The Contexts and Ideas of 19th-Century Science

Waseda University, SILS,
History of Modern Physical Sciences

National Rivalries and International Trends

By 1900, the research productivity (in papers per capita) of physicists was about the same in England, France, Germany, Holland, the US and Japan. The per capita numbers of physicists and physics students were also close. In chemistry, however, Germany was far ahead in terms of research, training and private jobs. It was the German companies that established the clearly defined tradition of the private research laboratories staffed with theoretically trained chemists.

Throughout the 19th century, every industrialized nation reformed its education system (some more than once); international meetings were convened to discuss consistency in units and measures; national institutes were established to develop standards and coordinate practical and theoretical work. This was particularly important for developing industries. By 1900, there was considerable international consensus on the problems that defined the different disciplines and the way to train the next generation of practitioners.

Theory and Practice

The 19th century was often called the *Age of Science*. By the end of the century, there was an incredible optimism about the power and benefit of science and the technologies it could produce. During the century, both chemistry and physics developed considerably in both theory and practice. Astronomy, which was the oldest exact theoretical science, continued to be developed throughout the century.

The driving force of theoretical physics was mathematics, while theoretical chemistry was still firmly based in laboratory practice. Astronomy both continued its ancient practice of increasing precision and using mathematical modeling, but it also incorporated new methods from physics and chemistry. These different sciences were institutionalized in different types of spaces. We will look at a few striking examples.

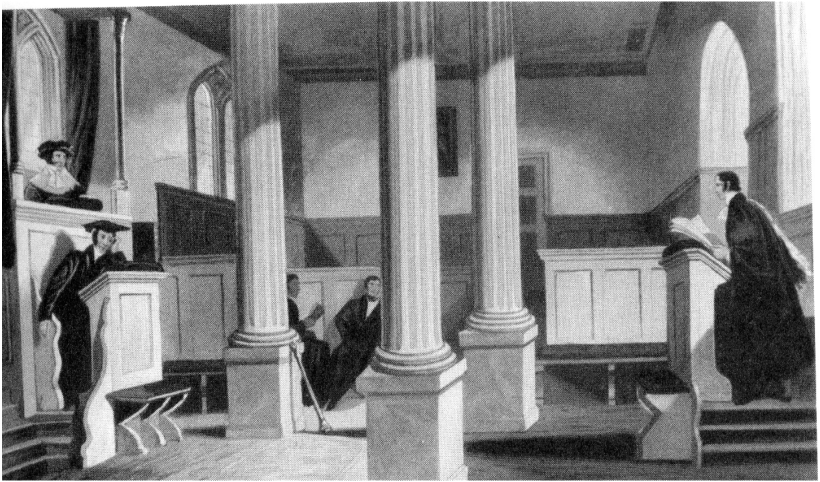
Cambridge University

Throughout the century, Cambridge University became a key training ground for British mathematical physicists. Initially, the mathematical curriculum was still based on Newton's *Principia Mathematica* and his *fluctions* methods in the calculus. In 1811, a group of young mathematicians – C. Babbage, J. Herschel, G. Peacock, and others – formed the Analytical Society to introduce the new French and Continental methods.

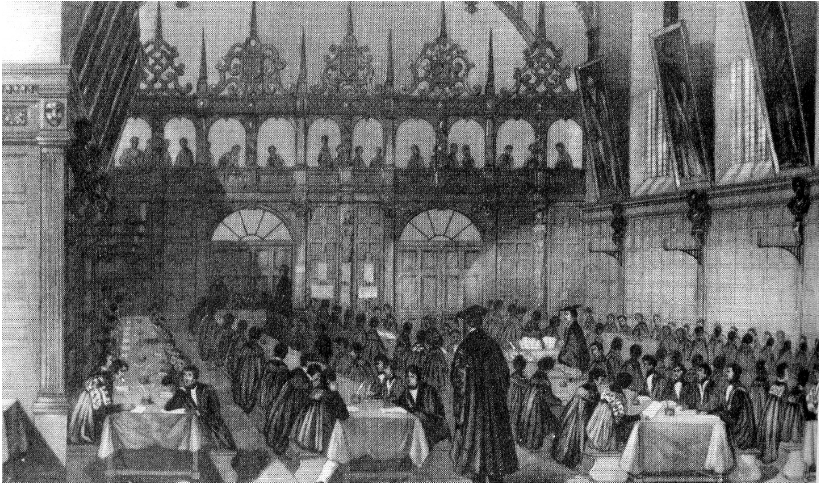
In the 19th-century tripos system, students – initially all male – went to lectures and read with tutors for four years in anticipation of nine full days of examinations. Originally the tripos exams were oral, but in the early decades of the 19th century they were changed to being written.

