Newtonianism and Enlightenment Science

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History of Modern Physical Sciences

Newtonianism

Throughout the 18th century, Newton's system of the world replaced that of Descartes, first among philosophers and then in the universities – especially following the suppression of the Jesuits in the 1770s.

In the early period, it was especially hard for the French to appreciate the value of Newton's ideas.

One of the first to promote Newton to the general French public was Voltaire.

Voltaire (1694–1778)

Born François-Marie Arouet. (He adopted the name Voltaire in 1718). His father was a treasury official and his mother was from a noble house.

He was educated by the Jesuits.

Against his father's wishes he pursued a literary career as opposed to going into law.

He became famous for his wit and style.

Voltaire's Legacy

Voltaire constantly attacked the current social order – ridiculing organized religion, orthodox moral values, the Bible, and the establishment institutions.

Although he attacked religious institutions, he did have spiritual beliefs – he called himself a deist.

He helped develop a style of philosophical irony. He was arrested a few times and sent into exile for offending the powerful and for his non-conformist views.

- "I have only ever made one prayer to God: O Lord, make my enemies ridiculous. And God granted it."
- "All murderers are punished, unless they kill in large numbers and to the sound of trumpets."
- "It is lamentable, that to be a good patriot one must become the enemy of the rest of mankind."

Voltaire on France and England

Voltaire, *Letters on the English Nation*, 1734

"A *Frenchman* who arrives in *London* will find Philosophy, like every Thing else, very much chang'd there. He had left the World a *Plenum*, and he now finds it a *Vacuum*. At *Paris*, the Universe is seen, compos'd of Vortices of subtile Matter; but nothing like it is seen in *London*. In *France*, 'tis the Pressure of the Moon that causes the Tides; but in *England*, 'tis the Sea that gravitates toward the Moon… According to your *Cartesians*, every Thing is perform'd by an Impulsion, of which we have very little Notion; and according to *Sir Isaac Newton*, 'tis by an Attraction, the Cause of which is as much unknown to us… The very Essence of Things is totally chang'd. You neither are agreed upon the Definition of the Soul, nor of Matter."

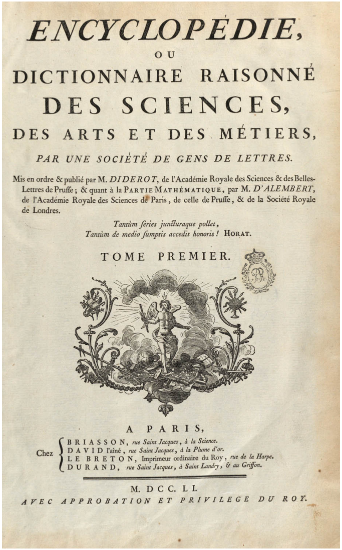
Voltaire on Newton and Descartes

Voltaire, *Letters on the English Nation*, 1734

"Very few people in *England* read *Descartes*, whose Works are indeed now useless. On the other Side, but a small Number peruse those of *Sir Isaac*, because to do this the Student must be deeply skill'd in the Mathematicks, otherwise those Works will be unintelligible to him. But notwithstanding this, these great Men are the Subject of every One's Discourse…

Indeed I believe few will dare compare Descartes' Philosophy to that of Sir Isaac Newton. The former is an Essay, the later a Master-Piece."

[The movie *Ridicule* (1996), directed by Patrice Leconte. Set some time later, but it captures the fascination with wit at the French court.]


ENCYCLOPÉDIE,
OU
DICTIONNAIRE RAISONNÉ
DES SCIENCES,
DES ARTS ET DES MÉTIERS,
PAR UNE SOCIÉTÉ DE GENS DE LETTRES.
Mis en ordre & publié par M. *DIDEROT*, de l'Académie Royale des Sciences & des Belles-Lettres de Pruſſe; & quant à la PARTIE MATHÉMATIQUE, par M. *D'ALEMBERT*, de l'Académie Royale des Sciences de Paris, de celle de Pruſſe, & de la Société Royale de Londres.
Tantùm ſeries juncturaque pollet,
Tantùm de medio ſumptis accedit honoris! HORAT.
TOME PREMIER.

A PARIS,
Chez BRIASSON, *rue Saint Jacques, à la Science.*
DAVID l'aîné, *rue Saint Jacques, à la Plume d'or.*
LE BRETON, Imprimeur ordinaire du Roy, *rue de la Harpe.*
DURAND, *rue Saint Jacques, à Saint Landry, & au Griffon.*
M. DCC. LI.
AVEC APPROBATION ET PRIVILEGE DU ROY.

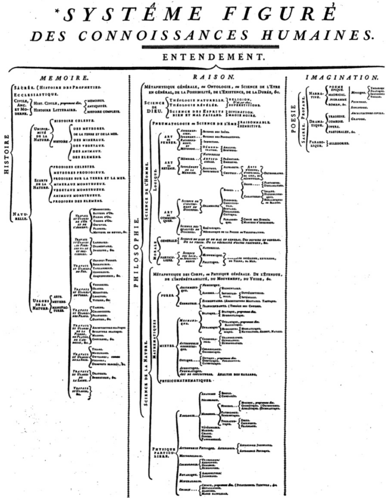
Encyclopédie ou Dictionnaire Raisonné de Sciences, des Arts et des Métiers

- First published 1751–1766, with later supplements and many translations, etc.
- Edited by Diderot, with d'Alembert's help for the mathematical sections.
- 35 volumes, 71,818 articles, 3,129 illustrations.
- The contributors were many of the most important scholars, thinkers and scientists in France. (Louis de Jaucourt wrote 17,266 articles.)

