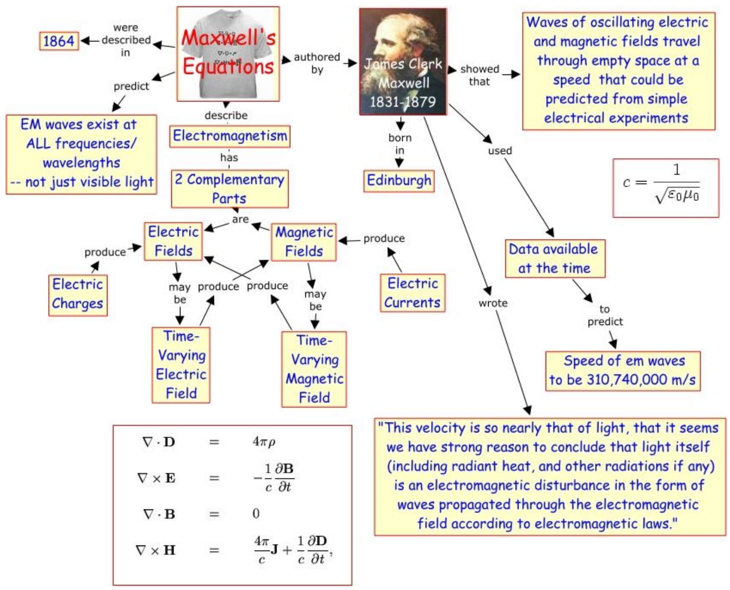
Michael Faraday
1791-1867



James Clerk Maxwell
(1831-1879)

"I think we have now strong reason to believe, whether my theory is a fact or not, that the luminiferous and the electromagnetic medium are one." In other words, light is indeed an electromagnetic undulation-a "ray-vibration," as you had called it in 1846.

Maxwell to Faraday, October 1861



"Now that the mathematical interpretation of Faraday's conceptions regarding the nature of electric and magnetic forces has been given by Clerk Maxwell, we see how great a degree of exactness and precision was really hidden behind the words which to Faraday's contemporaries appeared either vague or obscure; and it is in the highest degree astonishing to see what a large number of general theorems, the methodical deduction of which requires the highest powers of mathematical analysis, he found by a kind of intuition, with the security of instinct, without the help of a single mathematical formula."

Hermann von Helmholtz, 1881

"... the pair Faraday-Maxwell has a most inner similarity with the pair Galileo-Newton - the former of each pair grasping the relations intuitively, and the second one formulating those relations exactly and applying them Quantitatively."

A. Einstein,

Who is Maxwell

When Einstein was asked if he stood on the shoulders of Newton, he replied
"No, on the shoulders of Maxwell";

The special theory of relativity owes its origins to Maxwell's equations of the electromagnetic field.

There is scarcely a single topic that he touched upon which he did not change beyond recognition.

Charles A. Coulson

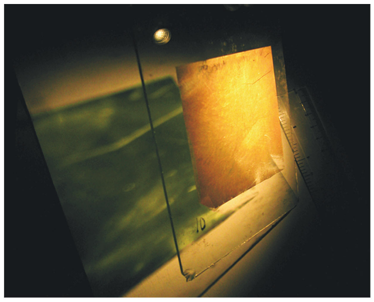
How to conceive of the continuous and progressive transmission of electric and magnetic forces through space?

Faraday: The field is responsible for the continuous, progressive transmission of electric and magnetic forces through space.

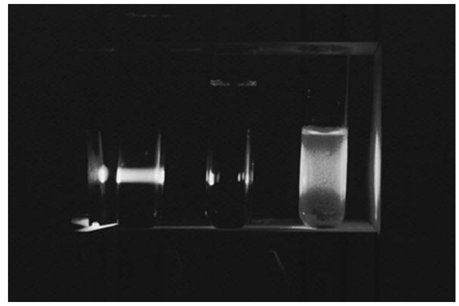
Maxwell: The electromagnetic field conveys electric and magnetic forces and light according to a specific set of mathematical formulae ('Maxwell's equations'). Electric and magnetic forces are propagated with the velocity of light

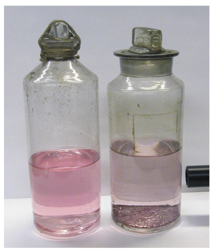
Lorentz: The electromagnetic field is a state of a rigid aether and is produced in the interaction of charged matter ("ions") and the aether. This interaction is governed by Maxwell's equations and the non-Newtonian 'Lorentz force'.