The degree was granted solely on the basis of a successful examination. The examinations were ranked and the outcome was of considerable local and national interest.

An Oral Exam at Cambridge



The Cambridge Written Exams



Students write the mathematical tripos; spectators watch from the balcony.

Cambridge Exam Culture

Wright's tutor at Cambridge:

"… all things – prizes, scholarships, and fellowships, are bestowed, not on the greatest readers, but on those who, without any assistance, can produce the most knowledge on paper. You must hence forth throw aside your slate … and take to scribbling upon paper. You must write out all you read, and read and write some six to eight hours a day."

The honors graduates were groups into classes: wranglers, senior optime and junior optime. The wranglers were ranked by number: Senior Wrangler, 2nd Wrangler, and so on. Professors might give some lectures in topics relating to the tripos, but the key to success in the examinations was a personal tutor or coach. Likewise, the key to institutional change was through the examination problems. If new methods, and fields were to be studied, they had to be placed on the tripos.

Many important British mathematicians and physicists were among the wranglers. From Japan, Dairoku Kikuchi 菊池 大麓 (1855–1917), the first professor of mathematics at Tokyo University, was the 19th wrangler in 1877.

“Above the Senior Wrangler …”

Mathematical Tripos, Part I. 1890

MODERATORS: WALTER WILLIAM ROUSE BALL, M.A., *Trinity College.*
ARNOLD JOSEPH WALLIS, M.A., *Corpus Christi College.*

EXAMINERS: WILLIAM LOUDON MOLLISON, M.A., *Clare College.*
EDWARD GURNER GALLOP, M.A., *Gonville and Caius College.*

WOMEN

Wranglers.

FAWCETT, P. G. Newnham
(above the Senior Wrangler)
Field, F. A. Girton
(equal to 21)
Lea, M. Girton
(between 27 and 28)

Senior Optimes.

Vinter, F. V. Girton
(between 40 and 41)
McAulay, M. Newnham
(equal to 41)
Webster, J. B. Girton
(equal to 45)
Appleyard, E. Newnham
(equal to 46)
McAfee, M. Girton
(equal to 47)
Deckers, A. Newnham
(between 53 and 54)
Lloyd, E. M. Newnham
(equal to 55)
Atherton, M. R. Newnham
(equal to 57)
Gaul, L. J. Girton
(equal to 57)
Parsons, E. M. Girton
(equal to 62)

Junior Optimes.

Tabor, M. E. Newnham
(between the brackets 72 and 75)
Hodge, M. A. Girton
(equal to 77)
Gullan, C. J. Girton
(equal to 83)
Crook, F. L. Newnham
(equal to 91)

Mathematical Tripos 1870s-1880s

The nine days of the exam were divided into two stages: three days of stage I, a day of easy questions from stage II, five days of stage II.

Stage I: Euclid, arithmetic, algebra, trigonometry, mechanics, statics, early sections of the *Principa* (in Newton's style), hydrostatics, geometric optics, elementary astronomy.

Stage II: Theory of equations, analytical geometry, calculus, differential equations, probability (error theory), later sections of *Principa* in more modern style, dynamics, hydrodynamics, theory of sound, physical optics, waves and vibrations, Fourier series, heat, electricity, magnetism.