The work was part of a grand Enlightenment project to use the development of scientific and rational knowledge to *improve the social order*.

Many authors considered it their responsibility to not only record and preserve current knowledge and practice but also to criticize and make recommendations.

As a result, the French state saw fit to censure the work and a number of authors were arrested.

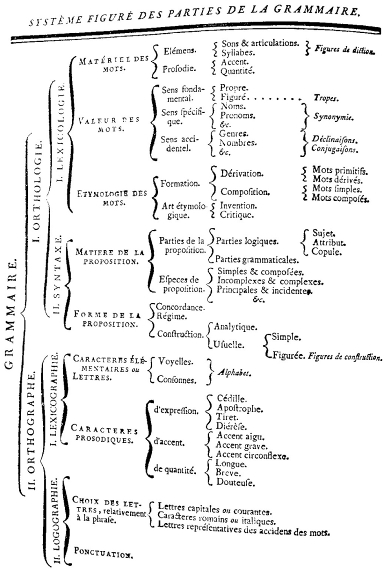


The Goal of *l'Encyclopédie*

Diderot, *l'Encyclopédie*, Preface, 1751

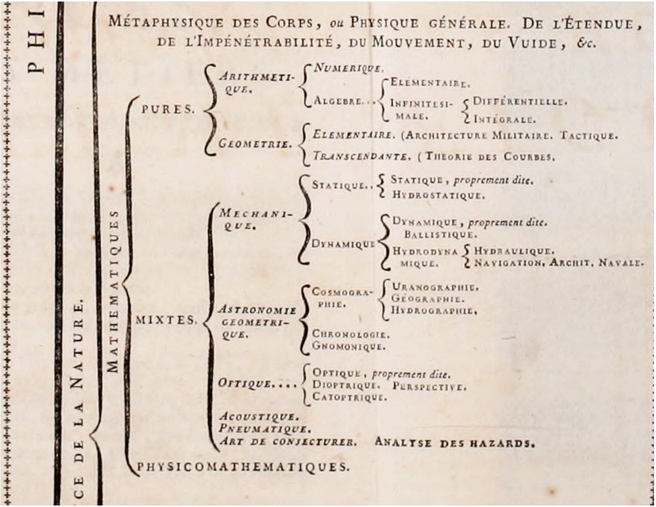
"… to collect all knowledge scattered over the face of the earth, to present its general outlines and structures to the men with whom we live, and to transmit this to those who will come after us, so that the work of the past centuries may be useful to the following centuries, that our children, by becoming more educated, may at the same time become more virtuous and happier, and that we may not die without having deserved well of the human race."

An Organization of Knowledge



l'Encyclopédie organized all human knowledge into a hierarchical tree-graph.