Einstein: the electromagnetic field has the mathematical structure of Lorentz' field concept, but it is not a state of an aether



Nanoscience

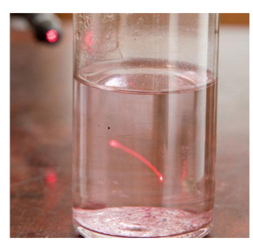




150 years old gold colloids of Faraday
on display at RI

Discovery of Faraday-Tyndall effect

Faraday realized that this cone effect was made because the fluid contained suspended gold particles that were too small to see with the scientific apparatus of the time but which scattered the light to the side (*Faraday-Tyndall effect*).



Faraday-Tyndall effect

Faraday is the father of modern nanoscience and nanotechnology.

Faraday's age, health and laboratory safety issues caught up with him

1866, Mrs. Faraday: "Don't you remember those beautiful gold experiments that you made?"

Faraday: "Oh yes, beautiful gold, beautiful gold"

8-25-1867, Faraday died while sitting in his chair at the age of 75

Priority Disputes

While the path is seldom straight, the road to discovery is almost always an exciting one.

Priority Disputes (Faraday)

- Electromagnetic motor (Wollaston and Davy)
- Liquefaction of chlorine (Davy)
- Magnetic induction (Italian researchers)

But, Faraday was grateful to Davy till the end: A revealing letter

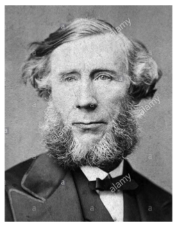
"You will observe that this took place at the end of the year 1812; and early in 1813 he requested to see me, and told me of the situation of assistant in the laboratory of the Royal Institution, then just vacant.

At the same time that he thus gratified my desires as to scientific employment, he still advised me not to give up the prospects I had before me, telling me that Science was a harsh mistress, and in a pecuniary point of view but poorly rewarding those who devoted themselves to her service. He smiled at my notion of the superior moral feelings of philosophic men, and said he would leave me to the experience of a few years to set me right on that matter."

Without Davy's faith and kindness to Faraday, it is likely we would never have been exposed to Faraday's brilliance, and physics may have progressed at a much slower pace.

A letter written to a friend in 1829

Similar yet dissimilar



John Tyndall
1820-1893

"Brothers in intellect, Davy and Faraday, however, could never have become brothers in feeling; their characters were too unlike. Davy loved the pomp and circumstance of fame; Faraday the inner consciousness that he had fairly won renown. They were both proud men. But with Davy pride projected itself into the outer world; while with Faraday it became a steadying and dignifying inward force."

"A father is not always wise enough to see that his son has ceased to be a boy, and estrangement on this account is not rare; nor was Davy wise enough to discern that Faraday had passed the mere assistant stage, and become a discoverer."

Faraday's advice for researchers
To err is human

"We are all liable to error, but ... we love the truth, and speak only what at the time we think to be the truth; and ought not to take offence when proved to be in error, since the error is not intentional, but be a little humbled, and so tum the correction to good account."

"The [natural] philosopher should be a man willing to listen to every suggestion, but determined to judge for himself. He should not be biassed by appearances; have no favourite hypothesis; be of no school; and in doctrine have no master. He should not be a respecter of persons, but of things. Truth should be his primary object. If to these qualities be added industry, he may indeed hope to walk within the veil of the temple of nature."

Davy's advice on doing research
To err is human

"I was perhaps wrong in publishing, in such haste, a new theory of chemistry. My mind was ardent and enthusiastic. I believed that I had discovered the truth. Since that time my knowledge of facts is increased since that time I have become more skeptical."

"Hypotheses . . . should be the instruments of thought, the secret amusements of the mind; but truth only should be brought to light."

"When we begin the study of any science... We ought to form no idea but what is a necessary consequence, and immediate effect, of an experiment or observation ... We should proceed from the known facts to the unknown."

Faraday's advice on publications
Never release results prior to publication

Priority dispute on the discovery of iodine with the gifted young chemist Joseph Gay-Lussac. Gay-Lu sac, Davy's exact contemporary.

