

ROMANTIC AGE

Physics & Chemistry

Collected and edited by Prof. Zvi Kam,
Weizmann Institute, Israel

The 19th century – the Romantic

Romantic Era – name carried on from the arts: literature, poetry, music. But the influence on biology is obvious: Emphasis on descriptive biology, classification of life and plants, and admiration of nature. The signature on **Physics** is less noticable...

Maxwell – Electromagnetic theory

Lorentz – tides

Tesla – distribution of electric power for lamps by radio waves, Alternating current.

Strong inclination to technological applications in the US –

Graham Bell, Morse, Thomas Edison.

In **Chemistry**, the isolation and characterization of more elements lead to the Mendeleev table of elements. Inorganic chemistry expand its capacity, but organic chemistry still “hides” behind Vitalism. Understanding gas properties is linked to thermodynamics, with its implications to engines and the industrial revolution.

PHYSICS

The 19th Century in Physics

Mechanics – Mathematical formulation of classical mechanics: Hamilton, Hilbert, Minkovsk, Lorentz.

Electricity – Electromagnetic field theory, The Battery (**Volta, Davy**).

Wave theory of Light – Fizeau, Fraunhofer, Fresnel, Wollaston, Michelson-Morley, Poisson, Ørsted, Ohm, Faraday, Henry, Doppler, Maxwell, Ritter, Tesla, Gibbs, Rayleigh.

Gases – Boyle, Gay-Lussac, Avogadro, Dalton, van der Waals.

Thermodynamics – Carnot, Watt, Joule, Coriolis, Helmholtz, Kelvin, Clausius, Clapeyron, Gibbs, Boltzmann, Maxwell, Nernst.

Liquids - Poisselle, Stokes, Venturi, Laplace, Plateau.

Birth of modern atomic physics – Röntgen, Becquerell, Planck, Rutherford, Curie, Thomson, Boltzmann, Zeeman.

Electricity – developed due to the battery as a stable source of current, and became an enabling technology in science: discovery of new chemical elements (by electrolysis), discovery of atomic particles (by vacuum tubes), eventually leading to quantum mechanics. After the development of generators the importance of bateries declined, but the development of high capacity rechargeable batteries today regained its central role in automotive technology, clean energy storage, cellphone and computer devices etc.

Physics and Technology

It is interesting to follow the long (sometimes twisted) road that brings a new theory to forefront of scientific consensus, and the incremental steps, typically linked with small details in many branches and to interdisciplinary hierarchies, that bring a new technology to application.

The obvious examples from the 19th century are electromagnetism and thermodynamics in physics, and aviation and communication in applied technologies. This is why the detailed summaries of scientific contributions are brought here, in order to appreciate the road, and not only the end result.

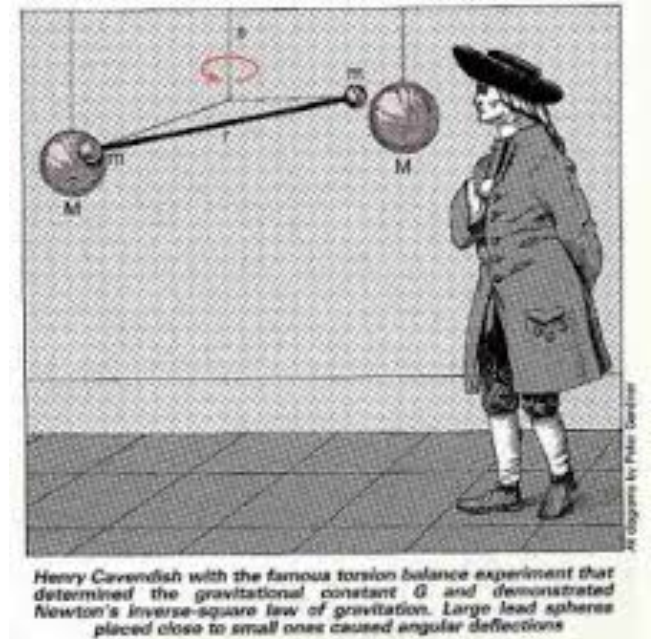
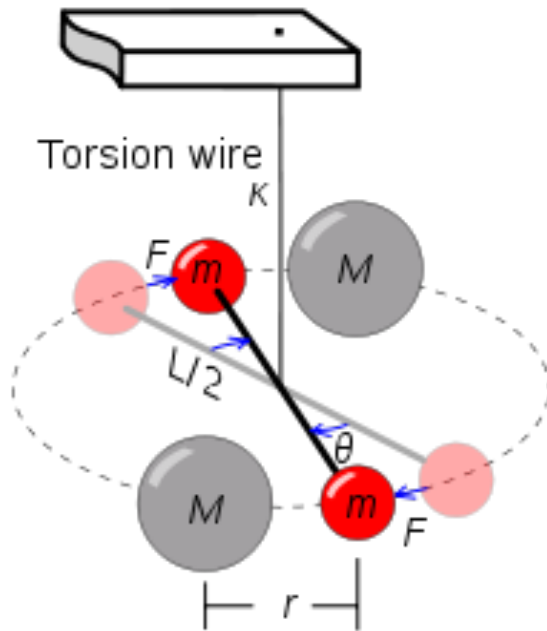
MECHANICS

William Cavendish 7th Duke of Devonshire 1731 –1810

A rich steel tycoon and talented scientist in Victorian England, who donated 6,300 pounds to establish in Cambridge a lab called after him.

Among his achievements: Isolated “flammable air”: Hydrogen, released from reactions of metals with acids, and recreated water upon its burning. Weighted gasses with high accuracy, and identifies misfits with “impurities” later identified by Ramsey and Rayleigh as the gas Argon.

1798 Most recognized Cavendish experiment: the measurement of the gravitation force constant using torsion balances he built from the **John Michell**’s design 1724-1793



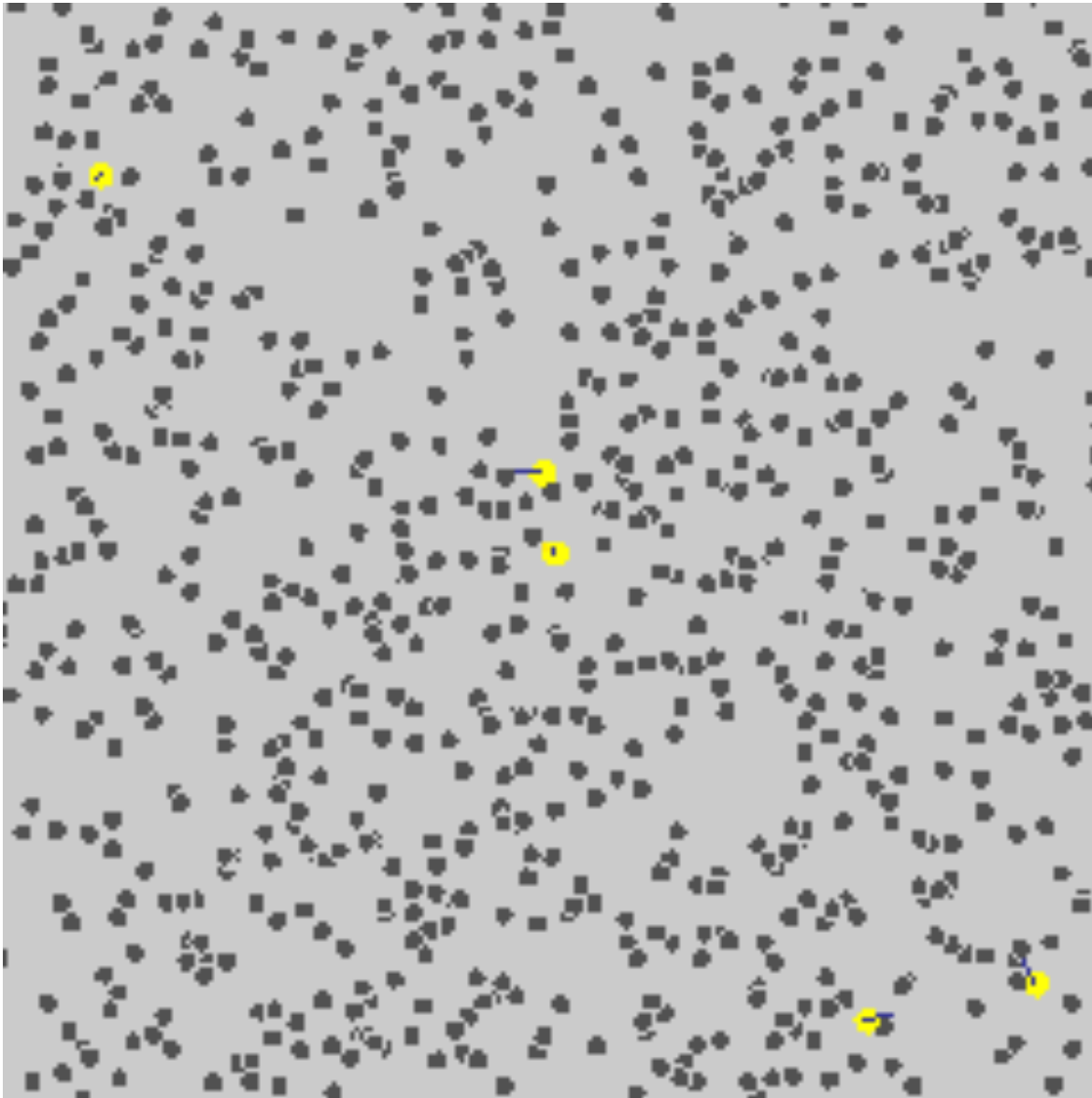
1874 Cavendish lab was founded in Cambridge.

Among its directors were Maxwell, Rayleigh, Thomson (the electron), Rutherford (radioactivity), Bragg (crystal x-ray diffraction), Wilson (cloud chamber), Aston (Isotopes), Chadwick (neutron), Watson (DNA). 29 of the lab scientists are Nobel prize laureates.

Robert Brown 1773-1858

1827 Brown observed in the microscope that pollen particles floating in water execute perpetual random movements – Brownian motion. As a biologist he first suspected some life activity. Brown also identified the nucleus in all cells.

1914 Brownian motion was explained by Einstein based on the atomic theory.



Gaspard-Gustave de Coriolis 1792 –1843

Contributed to relate work with kinetic energy.