Organization of Knowledge, physics and mathematics



SCIENC
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ZOOLOGIE...
ANATOMIE
SIMPLE.
COMPARÉE.
PHYSIOLOGIE.
MEDECINE..
HYGIENE...
HYGIENE, proprement dite.
COSMÉTIQUE. (ORTHOPEDIE.
ATHLÉTIQUE. (GYMNASTIQUE.
PATHOLOGIE.
SEMEIOTIQUE.
THERAPEU-TIQUE.
DIETE.
CHIRURGIE.
PHARMACIE.
VÉTÉRINAIRE.
MANEGE.
CHASSE.
PESCHE.
FAUCONNERIE.
ASTRONOMIE PHYSIQUE.
ASTROLOGIE.
ASTROLOGIE JUDICIAIRE.
ASTROLOGIE PHYSIQUE.
METEOROLOGIE.
COSMOLOGIE.
URANOLOGIE.
AEROLOGIE.
GEOLOGIE.
HYDROLOGIE.
BOTANIQUE.
AGRICULTURE.
JARDINAGE.
MINERALOGIE.
CHIMIE...
CHIMIE, proprement dite. (PYROTECHNIE. TEINTURE, &c.
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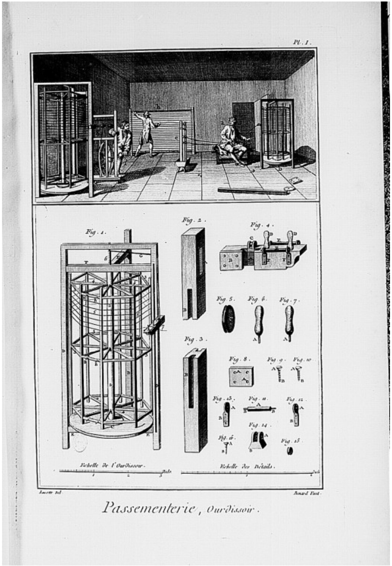
MAGIE NATURELLE.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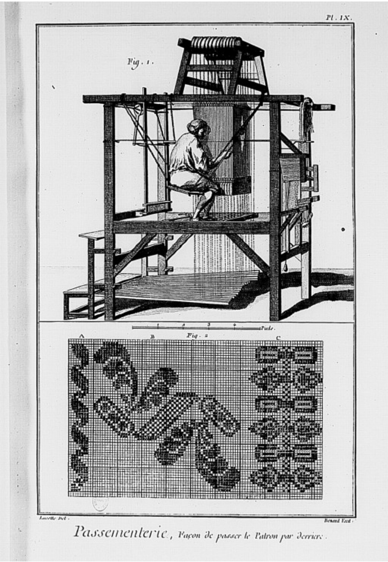
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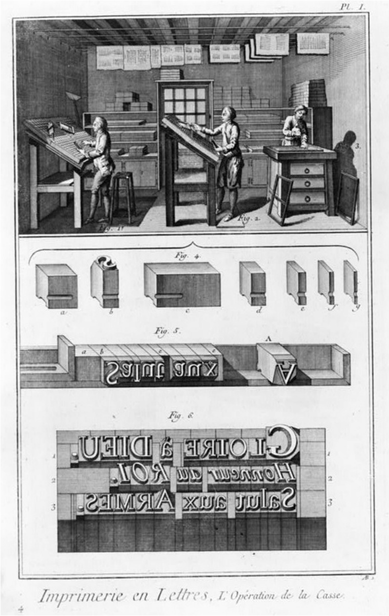
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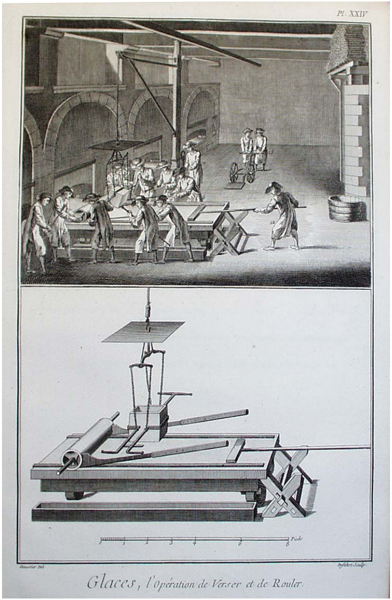
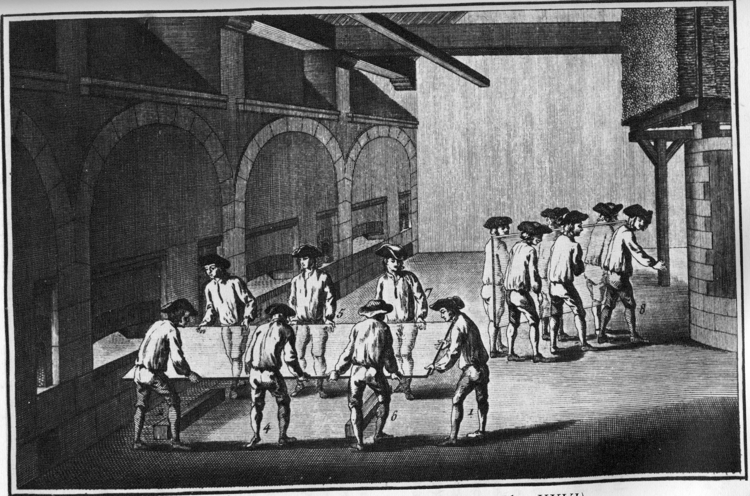
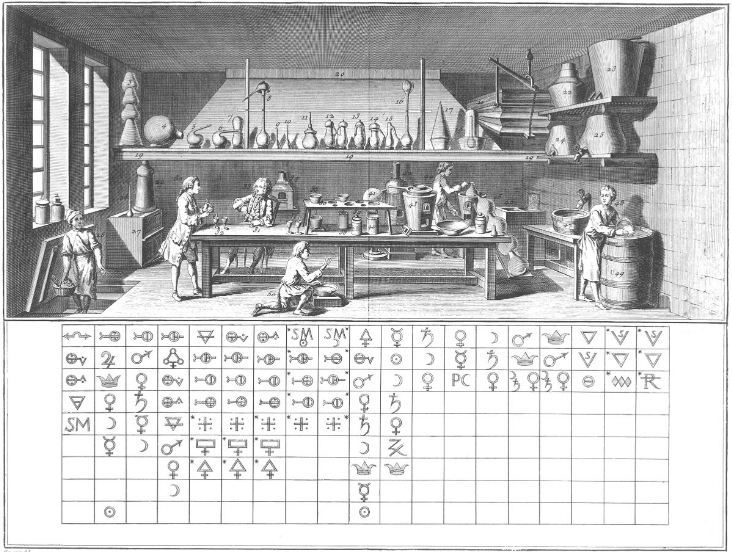
Imprimerie en Lettres, L'Opération de la Casse.


Pl. XXIV
Glaces, l'Opération de Verser et de Rouler.