Two not-so-well-known chemists, N. Clément and C. B. Desormes had reported that a strange new substance had been discovered in seaweed. Gay-Lussac was assigned to review their experiments and repeat them to make sure the results were correct. Six days before the announcement of the results by Gay-Lussac, Ampère, Clément, and Desormes paid a visit to Davy and showed him the sample. Davy immediately isolated and identified the element as iodine.

Gay-Lussac's short paper was actually presented and published first, on 12 December. Davy, taken by surprise, presented his to the Academie on 13 December, but antedated it to 11 December, and had it published as such in the Journal de Physique. He claimed, perhaps justly, that he had previously shared his key ideas with Gay-Lussac.

Davy's surprising sharpness in a 'priority' controversy was noticed by Faraday.

ChemMatters, December 2006, p. 18

Faraday's advice on publications
Never release results prior to publication

Trouble began when Faraday sent word of his discovery of 'induction' to French physicist J. N. P. Hachette.

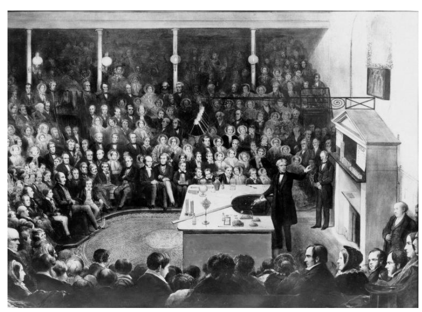
Three days later the magazine Le Lycee published a muddled account of Faraday's work attributed the discovery of induction to French scientists.

In January 1832, two Italian researchers read the first Lycee article, reproduced the experiments, and published their own paper on induction, taking care to properly credit Faraday for the discovery. But the journal in which their report appeared carried the date November 1831, giving the impression that the Italians, too, had preceded Faraday. (Although Faraday had announced his discovery to the Royal Society on November 24, 1831, his first paper on induction did not make it into print until early 1832.)

Faraday's advice on giving lectures

Michael Faraday's Advice to the Lecturer, R. Murray editorial, *Analytical Chem*., 6425, (2007)

Michael Faraday and the art of lecturing *Physics Today* **21**, *8*, 30 (1968)



M. Faraday

"In order to gain the attention of an audience---pay attention to the manner of expression. The utterance should not be rapid and hurried, but slow and deliberate, conveying ideas with ease. The lecturer should endeavor by all means to obtain a facility of utterance and the power of clothing his thoughts and ideas in a language smooth and harmonious and at the same time simple easy. A lecturer should exert his utmost effort to gain completely the mind and attention of his audience, and irresistibly make them join in his ideas to the end of the subject. A flame should be lighted at the commencement and kept alive with unremitting splendor to the end.

The generality of mankind can not accompany us one short hour unless the path is strewed with flowers"

Davy's advice on giving on lectures

"I was made to write out the first lecture entirely, and Davy took me into the lecture hall the evening before I was to talk and made me read it all out while Davy sat in the furthest corner and listened; and them Davy read the lecture while I listened. Next day I read it to an audience of about 150 to 200 people and they gave me a very generous plaudit at the conclusion."

John Dalton on his first lecture at Royal Institution in 1803

Faraday's advice on choice of research problems
Basic vs Applied Science

Faraday was not interested in pursuing the practical side of his invention: "I have rather ... been desirous of discovering new facts and new relations dependent on magneto-electric induction, than of exalting the force of those already obtained; being assured that the latter would find their full development hereafter."

Listen to the pioneers

Davy's pure scientific method:

Observation, Experiment, Analogy

Secret of Faraday's success as a scientific investigator

Work, Finish, Publish.

If I could live my life over again I would study mathematics; it is a great mistake not to do so, but it is too late now (Faraday 1857)

Transition from the Age of Steam to the Age of Electricity

Resources

National Magnetic Lab, USA

https://nationalmaglab.org/

Royal Institution, UK

https://www.rigb.org/whats-on

About Faraday and his experiments

https://nationalmaglab.org/customsearchresultmaglab?q=Michael+Faraday&cx=004099242236933193842%3A9shljmjve7a&cof=FORID%3A11&sa=SEARCH&x=0&y=0

The Electric Life of Michael Faraday, A. Hirshfield, 2006

Faraday Rediscovered, D. Gooding and F. A. J. L. James, 1985

Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics, N. Forbes and B. Mahon, 2014.