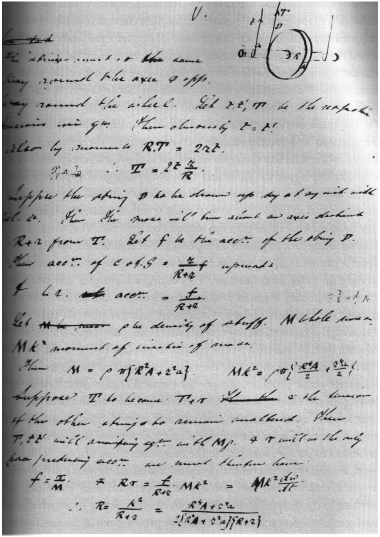
Another major institution responsible for the rise of theoretical physics was the University of Göttingen. At Göttingen the emphasis was on research, as opposed to education. There were *philosophical seminars* in both physics and mathematics. Researchers would work under the direction of a professor, and present their research at the seminar. The atmosphere was very competitive.

The Göttingen mathematicians collected a large mathematics library and conducted their seminars surrounded by books. They also had a habit of taking long hikes together and discussing mathematics while they walked. In both the seminars and on the hikes, junior members were encouraged to challenge the ideas of the senior members. Those who did not, were regarded as unlikely to succeed in the theoretical sciences.

The Importance of Theory

Both of these centers were almost entirely theoretical. The only equipment was paper and pens.

Every new mathematical theory of the 19th and early 20th century had to pass the gauntlet of these centers. In Cambridge, it had to become part of the tripos exam. In Göttingen, its problems had to become part of the research tradition.



An exam paper from Cambridge

Research Laboratories in France

To complement this rise in theoretical approaches, other institutions began to place an increasing emphasis on practical research.

The most important research in chemistry after the Napoleonic period was in the private school of Arcueil, north of Paris – where chemists like Laplace and Berthollet worked, and which had a laboratory and a journal.

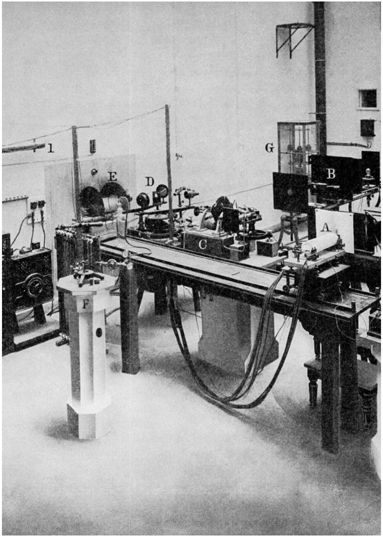
In general, professors taught to large classes where the emphasis was on lecture presentation and rhetorical style. The key to a successful scientific career was based more on examinations than research. By mid-century, the French had fallen behind the Germans, and even the English in laboratory research. After their defeat in the Franco-Prussian war, 1871, the French began to reform on the German model.

Research Laboratories in Germany

The German university focused on *seminars* of small groups of students working on specialized topics. The seminars in physics and chemistry became the basis for adding research laboratories.

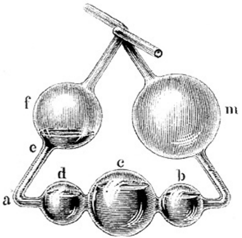
The first successful example of such a research lab was Liebig's chemistry lab at Giessen.

In 1884, the Physikalisch Technische Reichsanstalt was set up with von Helmholtz as director.



Physikalisch Technische Reichsanstalt

Liebig's Laboratory



Liebig's Apparatus, for isolating carbon

Julius Liebig (1880–1938) was trained in Paris, under J.L. Gay-Lussac, and returned to Germany with the intention of starting a new kind of training program.

His group was key in founding the new discipline of *organic chemistry* and developing practical methods that could be used in industry. His lab was the first example of a factory-like research facility – he assigned research topics, established technique and instrumentation, arranged access to publication, and placed his graduates in positions – academic, industry, and government. Students came to him from many different countries.

Justus Liebigs chemisches Laboratorium auf dem Seltersberg zu Gießen um das Jahr 1840.

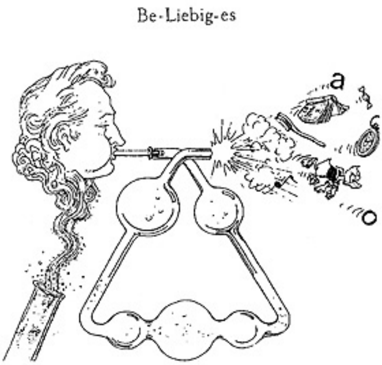
(Erbaut vom Universitäts-Baumeister Hofmann im Herbst 1839.)