Glaces: L'Opération de sortir les Glaces des Carcaises (Vol. IV, Glaces, *Plate XXVI)*



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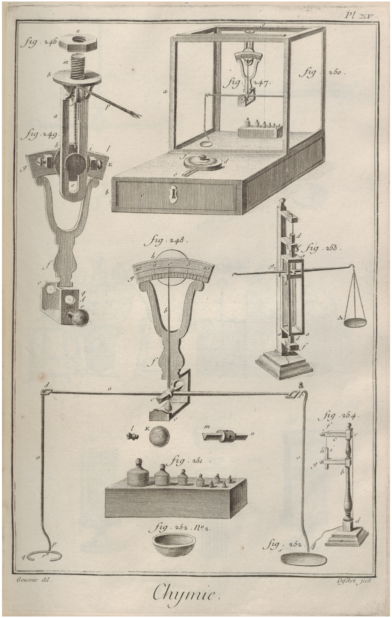
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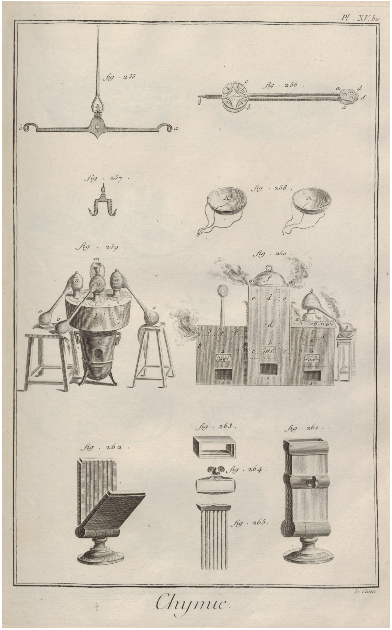
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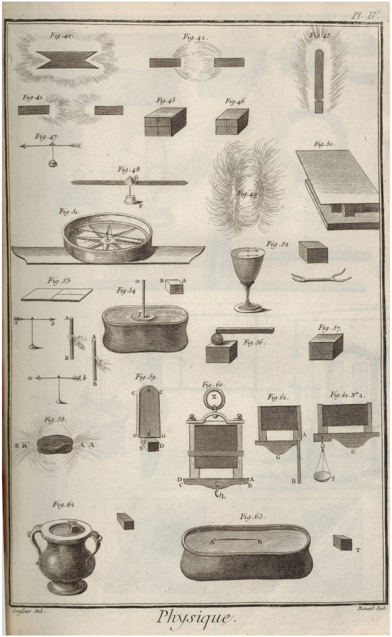
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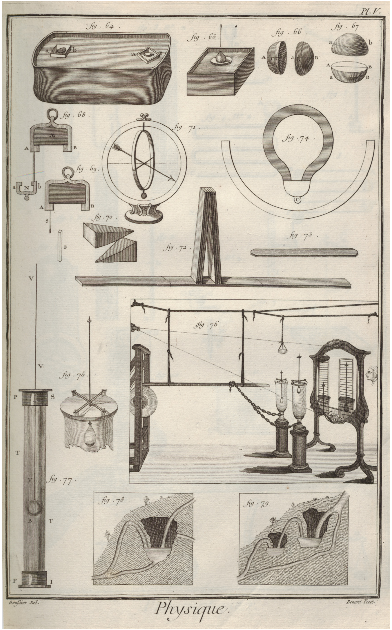
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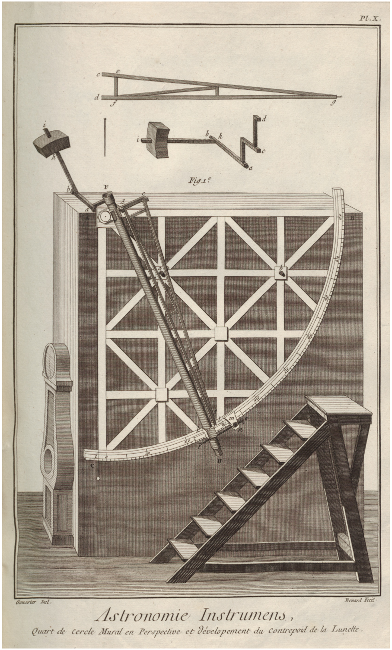
Pl. X.
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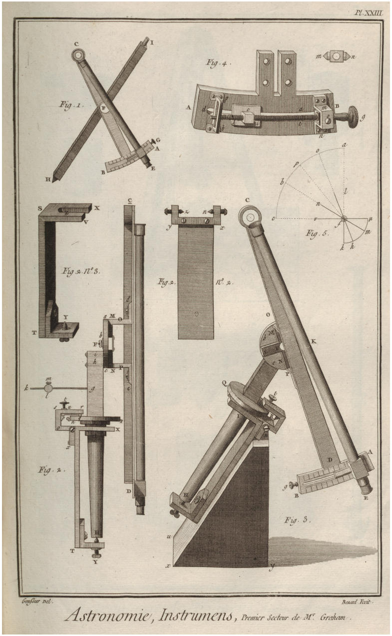
Benard Fecit.
Astronomie Instrumens,
Quart de Cercle Mural en Perspective et développement du Contrepoid de la Lunette.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Benard Fecit.
Astronomie, Instrumens, Premier Secteur de Mr. Graham.

A New System of Measurement

The development of the metric system is a fine example of the *scientistic movement* in Enlightenment France.

It was conceived as an idea to help the common people by making measurements universal and calculations simple. It was devised by elite scientists and bureaucrats and was initially largely rejected by the middle and lower classes.

Reformers in l'Académie saw the social changes of the French Revolution as a chance to institute the new system.