1835 Studies theoretically the efficiency of momentum transfer in water wheel (see Pelton).

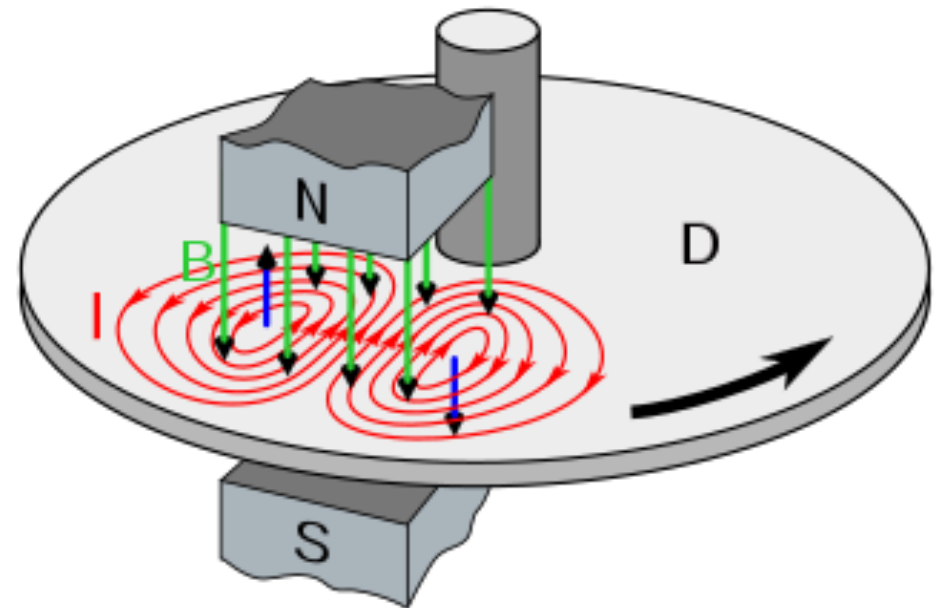
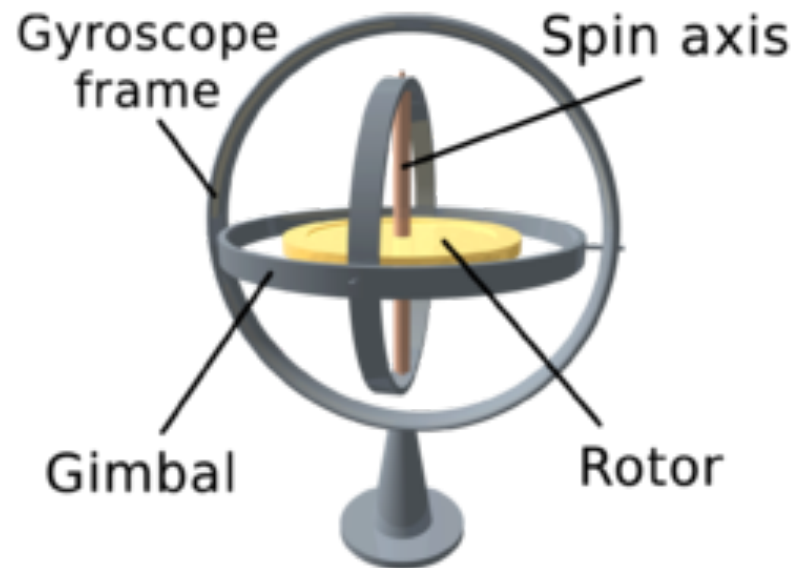
1838 Coriolis is mainly known for the force acting on rotating bodies perpendicular to the centrifugal force and the rotation axis. This is a “virtual” force explaining motion in transformation between non-inertial coordinate systems (accelerated or do not move in a straight line). This force acts for example on winds due to earth rotation, right-wise in the northern hemisphere, and left-wise in the south. Wrongly stated sometimes, it is not the cause for turbulent direction in water exiting the bathtub, since the Coriolis force is very small.

Coriolis force is an example of the equivalence of force and acceleration in non-inertial systems.

$$\vec{F}_c = -2m\vec{\omega} \times \vec{v}$$



Invention of the Gyroscope is attributed to **Coriolis**, as well as Eddy Currents in a rotating metal disk in a magnetic field.



Jean Bernard Léon Foucault 1819 -1868

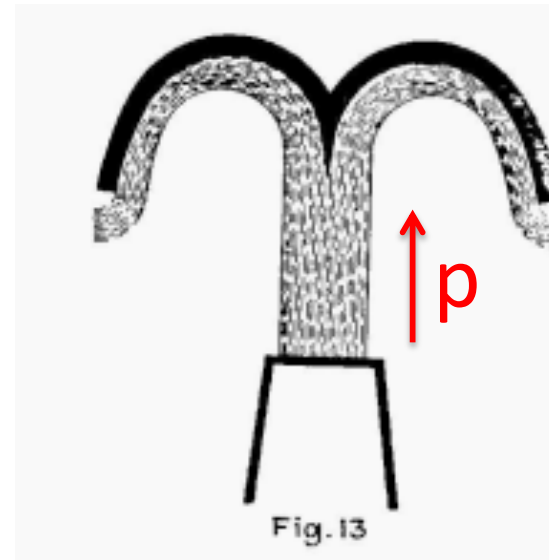
1851 Foucault demonstrated earth rotation by the precession of the plane of vibration of a long pendulum he hanged from the ceiling of the Pantheon in Paris. The length was 67 meters, and the pendulum weight 28 Kg. The pendulum was later transferred to the Arts et Métiers museum. In the north pole the pendulum rotates clockwise in exactly one day, and anticlockwise in the south pole. Along the equator the plane of vibration is constant, and along a longitudinal line φ the rotation in one day is $\omega = 360 \sin \varphi$ °/day (for example along 30° the pendulum completes a full rotation in 2 days. One can consider a Coriolis force acting on the the pendulum causing its rotation.



Lester Pelton 1829-1918

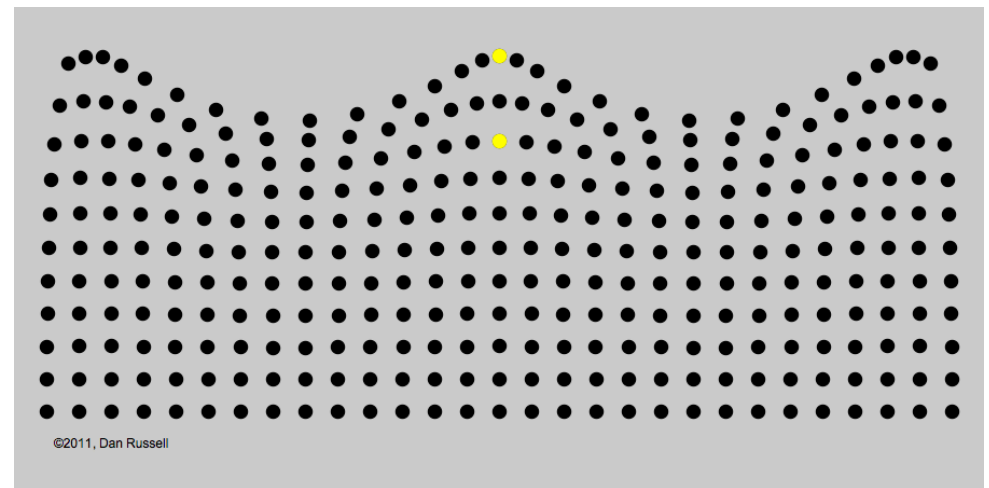
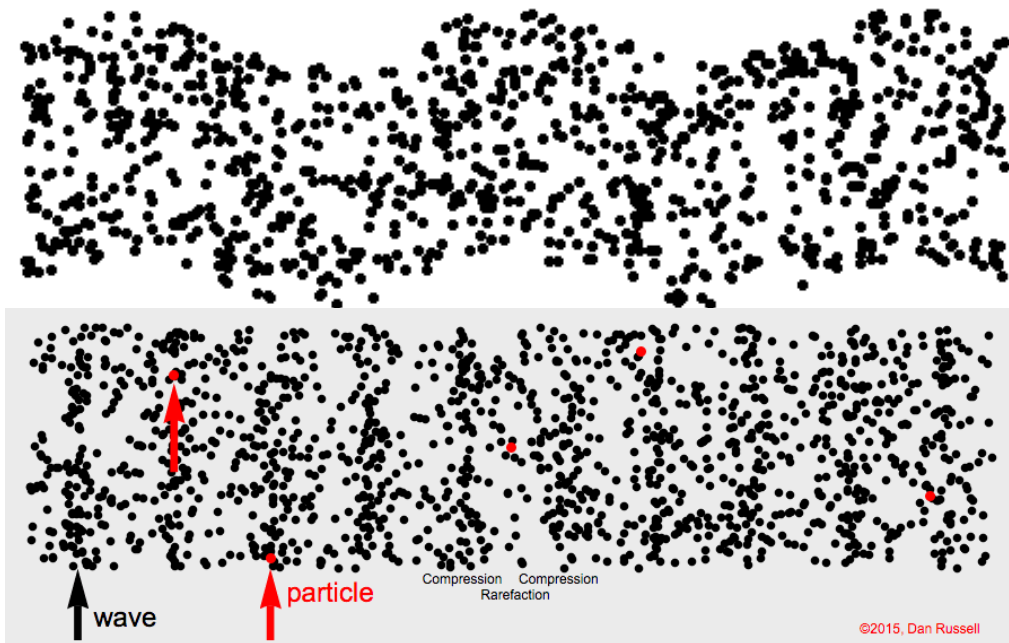
1879 Pelton turbine: the efficiency of this turbine is higher since the momentum of the incident water flow is inverted upon exit, after transferring maximal momentum to the turbine (why not quite double momentum?).

This is a fascinating example for usage of basic mechanical knowledge to applied engineering.



Elasticity of solids

The theory of forces, strains and stresses in materials, and propagation of sound waves in media continued for 250 years since Galileo (see next slide). Liquids and gases do not sustain shear forces, therefore transfer only longitudinal waves. Solids that have shear forces transfer both longitudinal and transversal waves. The advanced theory for sound motivated invention of aether as a medium for transporting light waves, as well as reflect and refract waves upon transfer from one medium to another. Aether was described as a liquid filling the whole world (also heat was perceived as the liquid caloric). Discovery of light polarization introduced “solid like” modifications of aether properties.



Ludwig Boltzmann 1844 –1906

1874 Introduced memory to strains and stresses in elastic materials (hysteresis).

Elasticity in history

1600 Galileo: assumed that materials consist of incompressible but bendable fibers.

1678 Hooke: spring elongation is proportional to force $F=kx$

1662 Boyle-Marriott law: $PV=\text{const}$ for gases.

Compression of elastic liquid by a factor- n increase elasticity n -times.