Liebig's Influence

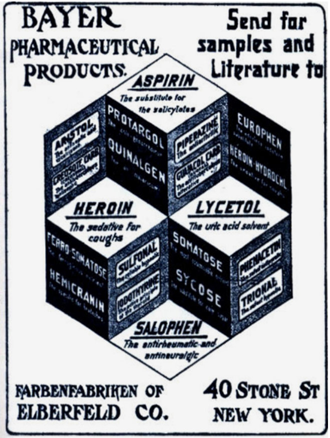
Liebig's potash apparatus was used to determine the carbon content of organic substances. It became symbolic of the power of organic chemistry.

Liebig's students filled the ranks of research chemists in Germany, Great Britain and the US.

Liebig showed that chemistry could lead to material wealth and progress.



Beliebig = anything



Bayer advertising new products

Chemistry was the first science to produce commercially viable products in the lab. The early industries that employed research chemists were textiles (aniline dyes), pharmaceuticals, agriculture, and so on.

The research chemists, trained in the universities, could also be hired into industrial jobs. A number of university professors founded their own companies.

Research in Great Britain

The Royal Institution was founded in 1800 with a charter promoting research and a small basement laboratory – some of the first early researchers were H. Davy, M. Faraday, and so on.

When William Thomson started in Glasgow, in 1845, there was no lab associated with natural philosophy. He annexed a nearby room and started using his students as lab assistants.

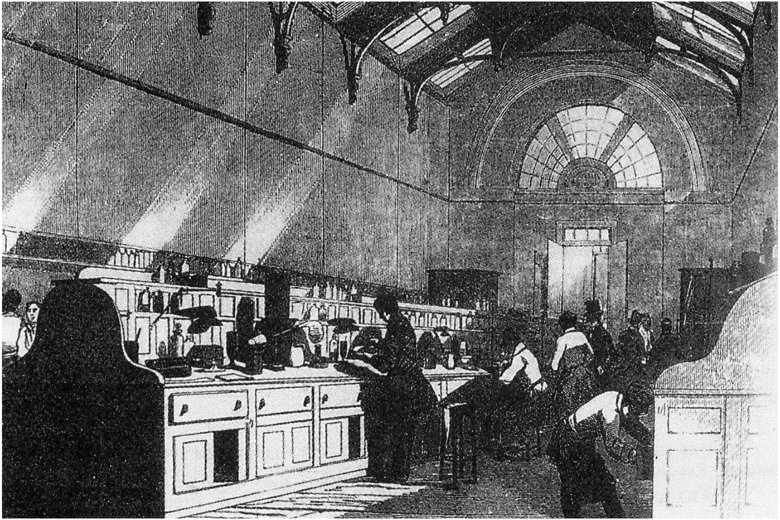
The dissenting schools – for example, University College London – and provincial universities – example, Manchester – set up research courses well before Oxford and Cambridge.

The Cavendish at Cambridge University was opened, in 1874, under the direction of James Clerk Maxwell. It became one of the most important research labs in the world.

The Laboratory at the Royal Institution

Faraday at the Royal Institution

Teaching Laboratory at University College



The Cavendish Laboratory

The Cavendish Laboratory was established at Cambridge with money from the House of Devonshire.

It was meant to train researchers in physics. The directors of the lab were chosen from the most important British physicists – J.C. Maxwell, Lord Rayleigh (John Strutt), J.J. Thomson, and so on.

The goal was to integrate training in research with a university education, in order to move away from the dominating influence of the mathematical tripos.

Maxwell's Opening Lecture at the Cavendish:

"In a course of Experimental Physics we may consider either the physics or the experiments as the leading feature. We may either employ the experiments to illustrate the phenomena of a particular branch of Physics, or we may make some physical research in order to exemplify a particular experimental method… We should begin, in the lecture room, with a course of lectures … aided by experiments of illustration, and conclude, in the Laboratory, with a course of experiments on research."