A number of international meetings were convened so that "all nations" might adopt the new system. These were only moderately successful. The French National Assembly struck committees to determine the fundamental units – whose members included A. Lavoisier, J.-C. Borda, P.S. Laplace, C.-F. Cassini, and so on.

Fundamental Units

The proposal of the committees was to base everything on two fundamental measures: weight and length.

The unit of weight, the gram, was to be that of 1cm^3 of pure water at $4°$ C.

- This was determined by Lavoisier.

The unit of length, the meter, was to be either the length of a seconds pendulum at sea level or one ten-millionth (1×10^{-7}, 0.0000001) of a quadrant of the earth's meridian through Paris. The committee decided on the later, although they still measured the pendulum as a provisional measure.

Two astronomers – J.B.J. d'Alembert (1749–1822) and P.F.A. Méchain (1744–1804) – were assigned the task of triangulating an arc of the meridian.

In 1793, d'Alembert headed north, Méchain went south.

The were interrupted repeatedly by wars and civil unrest – for example, the "Terror," 1793–95, war between France and Spain, and uprisings in the French countryside. But, in 1798, the work was done and an "international" conference was convened to announce the size of the new *meter*.

Resistance to Change

By the time France finally adopted the new measures in the 1840s, they were already in use in Holland and Belgium. Latin America was next, while Spain itself resisted.

The Germans adopted the system in the 1870s, when Prussia agreed not to impose its own measures on the rest of the German states. The Soviet Union went metric in the 1920s. China and India in the 1940s.

Japan permitted the metric system in 1921 but there was strong resistance. The process was only completed in the 1960s.

The introduction of the new measures was usually associated with social changes. Only the US and Liberia do not use this system for civic matters, but in many countries there are still many local measures, particularly in certain trade, or business, cultures.

18th Century Studies of Heat

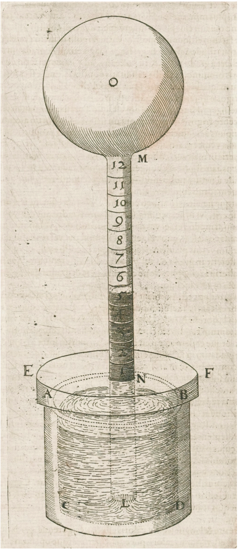
In the beginning of the century, natural philosophers vaguely assumed temperature was a *direct measure of heat*.

Black, and others, showed that this was not the case.

In the 18th century, the dominant model of heat was that of a *subtle fluid* – known as *caloric*. This accounted for the conservation of heat and its flow from hotter to colder bodies. (In the 19th century, this gave way to the mechanical theory of heat.)

Toward the end of the century Lavoisier and Laplace carried out experiments to try to precisely measure heat – that is, attempts to capture and measure *caloric*.

The Thermometer



A 17th c. "thermoscope"

For ancient and medieval philosophers, heat was thought to be a *quality* – like redness, or goodness.

In 1592, the Accademia Cimento – whose most famous member was Galileo – constructed the first water thermometer. It reacted very slowly and the scale was *arbitrary*. It was very sensitive to changes in atmospheric pressure.

By 1700, expanding-liquid thermometers were the norm. The scale was still *arbitrary*.

Scales and Heat

The early scales were perfectly arbitrary – *every thermoscope had its own scale*.

In 1742, Anders Celsius took 100 as the freezing point of water and 0 as the boiling point and divided the interval into 100 parts – that is, opposite to our current scale.

The thermometer *constructed* what it measured. In some sense, it *was* what it measured – that is, it created an equilibrium between measured and measurer.

The early experimenters assumed that there was some *thing* called heat, which was proportional to the expansion of some tangible fluid. We now know that the expansion is linearly proportional only in certain ranges.

In fact, a thermometer *does not measure heat*.

Joseph Black's (1728–1799) Studies on Heat

In the 1760s, Black carried out a number of experiments that clarified the difference between heat and temperature and lead to the ideas of *specific heat* and *latent heat*.

At the time, heat was assumed to be a fluid – that is, *caloric*. In this model, temperature is a measure of the *density* or *intensity* of the fluid, *not the total amount*.

Black on the Distribution of Heat

Black, *Harvard Case Studies...*

"An improvement in our knowledge of heat, which has been attained by the use of thermometers, is the more distinct notion we have now than formerly, of the *Distribution* of heat among different bodies...

We … perceive a tendency of heat to diffuse itself from any hotter body to the cooler around, until it be distributed among them, in such a manner that none of them are disposed to take any more heat from the rest. The heat is thus brought into a *state of equilibrium*. This equilibrium is somewhat curious. We find that when all mutual action is ended, a thermometer, applied to any one of the bodies, acquires the same degree of expansion: Therefore the temperature of them all is the same, and the equilibrium is universal."

Black on the Equilibrium of Heat

Black, *Harvard Case Studies...*

"If we take a thousand, or more, different kinds of matter, such as metals, stones, salts, woods, cork, feathers, wool, water … although they be all at first of different heats, let them be placed together in the same room without a fire, and into which the sun does not shine, the heat will be communicated from the hotter of these bodies to the colder, during some hours perhaps … at the end of which time, if we apply a thermometer to them all in succession, after the first to which it is applied has reduced the instrument to its own temperature, none of the rest are disposed to increase or diminish the quantity of heat which that first one left in it. This is what has been commonly called an *equal heat*… I call it the *equilibrium of heat*."