Marriott–Leibnitz: Material fibers expand and contract by forces.

Euler-Bernoulli: solved bending of anchored beam.

1773 Mohr-Coulomb: beam breaking criteria.

1798 Girard: A book summarizing knowledge about material strength.

1807 Young modulus: stress strain relation $F/A= e \, dL/L$

Navier:

Poisson ratio: transversal expansion at longitudinal force:

$$\nu = d\epsilon_x / d\epsilon_y$$

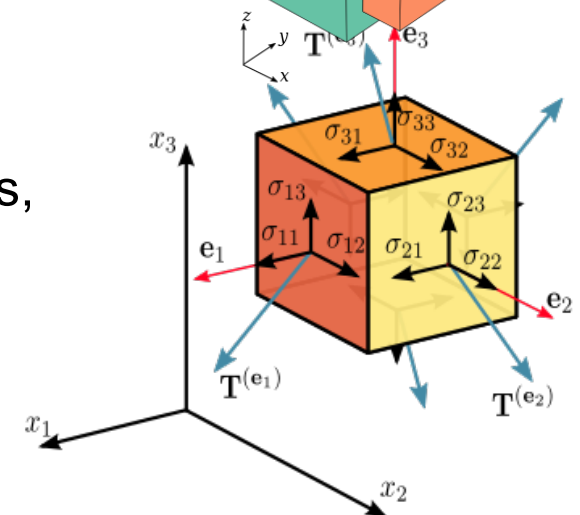
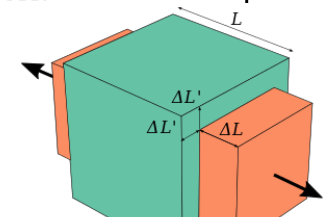
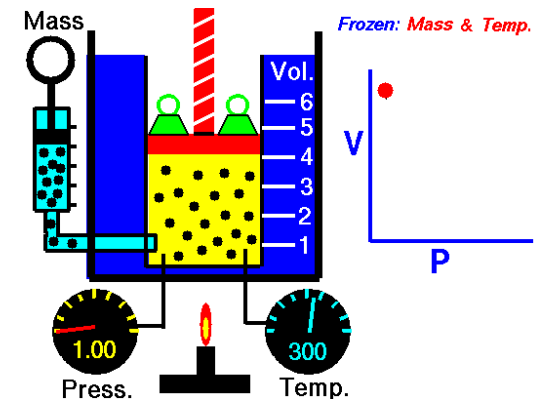
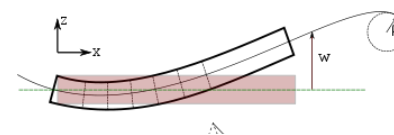
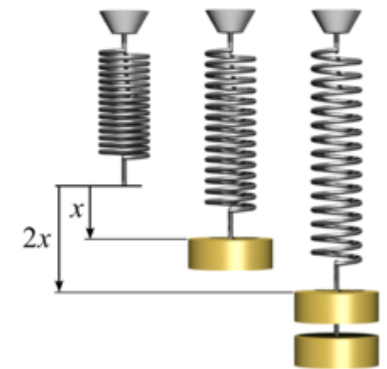
Augustin-Louis Cauchy: Elasticity tensor.

$$\mathbf{T}^{(n)} = \mathbf{n} \cdot \boldsymbol{\sigma} \quad \text{or} \quad T_j^{(n)} = \sigma_{ij} n_i.$$

This formula is the basis of “Finite Element Analysis”

A computer-based calculation method that help design airplanes, Buildings etc.

Wilhelm Weber: sound waves in strings and plates.
(moved on to study magnetism with Gauss).



David Hilbert | 1862-1943 Germany

algebraic number theory, Euclidian geometry

Hilbert space, 23 problems, dictionary, basis theorem, zeros theorem.

Studied in Königsberg University, where he met **Minkowski**. **Paul Albert Gordan** wrote that Hilbert's paper on the invariant theory (e.g. energy and momentum) is "theology, not mathematics".

1895 Moved, due to the influence of **Felix Christian Klein** to Göttingen, world center of mathematics (Gauss' students) where he stayed. Under the Nazis he evidenced the exile of Jews. To the Nazi science minister question "how is math in Göttingen" he answered "does not exist...".

Hilbert's most known contribution: Hilbert spaces, the mathematical foundation of quantum mechanics. They are vector space over a complete field (e.g. real numbers), with finite or infinite dimensions, and with internal product (the result is a scalar) that defines a norm (e.g. distance between points in space).



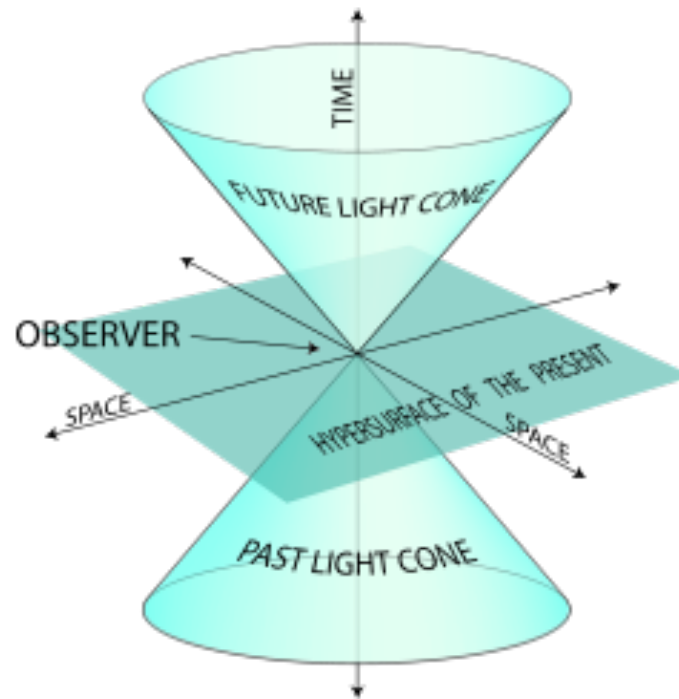
Herman Minkowski 1864-1909 Germany

number theory

Minkowski's theorem, inequality

Multidimensional space:

Einstein was his student, and the relativistic 4-dimensional space-time was his influence.



William Kingdon Clifford

1876 Proposed that motion of objects are due to geometrical changes of space.

Hendrik Antoon Lorentz 1853–1928 Holland, physicist

Developed the 4-dimensional equation used by Einstein to express the space-time transformations between inertial systems, with relative motion speed, v .
Nobel with Zeeman.

Nobel 1902

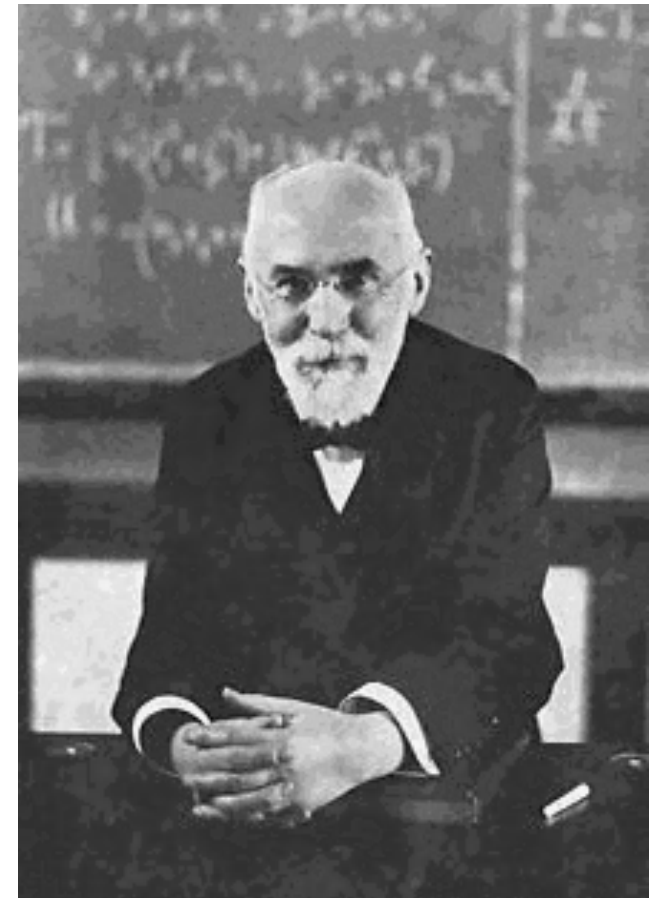
$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix},$$

$$t = \gamma \left(t' + \frac{vx'}{c^2} \right)$$

$$x = \gamma (x' + vt')$$

$$y = y'$$

$$z = z',$$



William Roan Hamilton (1805-1865) Ireland

graph theory, quaternion algebra, vector analysis
Hamiltonian , Hamiltonian path, Hamiltonian mechanics



1821 Analysis of body dynamics using Hamiltonians.

1828 Developed a general equation of motion for optics relating **Kepler's** light rays to **Young's** light particles.

1832 Explained how Hamiltonian as a function of optical path is implemented in **Fresnel's** wave optics. Predicted that at a specific Incident angle of light entry into bi-axial crystal undergo conical refraction and exit as a cylindrical envelop. This was experimentally confirmed by **Humphrey Lloyd**.

1833 **Fermat's** principle of light path minimizing time leads to Principle of Minimal Action – motion along a path stationary to local changes. This was later extended to dynamics – “Hamiltonian mechanics” expressing the energy of a moving system in terms of a continuous path in phase space: coordinates and momentum. The system motion is solved by minimizing energy, a continuous functional in phase space.

1835 Hamilton presented the canonical equation of motion.

A New Formlism to classical mechanics and electromagnetics:

Principle of minimal action: **Lagrangian** – Kinetic minus Potential energy $L=T-V$

$$\delta \int_{t_1}^{t_2} L dt = 0.$$

Extended **D'Alembert's** principle from the previous century:

$$\sum_i (\mathbf{F}_i - m_i \mathbf{a}_i) \cdot \delta \mathbf{r}_i = 0$$

Hamiltonian obeys the equation of motion:

$$H + \frac{\partial S}{\partial t} = 0$$

Where:

$$H = H \left(q_1, \dots, q_N; \frac{\partial S}{\partial q_1}, \dots, \frac{\partial S}{\partial q_N}; t \right)$$

$$S = S(q_1, q_2 \dots q_N, t)$$

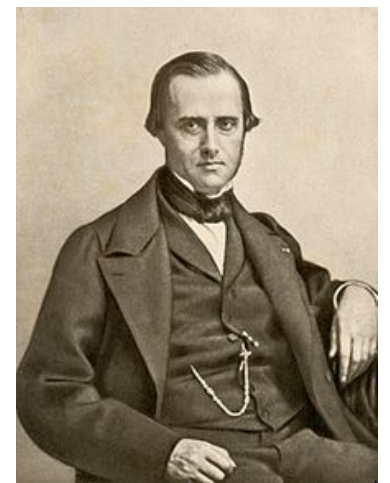
Energy is expressed as a function of coordinates q and momenta p .