Maxwell: Experiments

Maxwell's Opening Lecture at the Cavendish:

"Experiments of illustration may be of very different kinds. Some may be adaptations of the commonest operations of ordinary life, others may be carefully arranged exhibitions of some phenomenon which occurs only under peculiar circumstances… Their aim is to present some phenomena to the senses of the student in such a way that he may associate with it the appropriate scientific idea. When he has grasped this idea, the experiment which illustrates it has served its purpose.

In experiments of research, on the other hand, this is not the principle aim… In experimental researches… the ultimate object is to measure something which we have already seen – to obtain a numerical estimate of some magnitude… Experiments of this class… are the proper work of a Physical Laboratory."

The Cavendish Laboratory

Research in Japan

Tokyo University was founded in 1877 from a combination of existing schools. It was regarded as a training school for officials. Interest in research developed slowly, mostly by PhD students returning from abroad.

- Tokyo Meteorological Observatory, 1875; The Geological Survey Institute, 1882.

In the 19th century, the focus was almost entirely on training, not research.

Mendenhall and his four students in Japan "built everything with their own hands" because there was "no experimental equipment at all."

Yamagawa on the conditions in his lab:

"Unfortunately, we are are dependent on foreign supplies… While poorly equipped for work in electricity and magnetism, we do have equipment for optics, acoustics and heat studies."

Research in the US

In the 19th century, many Americans went to Germany to take a PhD in a scientific field. By the end of the century, Americans were less enthusiastic about German chemistry and many completed their PhDs in the States. It was clear that the US research infrastructure was now close to parity with Europe.

On the other hand, in the early 20th century, the new quantum mechanics brought the Brits and Americans back to Germany. They returned to positions in their home countries bringing both the theories and methods they had learned abroad.

New Researchers

In 1874, Sonia Kovalevsky was the first woman granted a PhD (Göttingen, mathematics). Others followed in various fields – almost all in the sciences, in the early period. They found it easier to obtain degrees abroad and more often than not could not secure an academic or research job. In 1890, Philippa Fawcett was ranked "above the senior wrangler."

In most European countries besides the German lands, Jewish scientists were also discriminated against all throughout the century. Gibbs was the first Jew to receive a PhD in the United States (Yale, 1863).

The first black American to receive a PhD was Bouchet (Yale, 1876). Up until the 1950s, about a dozen black Americans took PhDs in physics, four dozen in chemistry. Almost all of them (96%) taught at one of the Historically Black Colleges (HBCs) – then called the Negro Colleges.

Force

Forces – direct, or at a distance, attractive or repulsive – were used to explain interactions between physical bodies.

Newton, *Principia*:

"The whole business of philosophy seems to consist in this – from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena."

Newton, *Optics*:

"Perhaps God maintains his creation through the action of several aethers, subtle and elastic fluids. Some 'secret principle of unsociableness' and the contrary."

These forces were used to explain electrical and magnetic phenomena, cohesion of fundamental particles, capillary action, elasticity and chemical combination and separation, etc.

A Proliferation of Forces

Laplace:

"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."

Contrary to Newton's 1st rule of philosophy, scientists were compelled to invoke a growing number of forces to account for the known phenomena – ponderable matter was cohering and gravitating; the imponderable matter of heat (caloric) was self-repellent; light, electricity and magnetism were both attractive and repulsive by circumstance, and so on. Perhaps physical state was determined by forces: solids, elastic fluids (airs), inelastic fluids (liquids).

A Unified Force Theory

In the mid-18th century, Rudjer Boscovic (1711–1787) – a Croatian Jesuit – had proposed that the whole physical world could be explained by force alone. Matter would explained by infinitesimal force points.

The direction (attractive or repulsive) and strength of the force was given by an *as-yet-unknown* function of the distance from the point, $f(d)$.

Boscovic was able to use this theory in a vague way to give theoretical explanations for a wide number of phenomena but he was never able shed any light on the central problem of determining the function $f(d)$.

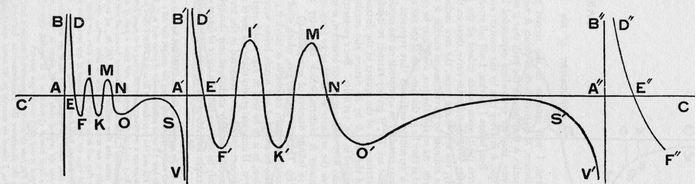


Fig. 14.