Black on Latent Heat

Black measured the time it took different mixtures of ice and water to climb from 0° C, the temperature of the ice, to 8° C, the temperature of his lecture room. He took these *time periods* as a *measure of heat* needed for the temperature change.

He concluded that the *amount of heat* required to melt a unit mass of ice – with no change in temperature – would heat the same amount of water from 0° to 78° C.

This extra heat is *latent* in the water and must be either given off or absorbed for a *change of state* to occur.

Black on Quantity of Heat

Black, *Lectures on the Elements of Chemistry...*

"I have ... put a lump of ice into an equal quantity of water, heated to the temperature 176 [80° C], and the result [after some time] was that the fluid was no hotter than water just ready to freeze. Nay, if a little sea salt be added to the water, and it be heated only to 166 [74.44° C] or 170 [76.66° C], we shall produce a fluid sensibly colder than the ice was in the beginning, which has appeared a curious and puzzling thing to those unacquainted with the general fact."

Black on Specific Heat

By studying heat transfer between different bodies heated to different temperatures, Black concluded that each substance has a unique *capacity to retain* latent heat.

Black, *Lectures on the Elements of Chemistry...*

"…Different bodies, although they be of the same size, or … weight, when they are reduced to the same temperature or degree of heat, whatever that may be, may contain very different quantities of the *matter of heat*; which different quantities are necessary to bring them to this level, or equilibrium, with one another."

This capacity was called a substance's *specific heat* by J.C. Wilcke (1732–1796) in Sweden.

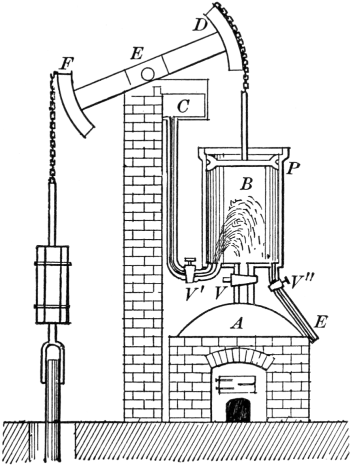
Heat and Industry

Heat *work* – mostly from coal – was an important component in the early industrial revolution, but these technological and industrial changes were not driven by scientific research – in fact, the scientific work was motivated by the technology.

Even the earliest steam engines – such as that made by Newcombe in 1712 – were not built with much theoretical design.

By the end of the century this was beginning to change.

Early Steam Engines



An atmospheric steam engine

The early steam engines were very inefficient.

They were powered by the low pressure created by condensing steam instead of the high pressure of the steam itself.

The chamber labeled *B* was sprayed with water causing the steam to condense, pulling the piston down.

The Discovery of Static Electricity

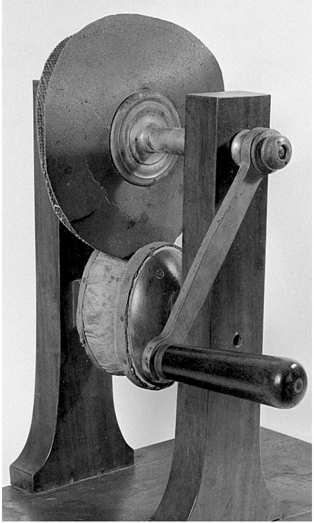
It had been known since antiquity that rubbing amber (and later glass) produced an *attractive effect* on certain substances such as straw, pith, cork and so on.

- The term *electricity* derives from the Greek word for amber.

In the 18th century, natural philosophers began to experiment with and eventually measure static electricity. They developed a number of different theories to explain the effects they produced and observed.

Because the first current-producing battery was not made until the turn of the 19th century, all of the theories of electricity in the 18th century were specific to the static field.

Demonstrating Electricity



Galvani's Electrostatic Device

Early *electricians* – which was the name used at the time – noticed that some bodies, such as amber, glass, wax, feathers, cork, could be "electrified" while others could not, such as metals, liquids, people.

- Some could hold a static charge, others could not.

Electrified bodies could pass on the electrical effect to other bodies capable of being electrified.

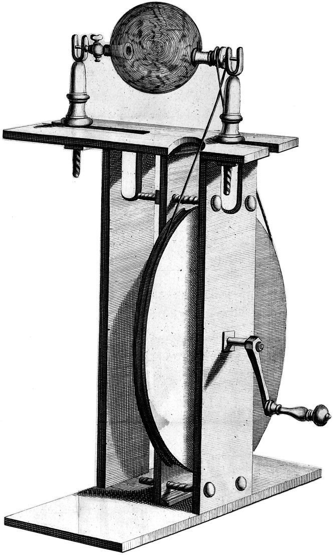
The demonstrators at the societies (Hauksbee and Desaguliers, Nollet) built machines for producing larger and larger amounts of static charge.