Hamilton's formulation, despite its esthetic beauty and elegance, did not introduce a revolution in classical mechanics. But, as seen later, had seminal contribution to quantum mechanics, since it offered a common framework that facilitated the evolution into quantum mechanics, despite the fact that energy levels were continuous in classical mechanics, but were quantized and discrete in the quantum mechanical regime.

Mechanics and Astronomy

Édoard Albert Roche 1820–1883

1849 Calculated the maximal distance of a satellite to a star -
Explaining the rings of moons around planets.



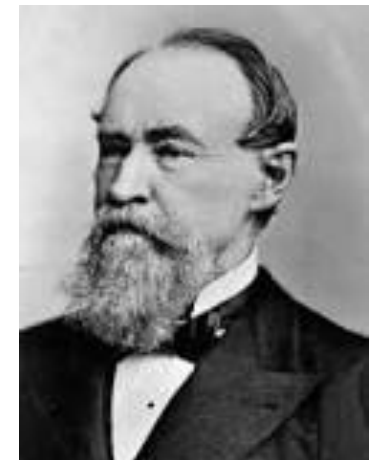
Léon Foucault 1819-1868

1851 Foucault's pendulum – see previous slides.



William Ferrel 1817–1891

1856 Published a paper about winds and ocean currents.



Mechanics

Ernst Mach 1838-1916

1870 Related momentum of a body to its interaction with the rest of the world – no momentum to a single body.

Mach collaborated with **Leibnitz** and **Mayer** "the Energists" who believed that energy is matter.

1883 Mach's principle – challenged Newton's absolute space concept.

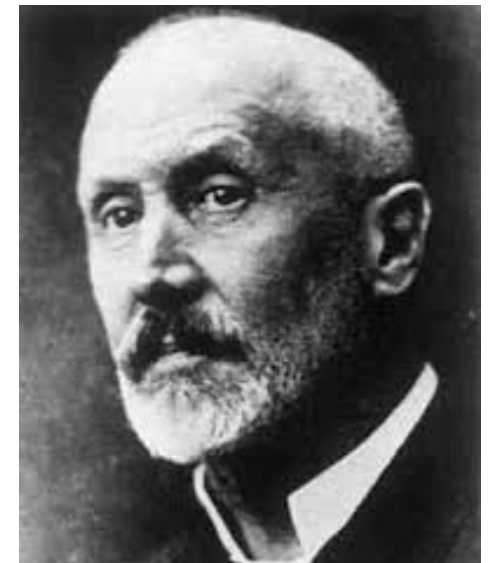
Studied ballistics. "Mach's number" speed in units of sound wave speed.

Was a bitter opponent of Relativity.



Loránd Eötvös 1848-1919

1889 Developed sensitive torsion balances that detected minute deviations in earth gravity, and helped discover oil fields in Texas. They also proved, with 1 to million accuracy, the equality of inertial and gravitational mass: Weak Equivalence Principle, which Einstein employed in his general relativity.



$$F = m_{\text{inertial}} * a$$

$$F = G * m_{\text{gravitational}} * M_{\text{gravitational}} / r^2$$

SOUND and MUSIC

Gustaf G. Hällström 1865–1950

1832 Claimed that beats can be heard in harmonies of two frequencies f_1 f_2 , for example f_1-f_2 , $2f_1-2f_2$, $3f_1-f_2$, etc.

1856 Beats were confirmed experimentally by **Helmholtz**.

Hermann Ludwig Ferdinand von Helmholtz 1821 –1894

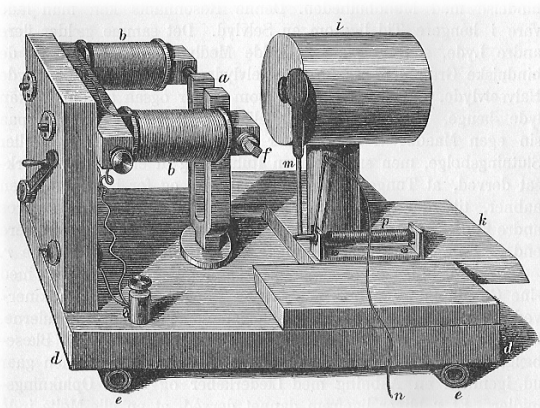
Built a resonator, vibrating a string at a desired frequency.

He understood that the “color” of a sound is determined by a spectrum of harmonic frequencies in addition to the basic frequency.

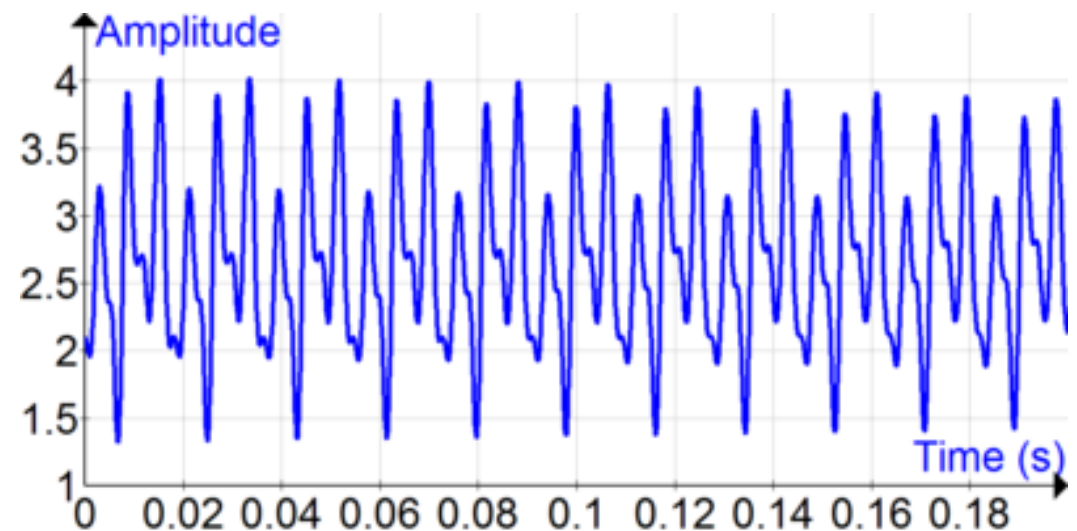
Studied sensation of sound by the ear, (as well as vision by the eye).



Graham Bell, who did not read German, misinterpreted the drawing of the resonator, and designed the speaker for his telephone based on this drawing.



Sound wave
from a Guitar
string.



TECHNOLOGY

AVIATION, TRAINS, BOATS
etc.

AVIATION DEVELOPMENT

Etienne Gaspar Robertson 1763-1837 & Auguste Lhoëst 1808-1860

1803 Elevated in a balloon from Hamburg to height of 7,280 meters.

Frenchman André-Jaques Garnerin 1769-1823

1803 Floated a distance of 395 Km from Paris to Clausen, Germany in a Montgolfiér.

Joseph-Lois Gay-Lussac 1778-1850 & Jean Baptiste Biot 1774-1862

1804 A series of measurements of gravity vs. height deny dependence on height.

J. Kaiserer

1804 Proposed to maneuver Montgolfiér flights by trained eagles.

Sir George Cayley 1773-1857

1804 Tried successfully a glider with adjustable surfaces as steering wheels like a modern airplane.

Jakob Degen 1760-1848

1807 The clock maker from Vienna carried experiments in wing flight powered by valves.

1807 Tried to incorporate his wings in a Montgolfiér.

1809 Drived a hydrogen balloon by propellers.

Sir George Cayley 1773-1857

1809 Published a book “Air floatation” discussing for the first time physical principles of aviation.

Albrecht Ludwig Berblinger 1770-1829

1811 Crushed into the Danube with Degen’s flight machine. He was called “The tailor from Ulm”

Charles Green 1785-1870

1812 Used gas lamp to heat the air in a Montgolfiér.

1836 Floated from London to Wilburg, 722 Km with two passengers in a Montgolfiér heated with coal gas (hydrogen Methane CO mixture).

Samuel Morey 1762-1843

1826 Internal combustion engine.

John Wise 1808-1879

1838 Built a device to anchore the Montgolfiér to prevent its drag by winds upon descending.

Charles Green 1785-1870 & Spencer Rush

1839 Elevated to 7,900 meters in a balloon.

William Samuel Henson 1812-1888

1842 Designed an airplane driven by a steam engine, followed Cayley’s glider with steering wheels. The British authorities rejected mockingly establishing “aviation carrier” company.

1849 Austrian balloon threw bombs on Venice.

Francisque Arban 1815-1849

1849 Floated over the Alps near Turino.

Sir George Cayley 1773-1857

1849 Built an airplane with 3 wings drafted like a glider.

1853 Floated in a balloon with his horseman as the pilot.

Henry Giffard 1825-1882

1852 Air ship moving by steam reached a speed of 10 Km/hour.

1852 The French Aeronautical Society is formed.



Félix 1823-1890 & Louis, brothers du Temple de la Croix

1857 Applied for a patent on an airplane powered by steam engine,
Following successful experiments on models.

Captain Jean Marie Le Bries 1817-1872

1857 Flew in a device he built following study of Albatrosses,
a bird that crossed oceans in flight.



Gaspard-Félix Tournachon, Nadar 1820-1910

1858 First Aerial photography.

John Wise 18081-1879 and 3 companions

1859 Floated in a balloon 1,292 Km from St. Louis to New York.

Henry Tracey Coxwell 1819-1900 & James Glaisher 1809-1903

1862 The aeronaut and physicist launched to height of 9,000 meters.

Jules Verne 1828-1905

1865 Published "A trip to the moon" describing a launch of a missile from Cape Canaveral in Florida. 100 years later the US send from there men to the moon.

Le Comte Ferdinand Charles Honore Phillipe d'Esterno 1805-1883

1865 In his story "on birds flight" he noted that gliding is typical of large-heavy birds, thus man can glide in winds too.

Louise Pierre Mouillard 1834-1897

1865 A French farmer and artist who flew in a glider. Published a book " Empire of Air" on bird's flight. He predicted that gliding and cruising but not wing flipping will enable flying.