Boscovic on Forces

Boscovic, *Theory of Natural Philosophy*, 1763:

"Matter is unchangeable, and consists of points that are perfectly simple, indivisible, of no extent, and separated from one another; that each of these points has a property of inertia, and in addition a mutual active force depending on the distance in such a way that, if the distance is given, both the magnitude and the direction of this force are given...

If the distance is altered, so also is the force altered; and if the distance is diminished indefinitely, the force is repulsive, and in fact also increases indefinitely; whilst if the distance is increased, the force will be diminished, vanish, be changed to an attractive force that first of all increases, then decreases, vanishes, is again turned into a repulsive force, and so on many times over; until at greater distances it finally becomes an attractive force that decreases approximately in the inverse ratio of the squares of the distances."

Boscovic on Matter

Boscovic, *Theory of Natural Philosophy*, 1763:

"The primary elements of matter are … perfectly indivisible and non-extended points; they are so scattered in an immense vacuum that every two of them are separated from one another by a definite interval; this interval can be indefinitely increased or diminished, but can never vanish altogether without compenetration of the points themselves; for I do not admit as possible any immediate contact between them…

On the contrary, I consider that it is a certainty that, if the distance between two points of matter should become absolutely nothing, then the very same indivisible point of space, according to the usual idea of it, must be occupied by both together, and we have true compenetration in every way. Therefore, indeed I do not admit the idea of vacuum interspersed amongst matter, but I consider that matter is interspersed in a vacuum and floats in it."

Boscovic's Reductionism

Boscovic, *Theory of Natural Philosophy*, 1763:

"The principles of chemical operations are derived … from the distinctions between particles; some of these being inert with regard to themselves and in combination with certain others, some attract others to themselves, some repel others continuously through a fairly great interval; and the attraction itself with some is greater, and with others is less, until when the distance is sufficiently increased it becomes practically nothing… In this case, there follows another law of forces for the compound particles, which is different to that which we saw obeyed by the simple particles. If all these things are kept carefully in view, I really think that there can be found in this Theory the general theory for all chemical operations."

Imponderable Fluids

By the turn of the 19th century, many scientist were trying to solve the problem of the multiplication of forces by introducing weightless, fluid substances as carriers of the forces associated with heat, light, fire, electricity and magnetism.

There was a broad range of theoretical entities: two electrical and two magnetic fluids, light particles, light waves in an aether, phlogiston, caloric, other aethers for short range forces, and so on.

This multiplicity of explanatory models was an embarrassment but was necessitated by the increase in experimental phenomena coupled with the lack of quantitative unifying theories.

Instrumentalism

Van Marum, 1793:

"The adequacy of a proposed substance to explain a number of natural phenomena can never prove the existence of that substance."

A number of scientists began to believe that attraction and repulsion were simply effects. They were descriptive properties of phenomena and obeyed mathematical rules, but any underlying forces were "impossible to conceive." This was a retreat to *instrumentalism*.

By 1800, textbooks were openly teaching instrumentalism. They claimed that we would never get to the bottom of things, that we should stop searching for causes: "These things are beyond the reach of our senses, consequently beyond the sphere of our understanding." Under this view, forces become mathematical abstractions, "ideas of the mind, not in the real world."

Quantification

Archard, 1782:

"The determination of the relative and mutual dependence of the facts in particular cases must be the goal of the physicist; and to that effect he requires an exact instrument that will perform in an exact and invariable manner in every place in the earth… The physicist who does not measure only plays, and differs from a child only in the nature of his game and the construction of his toys."

In order to carry out measurements the scientist must posses a clear and definite concept, which is capable of being measured, and an instrument which can be used to do the measuring. Precise experiments and precision instruments were advocated as a way to correct the then-current taste for vague, and *overly explanatory*, theories. This emphasis on quantification was explicitly made by new journals such as *Annales de chimie et de physique* (1789) and *Journal der Physik* (1790).

Instrumentation: Improved Instruments

By 1800, the numbers of instrument-making firms was rising sharply and the number of their employees and production soared. There were three basic types of instruments: (1) demonstration apparatus (numerous), (2) measuring instruments (barometers, thermometers, magnetic needles, electrometers), and (3) research tools (air pump, precision balance, gasometer, electric machines).