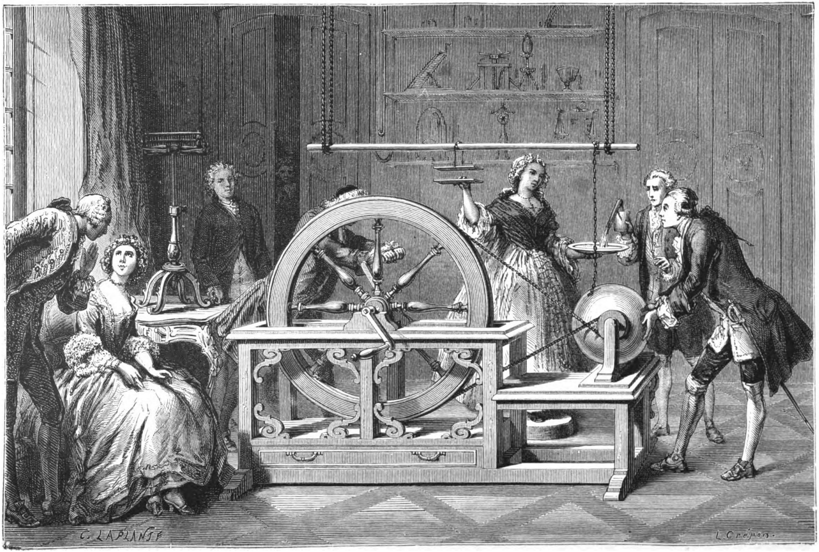
Hauksbee's Electrostatic Machine

Hauksbee developed his electrostatic machine while studying *barometric light* – that is, electrical sparking in low pressure.

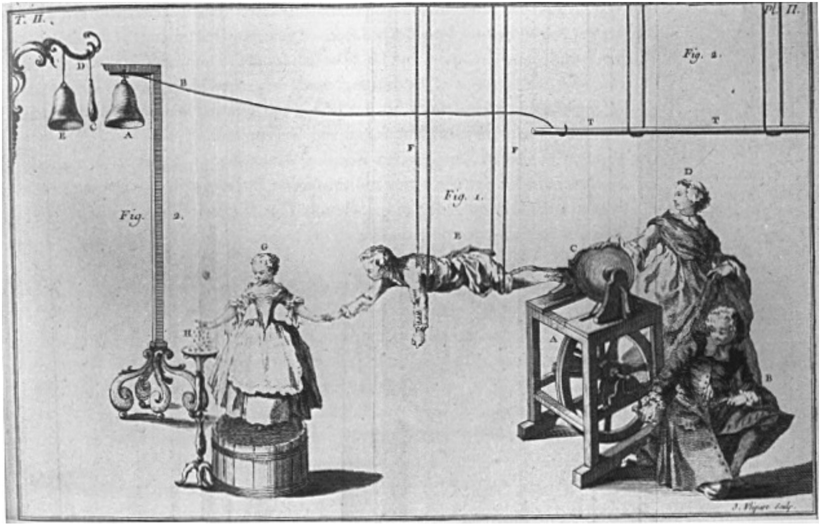
The large wheel is turned, causing the glass bulb to spin rapidly. If one holds one's hand near the bulb, a charge develops.

Or the bulb can be filled with a rotating whisk which will produce a charge in the bulb.





Jean-Antoine Nollet's Electrostatic Machine



The “electric boy” demonstation

Attraction – Contact – Repulsion

The standard set of phenomena which was observed in static electrical demonstrations was “attraction, contact, repulsion.”

- An “electrifiable” body (an insulator) was first attracted to the charged body, it made contact with the charged body and was then repelled.

Some substances (straw, cork, glass, etc. – that is, insulators) demonstrated this phenomenon, while others (metals, liquids, people, etc. – that is, conductors) did not.

Natural philsophers interpreted this by either claiming that the electrical force was capable of both attracting and repelling, or by claiming that there were two kinds of electrical force.

Early Theories of Electricity

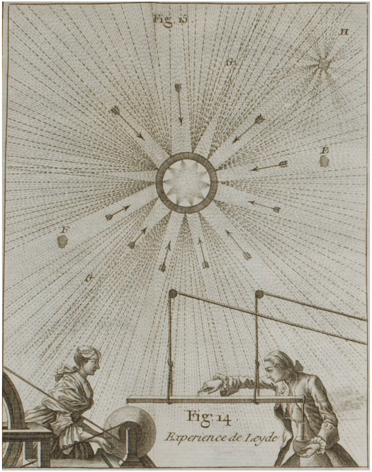
There were a number of conflicting, *non-quantitative* theories.

They all involved the natural-language concepts like *effluvia* and *atmosphere*.

The fundamental entity was taken to be an *electrical fluid* which exerted *a force at a distance*.

- Its motion caused a violent discharge – an effluvia – and its presence induced an effect in nearby objects – an atmosphere.
- Different effects were produced by the direction of the motion or force.

Nollet's Theory



- *E* and *F* have no electrical atmosphere, hence they are drawn into the central body.
- The *G*s are non-electrifiable bodies, hence they are not attracted.
- *H* is an electrifiable body that has touched the central body and acquired its own atmosphere. The two atmospheres somehow interfere with each other and *H* is repelled.

This was a purely descriptive, qualitative account.

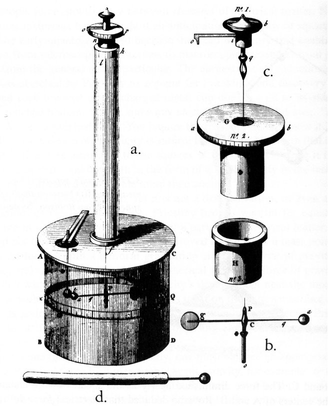
In 1746, von Kleist made the first *Leyden Jar* by accident – he put a nail into a bottle of liquid and charged it. He gave himself a massive shock.