Henry Giffard 1825-1882

1867 Built a balloon for the international exhibition in Paris with 20 passengers.

Matthew Boulton 1728-1809

1868 Submitted a patent on wing flight. First aviation exhibition in the crystal palace, London.

1870-71 During the French-Prussian war balloons are used to break the siege on Paris.

Alphonse Pénaud 1850-1880

1871 Built a glider model powered by a rubber band.



Francis Herbert Wenham 1824-1908 & John Browning 1831-1925

1871 Experimental studies in a wind tunnel.

Dupuy de Lome 1851-1904

1872 A naval engineer who reached a speed of 9-11 Km/hour in a muscles powered airship (balloon).

Paul Haenlein 1835-1905

1872 Tested the first airship with gas engine that reached 19 Km/hour. Development stopped due to lack of funds.

Vincent de Groof -1874

1874 Crashed while flying a balloon with flipping.

Otto 1848-1896 & Gustav Lilienthal 1849-1933

1874 Experiments of elevation and drift forces of wings published in 1889 and emphasized the advantages of convex wing profile.

Thomas Moy 1823-1910

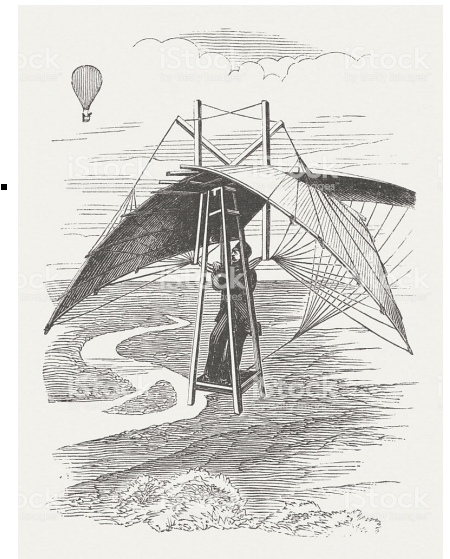
1875 Tested a motorized airplane with 4 meter long wings.

Gaston Tissandier 1843-1899

1875 A scientific flight of a Montpelier “Zenith” to 8000 meters height ended with death of the two aeronauts.

Alphonse Pénaud 1850-1880 & Paul Gauchot 1840-1905

1876 Applied for a patent on a design for two-person of amphibious aircraft that featured retractable landing gear, twin tractor propellers, and a well-designed control panel with unified rudder and elevator control.



Enrico Forlanini 1848-1930

1877 First flight of helicopter powered by a steam engine.

Victor Tatin 1843-1913

1879 Built an airplane model with pressured air and two propellers, that he launched.

Alexander Fjodorowitsch Moshaiski 1825-1890

1881 Awarded a patent for steam-powered airplane.

1882 “The German society for the advancement of aviation” published a journal.

Gottlieb Daimler 1834-1900

1883-6 Invented internal benzene powered fast speed combustion engine well adapted for aviation due to the high power-to-weight ratio. Daimler Motor Company built cars and merged with their competitor Benz at 1926.

Albert 1839-1906 & Gaston Tissandier 1843-1899

Charles Renard 1847-1905 & Arthur Constantin Krebs 1850-1935

1883-4 Airship with electric motor by Siemens. They launched and landed at the same point. Launched an airship to 8 Km in 23 minutes.

Horatio Frederick Philipps 1845-1924

1884 Patented a curved wing profile.

Henry Hervé & Gaston Alluard

1886 24 hours long Montgolfier flight.

Otto Lilienthal 1848-1896

1889 “Birds flight as a model for aviation”. Analyzed the advantages of arched wings.

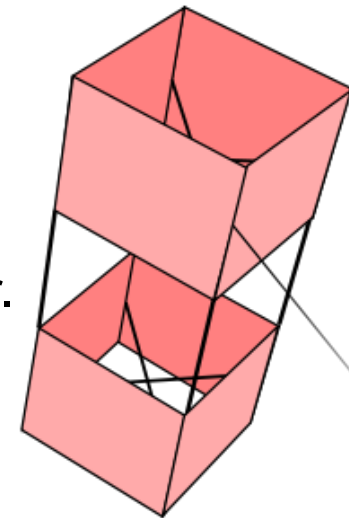


Clément Ader 1841-1925

1890 “Eole” or “Avion” , a French steam powered airplane launched.

Otto Lilienthal 1848-1896

1891 Glided 52 meters, first time without jumping on an accelerated glider.

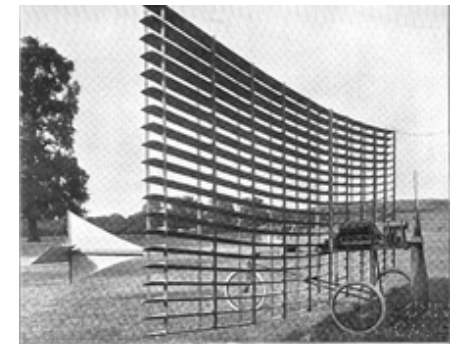


Lawrence Hargrave 1850-1915

1893 Lifted himself in Australia by box kites used as a model to design kites and planes.

Horatio Philipps 1845-1924

1893 Failed attempt to fly a plane with 50 wings, then 4 wings. Misconception about wing elevation by airflow.



Arthur Berson 1859-1942

1894 The German meteorologist climbs in a balloon to 9,155 meters.

H. S. Maxim

1894 Demonstrated the advantage of acceleration on the ground before launching an airplane. He ceased his experiments after he crashed and lost funding.

Otto Lilienthal

1894 A serial builder of gliders that reached 250 meters flight.

1896 Killed in a crash.

Octave Chanute

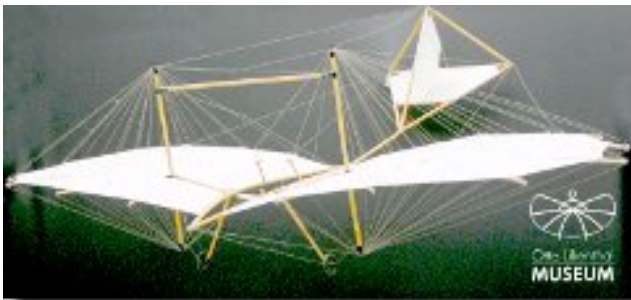
1894 Edited a book “Advancement in Aviation” summarizing the known technology.

Percy Sinclair Pilcher

1895-9 Developed in England motorized gliders, but killed in a flight accident.

Prof. Samuel Pierpont Langley

1896 In America, first flight in steam-engine powered airplane to 1 km distance.



Octave Chanute 1832-1910

1896 Opened a gliding camp near lake Michigan. Developed double-wing glider.

August von Parseval 1861-1942 & Bartsch von Sigsfeld 1861-1902

1896 Invented a balloon kite useful for floating despite strong winds.

Salomon August Andrée 1854-1897, Nils Strindberg 1872-1897 & Knut Fraenkel 1870-1897

1897 Arctic balloon expedition from Spitsbergen. Found dead 3 years later, but their photos survived.

Friedrich Hermann Wölfert 1850-1897

1897 Benzene- fueled airplane was set in flame causing his death.

David Schwarz 1850-1897

1897 A Hungarian who built an aluminum-made airplane he launched from Berlin.

Gustave Whitehead 1874-1927

1899-1901 Flew 500 meters in a steam engine powered airplane in Connecticut.

Orville 1871–1948 & Wilbur 1867–1912 the Wright brothers

1900-3 Experiments in gliding, air tunnels, control and engines lead to flight in a plane heavier than air.

Ferdinand Earl of Zeppelin 1838-1917

1900 First floatation in metallic balloon.

Arthur Berson 1859-1942 & Reinhard Süring 1866-1950

1901 Rised in a balloon to 10,800 meters for meteorological study.

Alberto Santos-Dumont 1873-1932

1901 The Brazilian floats around Eifel tower and lands where he started. Wins Deutch prize of 100,000 Franks.

Wilhelm Kress 1836-1913

1901 A naval plane he built crashed at launching

Prof. Samuel Pierpont Langley 1834-1906

1901 First flight in an airplane powered by a benzene engine

Orville 1871–1948 & Wilbur 1867–1912 the Wright brothers

1899 Start experiments to control airplane navigation by moving wings and steerers.

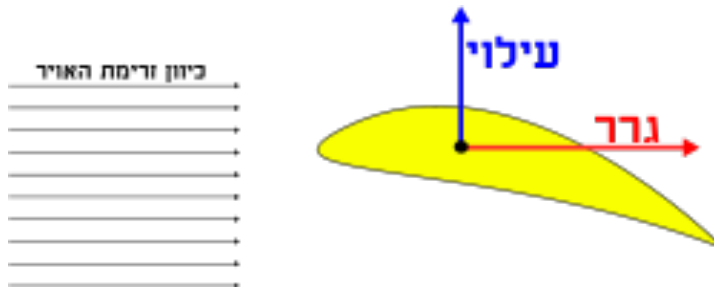
1901 Improved wing structure by wind tunnel tests.



The Wright brothers learnt from previous failures to stabilize planes, and created counter force to wing tilt by wings structure and steering by angle change of wing ends like birds.

Estimation of elevation forces

- A. Calculate the elevation force of 10 meter diameter spherical balloon filled with:
1. Hot air at 150 degrees centigrade.
 2. Hydrogen.
- B. Calculate the elevation force acting on an airplane moving at 30 km/hour with wing area of 40 meters square, and air speed difference above and below the wing of 10 km/hour.



TRAINS AND CAR ENGINES

George Stephenson 1781-1848

1814 Stephenson built the first locomotive to carry coal from mines. At that time rails and carts were driven by horses. Horses also drove barges in water canals.

1825 The first railway line is completed: Stockton & Darlington Railway. Passengers were driven to and from the station by horse carriages...

1829 “Rocket” the steam locomotive design of George and his son **Robert 1803-1859**, won the competition for the best design for the first passenger line.

Charles Fox 1810-1874

1832 Patented railway switches.

John Deere 1804-1886

1837 Steel ploughs. Founder of the tractor company.

Robert Davidson 1804-1894

1837 Electric locomotive.

Rudolf Diesel

1895 Diesel engine.

Nikolas August Otto

1876 Designed 4-stroke engine.

TRAINS AND RIVER BOATS

John Scott Russell 1808-1882

1834 Designed a steam carriage car. 6 cars were built and ran hourly in Glasgow-Paisley line at speed of 15 miles/hour. The competing horse carriage coachmen accused the steam carriages of ruining the road with their heavy weight. The service stopped after a carriage turned over and killed passengers.