Scientific instruments were also improving. In the early 1700s, it was considered useless to correct a barometer for temperature, since the correction fell within the instrument's error. By 1800, the best could be read to a few thousandths of an inch. Around 1700, the scale of a thermometer could still safely be drawn on paper. By 1800, it could be read to thousandths of a degree. Boyles' air pump reduced pressure to about 1/40 atm. By 1800, pumps could produce 1/300 to 1/600 atm.

Romanticism

In the German lands and eastern Europe, there was also a different reaction to the then-current confusion of natural philosophy. Instead of viewing the world as a machine, they chose the metaphor of an organic being.

This was an unifying and holistic philosophy, but it was also individualistic. The world had a single unifying soul (*Weltseele*) and it was the role of *Naturphilosophie* to understand this soul and explain the world on the basis of this understanding.

Naturphilosophie was a sort of spiritual project. The world soul was thought to reveal itself most readily, not to the mathematician or the experimenter, but rather, to the individual who had the right kind of faculties, the right kind of soul – a *genius*. This was not something that could be learned, like mathematics or experimental science. This kind of knowledge was the result of original, personal *insight*, as opposed to *research*.

Goethe's Natural Philosophy

The great German poet Johann W. von Goethe (1749–1832) rejected reductionism. He advanced a completely different type of natural philosophy based on the ideas of *polarity* and *intensification* (*Steingerung*) – believing a scientific theory should give a *spiritual* as well as *material* account. His most influential theories treated the parts of plants and color.

Goethe on Polarity and Intensity:

Polarity is "a property of matter insofar as we think of it as material," while intensity is a property "insofar as we think of it as spiritual. Polarity is a state of constant attraction and repulsion, while intensification is a state of ever-striving ascent. Since, however, matter can never exist and act without spirit, nor spirit without matter, matter is also capable of undergoing intensification, and spirit cannot be denied its attraction and repulsion."

Polarity

Goethe, *Maxims and Reflections*:

"Genesis and decay, creation and destruction, birth and death… are all interwoven with equal effect and weight, thus even the most isolated event always presents itself as an image and metaphor for the most universal."

Light and dark, body and soul, male and female, attraction and repulsion, being and desire, and so on. The key to understanding polarities, however, lies in their essential unity.

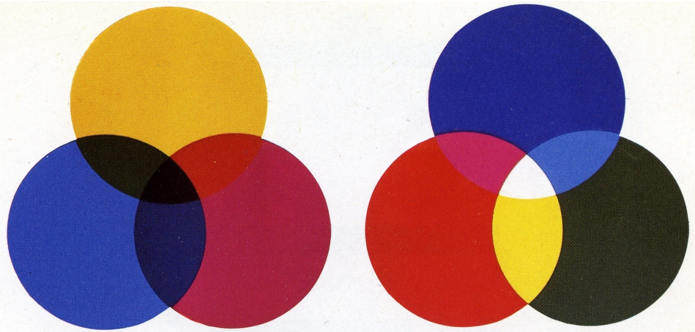
Goethe, *Fragments*:

"One cannot grasp the right concept of the two sexes if one does not imagine them on one individual. This sentence seems all too paradoxical because our concepts begin from human beings or from developed animals, and we therefore most easily distinguish the two sexes, when we picture them on two individuals. For this the plants give us the best opportunity."

Goethe's theory of color

Goethe characterized color as an interplay in the polarity of light and dark. He treated colors in many different aspects, including spiritual and psychological attributes. He distinguished between the additive color mixing of light and the subtractive color mixing of pigments.

Although scientists have found little value in his work on colors, it is still read by artists.



William Blake's Newton (1795)

Overview

Throughout the 19th century, we see the rise of new institutional spaces for science. The university systems are reformed, and they become a natural place for scientific education. We see the beginning of the professionalization of science, and the rise of distinct disciplines. We see a growing diversity of researchers.

Although in Western Europe the century begins with a proliferation of the Newtonian approach, in the German lands and Eastern Europe we see a reaction in the rise of the philosophy of Romanticism, which eventually moves west as well.