He tried it out on some children, who were all *knocked down* by the force.

Mussschenbroek to Réaumur, 1746

"I would like to tell you about a new, but terrible experiment, which I advise you never to try yourself, nor would I, who have experienced it and survived, by the grace of God, do it again for all the kingdom of France... my whole body quivered just like someone hit by lightning … the arm and the entire body are affected so terribly I cannot describe it. I thought I was done for."

Quantitative Approaches



Coulomb's torson balance

Aepinus, in 1757, developed a purely *instrumentalist* theory that explained all known electrical effect in terms of an algebra of positive and negative states.

Toward the end of the 18th century, electricians began to develop *quantifiable* concepts (*charge*, *capacity*, *potential*, *tension*, etc.) and to make instruments to measure of them.

In 1785, Coulomb designed an instrument to determine the *force of electrical charge*. He found that this force, like gravity, varies inversely as the square of the distance ($F \propto 1/d^2$).

- Born into a wealthy farming family.
- Attended Caen University for a clerical career, but there discovered his mathematical talent.
- He left for Paris at the age of 22, and was elected to l'Académie at 24.
- He began teaching and working under the direction of the mathematician d'Alembert.
- He quickly established himself as one of the best mathematicians in the world.
- He spent his entire career in, or near, Paris.

Laplace's Life and Legacy

Laplace was a political opportunist who supported every government that came to power – the Ancient Regime, the Republic, Napoleon, new Bourbon monarchy.

He worked at, or helped found, many of the key French scientific institutions of his time – *l'Académie*, *École Normale*, *Institute National* (Rev. *AS*), *Bureau des Longitudes*, etc.).

He was a central figure in the new school of French mathematics and rational mechanics – a leading proponent of the new Newtonianism, in which every physical phenomena was reduced to the mathematics of points of matter and forces acting at a distance.

- "All the effects of Nature are only the mathematical consequences of a small number of immutable laws."

He maintained control of this program through the high caliber of his own work, by setting prize questions, overseeing course syllabi and textbooks, and so on.

Laplace's Work

He worked on mathematics and the mathematical foundations of a number of important physical theories – such as as the theory of differential equations, probability and error theory, the application of differential equations to mechanics, particularly celestial mechanics, the mathematical study of "imponderable" fluids, particularly *caloric*.

The two most important areas of his work were carried out in parallel forms: (1) a more philosophical, popular work for the general, educated public and (2) a technical mathematical treatise for the expert scientist.

- *Exposition du système du monde*, 2 vols., 1796 (year IV).
- *Traité de mécanique céleste*, 5 vols., 1799–1823.
- *Théorie analytique des probabilités*, 1812.
- *Essai philosophique sur les probabilités*, 1814.

Celestial Mechanics

Laplace modeled the entire solar system using differential equations. He took it to be composed of points of matter acting upon each other at a distance. By integrating from this local model, he could derive equations for the whole system.

Newton had not been able to solve the 3-body problem and had suggested that God might need to intervene in the world from time to time to stabilize the solar system. Laplace was particularly interested in showing that the system was naturally stable. Laplace solved many cases of this problem and argued that divine intervention was unnecessary for the solar system. He also argued that God was unnecessary to explain the origins of the solar system.

On being presented with one of the volumes of his work, Napoleon is said to have asked about the role of God. Laplace replied, “Sire, I have no need of that hypothesis.”

Laplace's Determinism

Following the ideas of Leibniz, Laplace believed in complete *physical determinism*.

Laplace, *Mémoire sur la probabilité ...*, 1776

"An intelligence which at a given instant comprehends all the relations of the universe could state their positions, motions and general effects at any time in the past or future. So it is that we owe to the weakness of the human mind the science of chance or probability."

There is no such thing as *real chance*. It is just a word that we use loosely for our own ignorance.

The world itself is absolutely *determined*, and all past and future states are in principle *knowable*.

Laplace's Reductionism

Laplace claimed that every natural phenomena can be reduced to material points and forces acting between them.

Laplace, *Mécanique céleste*, vol. 5, 1823

"The phenomena of expansion, heat and vibrational motion in gases are explained in terms of attractive and repulsive forces which act only over insensible distances … All terrestrial phenomena depend on forces of these kinds, just as celestial phenomena depend on universal gravitation. It seems to me that the study of these forces should now be the chief goal of mathematical philosophy."

This means that all sciences can eventually be reduced to this "mathematical philosophy." Experiments are used to discover the laws which govern the relationship between matter and force. Mathematics is used to develop full models which will exactly describe all physical processes.

Overview

In this lecture we have covered a number of key aspects of 18th-century, or Enlightenment, science.

- We have seen the prevalence of Newtonian ideas, especially as defined by French *philosophes*.
- We have looked at the great encyclopedia project of Enlightenment France.
- We have covered the studies of heat and static electricity, and the beginning of quantification.
- We have looked at the project to rationalize quantification.
- We have looked at the philosophical ideas of *determinism* and *reductionism*, especially in the work of Laplace.