1834 Noticed a “solitary wave” of “water mountain” running up a water canal after a barge stopped. He built a water tank in his home to study the effect. He found that the speed and height of the wave depend on the canal depth, and that two waves do not interfere but the larger takes over. The phenomenon lead to nonlinear wave equation with saturation (**Rayleigh 1876**). “Solitons” exist in fiber optics and in protein dynamics.

1848 Experiments that corroborated **Doppler effect from 1842**

1873 Designed the rotunda for the international exhibition in Vienna – a dome 108 meter diameter with only peripheral support.

OTHER TECHNOLOGIES

Lewis Waterman 1837-1901

1884 Fountain pen. Filed many patents, and following thousands of years of inkwells with feathers and sharpened writing tools, revolutionized hand writing.

1884 In an international meeting uniform earth timing standard referenced to **Greenwich Mean time** was agreed upon. Local times are based on **Nevil Maskelyne** (1732-1811) measurement of longitudinal coordinated from the position of the moon – Method of Lunar Distance.

Joseph-Marie Jacquard

1801 Invented knitting loom programed by punched cards.



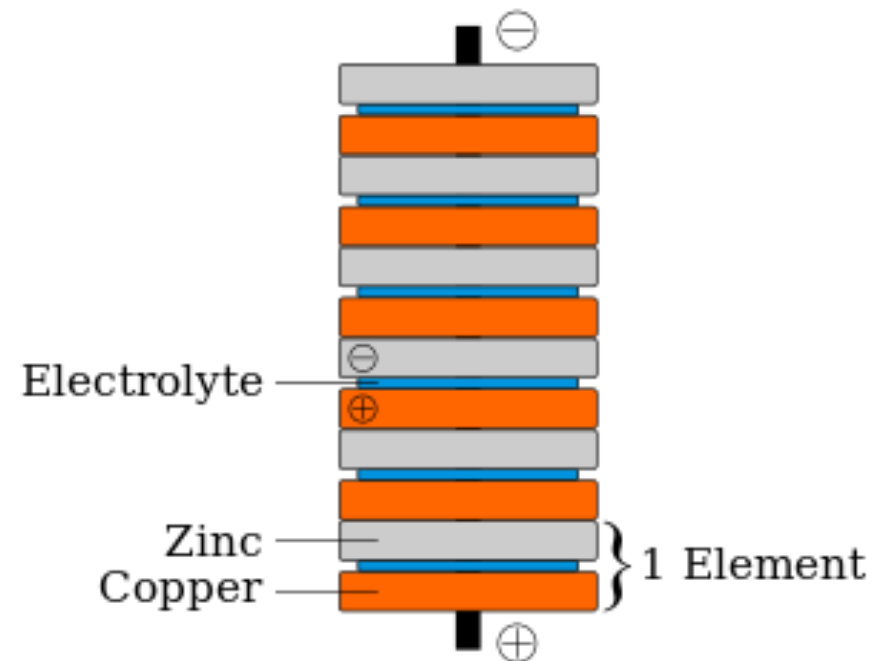
TECHNOLOGY

BATERIES

Alessandro Volta 1745-1827 Italy. Legion of Honour by Napoleon

1800 Discovered electrochemical generation of electricity, and built a pile (battery) of alternating Zinc and Copper disks with cloth soaked in salt solution (electrolyte). The name “battery” comes from this tandem structure, accumulating higher potential difference. The unit of electric potential, “Volt” is named after Volta.

The invention was an enabling technology in research, since it supplied a stable source for electricity in experiments of Faraday and others. Even when electric generators were developed, the battery remained the source of stable current for precise measurements.



HISTORY OF THE ELECTRIC BATTERY

1748 Benjamin Franklin 1706-1790 coined the name “battery” for a pile of charged glass plates.

1780-86 Luigi Galvani 1737-1798 demonstrated the electric basis of nerve impulse in dead frogs.

1800 Alessandro Volta 1745-1827 built a wet chemical battery, first practical electric source.

1836 John Daniel 1790-1845 built “Daniel cell” from two electrodes: CuSO_4 ZnSO_4 nondigestive battery.

1839 Robert Grove 1811-1896 developed the first fuel cell from hydrogen and oxygen.

1842 Robert Bunsen 1811-1899 developed batteries with liquid electrodes.

1859 Gaston Plant 1834-1889 developed rechargeable lead-acid batteries, still used in cars.

1866 George Leclanché 1839-1882 Patented dry battery – Ammonium chloride electrolyte, Zink and MnO_2 electrodes.

1868 20,000 batteries are used in telegraph networks.

1881 Thibaut patented a battery with porous clay container as negative electrode inside zink can.

1881 Carl Gassner 1855-1942 invented the Zink battery with carbon rod – commercial dry battery.

1899 Waldmar Jungner 1869-1924 invented the Nickel-Cadmium battery.

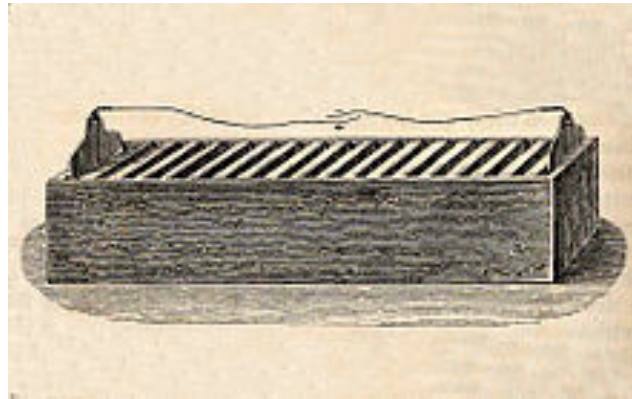
1899 Thomas Edison 1847-1931 invented alkaline battery.

1949 Lew Urry 1927-2004 invented a small alkaline battery that lives 5-8 times longer than zink-carbon battery

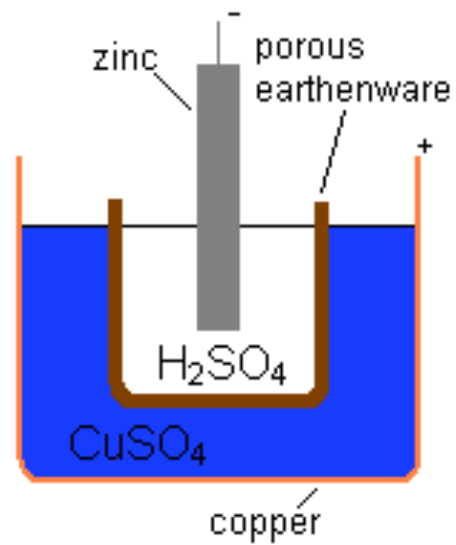
**1954 Gerald Pearson 1905-1987, Calvin Fuller 1902-1994
& Saryl Chapin 1906-1995**

1954 Developed the solar cell at AT&T Bell labs (where solid state diodes and transistors were developed before).

Liquid electrolyte cell



Daniel cell



Lyden glass jars



Volat Pile



Lead-acid car batteries



Lithium battery



Dry battery



Lithium batteries (anode is metal lithium) yields higher power for smaller weight, but is more expensive. Rechargeable Lithium-ion batteries are with MnO_2 cathodes.

The significance of batteries in modern life is tremendous: in cars (from ignition and lights to whole electric cars), airplanes, computers, cellular phones, watches, flashlights, cameras, satellites (charged by solar cells) and more.

High-capacity batteries can be charged by solar energy during the day, and supply electricity at night. This is still not very efficient, expensive, and therefore invalid option commercially as the source of clean energy.

Present problems and limitations: high price, short life, low capacity per weight, long charging time, dependence of rare metals, and dangerous polluting source when disposed.

ELECTROLYSIS and ISOLATION OF METALS

Joseph-Louis Proust 1754-1826

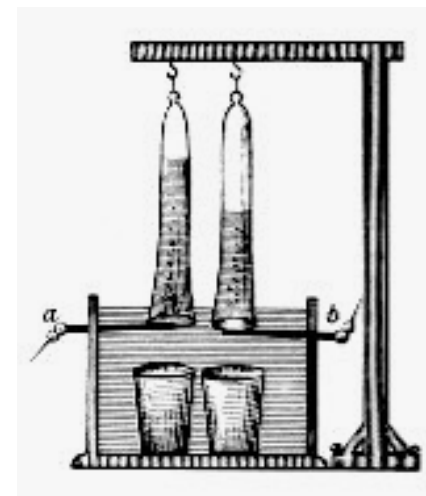
1799 Discovered that in chemical reactions atoms combine in constant ratios: Proust's Law

From this finding Dalton derived the basis of his Atomic Theory.

Johann Wilhelm Ritter 1776-1809 Germany

1800 Demonstrated that electrolysis of water generated two volumes of hydrogen for each volume of oxygen.

Developed electroplating on metals.



William Nicholson 1753-1815 & Anthony Carlisle 1768-1840

1800 Showed independently electrolytic decomposition of water into hydrogen and oxygen using Volta cells.

Humphrey Davy 1778-1829

1807 Volta battery is driven by chemistry. Water does not generate voltage. Alkalines are metal oxides. Hydrogen is found in acids. Chemical affinities are electrical.

Isolated by electrolysis Potassium, Sodium, Calcium, Strontium and Barium. Proved that Chloride and Iodine are elements. First discovery of Aluminum.

TECHNOLOGY

TELEGRAPH, RADIO, LAMPS

TELEGRAPH AND TELEPHONE

Samuel Finley Breese Morse 1791 –1872 U.S.A.

1844 Invented the telegraph. Used a code similar to Semaphore.

1844 The first to describe “Speaking Telegraph” or Telephone.



Michael Faraday 1791-1867

1854 Treated dependence on capacity of speed of signal transf in telegraph lines.

William Thomson baron Kelvin 1824-1907

1854 In a letter to **Stokes** he formulated the telegraph equation with resistance and capacitance of the conducting wire. Ignored induction. The equation is diffusional, and speed of signal transfer is not constant.

Gustav Kirchhoff 1824 1887

1857 Developed the “Telegraph Equation” for coaxial cable: For low resistance yields speed of signal propagation close to speed of light. He understood the link between electromagnetism and light.

Thomas Elva Edison 1847-1931

1873 Edison discovered the change with pressure of the conductance of coal powder. He constructed a rheostat based on this phenomenon, but neglected the idea due to sensitivity to vibrations.

1876 Use coal powder as a microphone.

Alexander Graham Bell 1847-1922

1875 Electrically transmitted a sound of plucked string. Patented a year later.

1876 A speaker, completed sound-to-electric signal-to-sound devices: the Telephone. Speaker idea is induced by Helmholtz' drawing of a magnetic resonator to drive strings to vibrate at a given frequency.

Almon Strowger 1839-1902

1892 Automatic telephone switchboard (Electromechanical switches) commercially used.

RADIO

Heinrich Rudolf Hertz 1857-1894

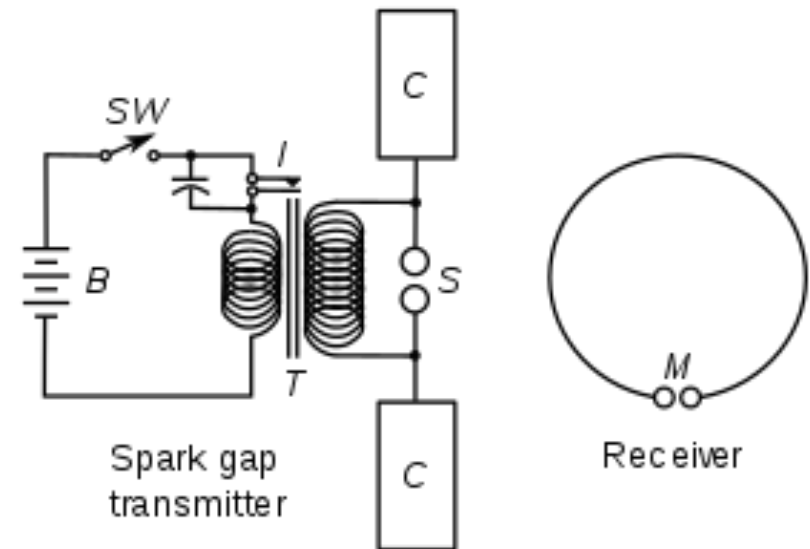
1884 Waves generated by moving charges are identical to waves generated by moving magnets.

1887 Created electromagnetic radiation – radio waves, by an oscillating circuit in resonance. The waves propagate in air and inside metals, can be polarized by parallel grid of wires, and can be reflected and refracted like light waves.

His research on radio waves made him abort the “action from far” of Helmholtz. The unit of frequency (vibrations per second) is named after Hertz.

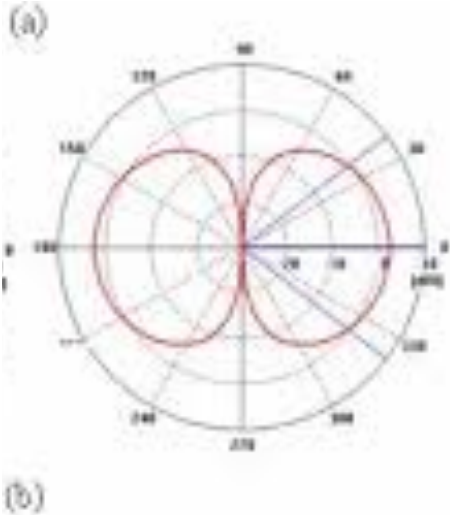
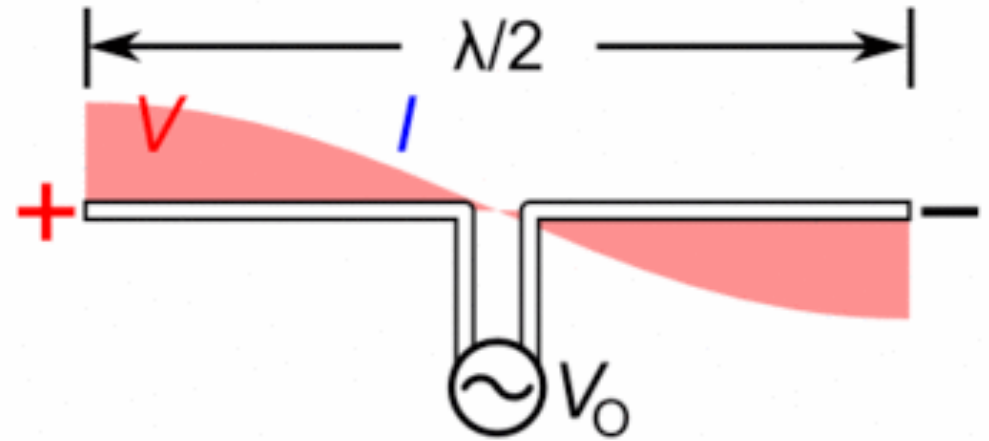
1887 Hertz discovered the photoelectric effect:
Ultraviolet illumination of an anode in a spark-gap “reduced” the resistance of air between the electrodes.

1889 Theory for radio waves radiation from oscillating spark gap.



George Francis FitzGerald 1851-1901

1890 Used Lorenz delayed potential to calculate radiation from Hertz dipole antenna



The radiating radio field from a dipole antenna

Oliver Joseph Lodge 1851-1940

1894 Invented the radio wave detector he called “coherer”

Guglielmo Marconi 1874-1937

1895 Sent telegraph (radio) waves and detected them at a distance of 1.6 Km.

Nicola Tesla 1856 –1943 Serbia –USA

1884 Emigrated to America

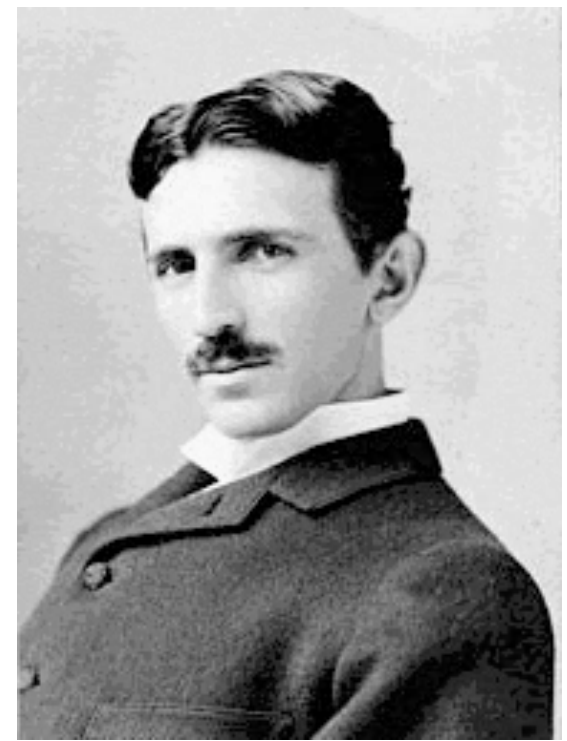
1888 Patented alternating electric current

1893 Discovered radio wave radiation, and designed to “electrify cities by radiation with “Tesla coil” receptors”: a variable transformer that changes voltage.

1895 Studied radiation from arc lamp. Abandoned the subject after Hertz’ work. Worked for Thomas Edison, improved his generators, but resigned when he was refused royalties. He founded his own company, developed alternating current generators, (AC), and was hired by Westinghouse to distribute AC electricity in NY homes to compete with Edison’s direct current (DC). Edison’s company became General Electric (GE), after losing to Westinghouse in the bidding for electrifying the international exhibition in Chicago.

1893 AC won the “current war” , see following.

Tesla was imaginative, although many of his inventions were not practical at his time, they found uses later. The unit of magnetic field strength is named “Tesla”, as well as the electric car co. Tesla built a communication tower to transmit radio waves across the Atlantic, and held a patent. But radio application was advanced by Marconi. Tesla was on the short list of Nobel Prize with Edison, but due to the animosity between them the Prize was donated to Bragg for x-ray crystal diffraction.



PHOTOGRAPHY

Johann Wilhelm Ritter 1776-1809

1801 Discovered that ultraviolet radiation disintegrated AgCl forming free silver.

John Herschel 1792-1871 (son of the astronomer William)

1820 Developed photography.

Joseph Nicéphore Niépce 1765-1833

1826 Photographic plates.

George Eastman 1854-1932

1888 Box camera by Kodak.

Charles Wheatstone 1802-1875

1833 Understood the physics of depth perception in vision, and invented the stereoscope – presenting to the two eyes two pictures taken at two angles.

Louis Jacques Mandé Daguerre 1787-1851

1839 Published the photographic process.

John Gribbin & Marry Gribbin

1845 Photographed the sun (Paris). Improved the photographic emulsions in speed and sensitivity. Important application in astronomy, spectroscopy and in non-visible radiations: Infrared, Ultraviolet, x-rays and radioactivity.

Frederic E. Ives 1856-1937

1892 Color photography.



PRACTICAL ELECTRICITY

Zénobe Gramme 1826-1901 Belgium

1873 Modern direct current (DC) motors.

William Arnold Anthony 1835-1908

1875 Dynamo.

Nikola Tesla 1856 –1943

1877 Induction motor.

Lucian Gaulard 1850-1888 & John Dixon Gibbs 1834-1912 France & England

1881 Registered AC patents, such as high power step-down transformers bought for Pittsburg and Massachusetts electrification projects at 1886 by Westinghouse. The hydroelectric generator was converted by such transformers to 3000 volts, sent to long distances with lower resistance losses, and down-transformed to 100 volts.

William Stanley 1858-1916

1885 The first practical AC transformer.

Nikola Tesla 1856 –1943

1888 Registered 30 patents for multiphase AC electrical systems.



LAMPS

Sir Humphry Davy 1778-1829

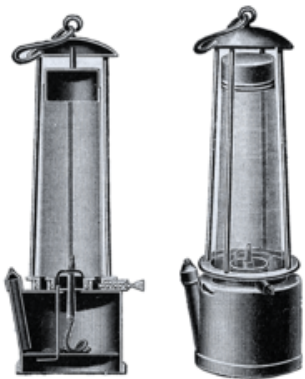
Famous as a chemist who isolate Alkaline elements: Potassium, Sodium, Calcium, Magnesium, Boron, Strontium, Barium, Chlorine, Iodine.

1802 Showed that electricity created by a battery of 2000 cells generated light when conducted through platinum strip: the first incandescent light bulb.

1806 Electric Arc between two carbon electrodes: strong light source.

1815 Invented secure lantern that prevented explosions in coal mines and saved lives. The principle was isolation between the flame and the outside by a metal grid, which conductance cooled down the flame that reached it, thus isolated the inner flame from the outside. Since cold combustible gases could however enter through the net, they were detected by enhanced burning of the flame.

Secure lantern



James Bowman Lindsay 1799-1862

1835 Demonstrated a lamp in Scotland, but did not follow its application.

Joseph Wilson Swan 1828-1914 England

1860 Incandescent lamp with carbon wire in vacuum.

Henry Woodward & Mathew Evans

1874 Patented carbon wire lamp in nitrogen gas – sold to Edison.

Thomas Alva Edison 1847-1931 America

Founded Edison company for electricity and light in New York. Acquired patents related to electric lamps, and started developing DC electricity distribution systems.

1880 Further developed incandescent lamps with carbon wire on bamboo stick in vacuum. Lifetime of the lamp was 1200 hours.

Walther Nernst 1864-1941

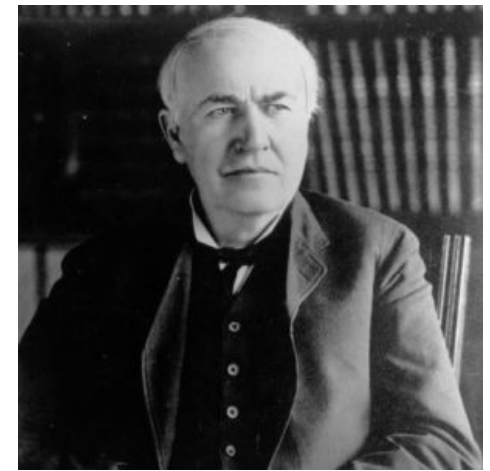
1897 Invented incandescent lamp with ceramic wire that replaced Edison's carbon, and made Nernst rich. He probably funded Einstein's cathedra in Berlin.

1905 Nernst ceramic lamp was replaced by tungsten lamps.
(see following for Nernst contributions in osmotic pressure)

Thomas Elva Edison 1847-1931

Thomas Edison was such a bad pupil that his mother was home-schooling for him. He loved mechanics and chemistry, and growing up he became a productive inventor:

1877 Cylindrical Phonograph with aluminum or lead foil, based on telephone. A sharp needle connected to a microphone scribed into the cylinder. A blunt needle was used for listening. Brought him publicity, but soon lost to the disk recorder.



1879 Demonstrated incandescent lamp from platinum strip in vacuum. Was developed based on previous inventions. He developed next year the carbon wire lamp in improved vacuum that lasted 13.5 hours, and replaced the gas lantern. The electric supply included parallel circuit, improved dynamo, underground electric wires, current stabilizer, fuses, isolators, and lamp housing with a switch.

1882 The first electric station in Manhattan supplied 1 mile radius lightening at 3 times the efficiency of gas lamps. Till the end of that decade day long electric supply also for transportation and industry came from tens of power stations all over the city. The problem was the voltage dropping in the supply lines.

Edison General Electric Company was not controlled by Edison, due to the huge investments by Morgan and others. At 1892 the company merged with the competitor, Thompson-Houston, and became General Electric (GE), dropping Edison's name.

1888 Kinetoscope—Kodak started to manufacture photographic films for moving pictures

1893 Edison built a studio with opening roof for sunlight.

C. Francis Jenkins & Thomas Armat manufactured a projector that Edison, distributed it, and later built a model of their own.

1896 First movie was shown

1913 Kinetophone was synchronized with a phonograph.

"THE CURRENT WAR"

By 1887 Edison built 121 power stations supplying DC, and Westinghouse had 68 power stations supplying AC. Edison publicized that AC is dangerous, and proposed to execute death sentences on electrical chairs powered by Westinghouse AC.

He finally realized that the great advantage of AC is long supply lines at high voltage, and step-down transformers at the place of demand.

After Edison lost control of GE, the new owners abandoned DC. Westinghouse acquired patents for AC generators, motors and lamps from **Tesla** & others and developed AC technologies and capabilities. DC was finally defeated by losing the bid for lightening the Chicago International Exhibition, the bid for the power station on the Niagara falls, and development of AC steam generators.

Why are long high-voltage supply lines more efficient?

The heat energy E , lost in a resistance R with current I is $E=R \cdot I^2$

$W=V \cdot I$ watts of power are supplied by voltage V and current I . In a transformer $V_1 I_1 = V_2 I_2$

Thus for long supply line with resistance R , the heat loss at $V=100$ volts is $E=R \cdot I^2$ and with stepping up the voltage to $V_2=3000$ $I_2=I/30$ thus the heat loss is 900 times smaller.

Sándor Just 1874-1937 Hungary
& Franjo Hanaman 1878-1941 Croatia

1904 Patented tungsten vacuum bulb: brighter and long life.

1906 GE developed twisted tungsten – higher resistance, low tungsten evaporation allows higher temperature and brightness.



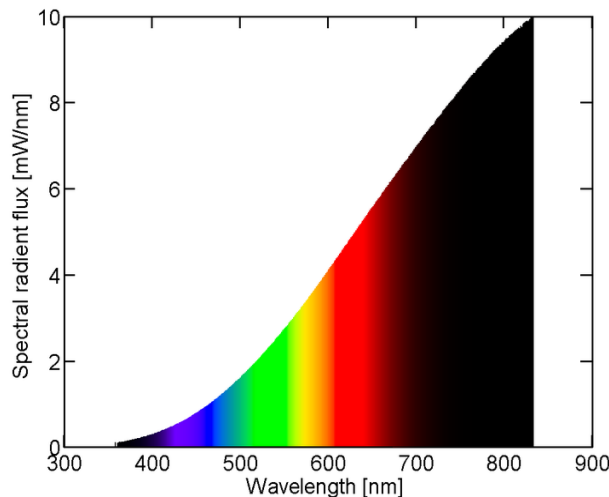
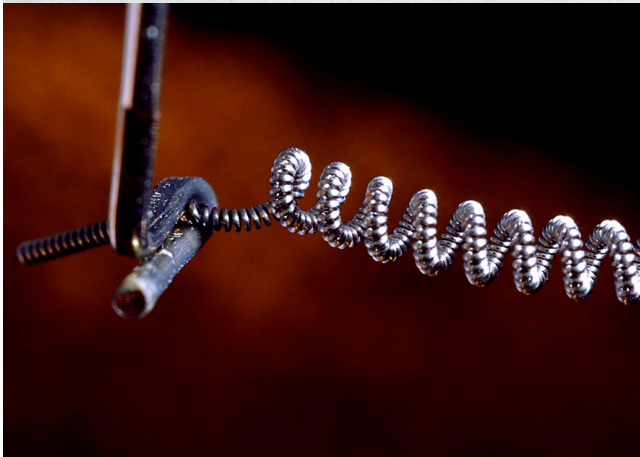
Nobel 1932 **Irving Langmuir 1881–1957**

1913 During his work with GE he developed a long life incandescent lamp with bulb filled with Nobel gases. He also developed welding with hydrogen.

1932 Nobel prize for surface chemistry

Halogen lamp - reduced tungsten evaporation, allowing higher filament temperature.

Fluorescent lamps – Electric current via Mercury ions emit light. Gas ionization need startup by a spark. They were developed following vacuum tubes that were used to discover electrons and protons. Fluorescent lamps are 3 times more efficient than tungsten due to the latter strong wasted emission in the IR.



Emission spectrum of a tungsten lamp

GASES

What is the significance of gas research ?

Gases paved the road to the atomic theory of matter. It could not have been conceived in solids or liquids.

Gases made the basis for thermodynamics: Absolute zero, entropy and limits on engines efficiency leading to practical steam engines and to the industrial revolution.

Gases helped formulate chemical laws e.g. energy conservation and the equivalence of heat, mechanical kinetic and potential energies and chemical energies, later nuclear too.

Vacuum enabled experiments discovering elementary particles.

Aerodynamics and laws of gas flow based on the kinetic theory of gases.

Divergence from ideal gas behavior seeded understanding of phase transition and refrigeration systems.

The research on gases gave a final burial to old ideas such as “perpetuum mobile” and defined the limits for more efficient conversion of heat to mechanical work and electricity.

THEORIES OF IDEAL AND REAL GASES

Ideal gases are assembly of molecules colliding elastically between themselves and the vessel walls. Their properties can be calculated statistically.

Experiments with real gases where one variable was changed yielded:

1662 Boyle's law: $PV = \text{const}$

1699 Amontons' law: $P/T = \text{const}$

1780 Charles' law: $V/T = \text{const}$ (also by Jeseeph Louis Gay-Lussac).

1801 Dalton's law of partial preasures: $p = p_1 + p_2 + \dots$ Mixing two gases in a vessel creates a pressure as if each is by itself.

1802 Gay-Lussac floated in hot air balloon.

1811 Avogadro's law: $V/n = \text{const}$

1848 Graham's law for gas diffusion: $D = \text{const} / \sqrt{\text{density}}$

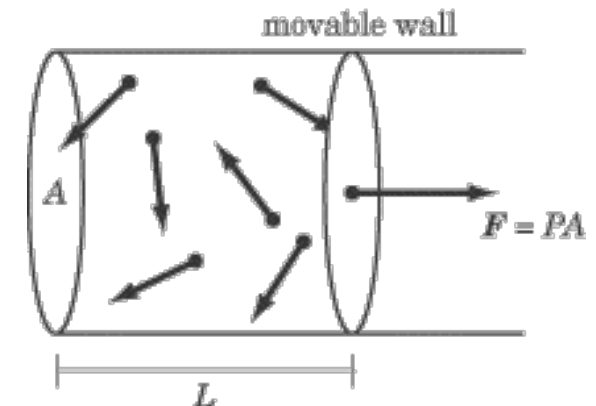
“State equation” of ideal gases: $PV = nRT$

Depend only on number of molecules, not size: since molecules kinetic energy depend on temperature $\frac{1}{2}mv^2 = kT$ bigger molecules move at slower speed, therefore pressure from momentum transfer by the walls (proportional to speed) time number of collisions (also proportional to speed) is proportional to v^2 , thus is the same for a given temperature.

Based on statistical mechanics it is possible to calculate the heat capacity, speed of sound wave, entropy and other properties for ideal gases, and compare them to real gases. Gas-liquid phase transition result from non-ideal (non-elastic) interactions between molecules.

1910 van der Waals Nobel prize

Nobel 1910



John Dalton 1766-1844

1801 Paper discussing gas solubility in water.

1803 Formulated the atomic theory of matter (first described by ancient Greek philosophers): all materials are built from atoms. Splitting or combining ,molecules change their properties. Molecules are combined from an integer number of atoms. Atoms cannot be created or destroyed. All atoms of the same material are equal. Atoms have different weights. Dalton published a table of atomic weights as multiples of hydrogen weight. e.g. Oxygen = 7. (It is really 16, since hydrogen and oxygen gases are molecules of two atoms).

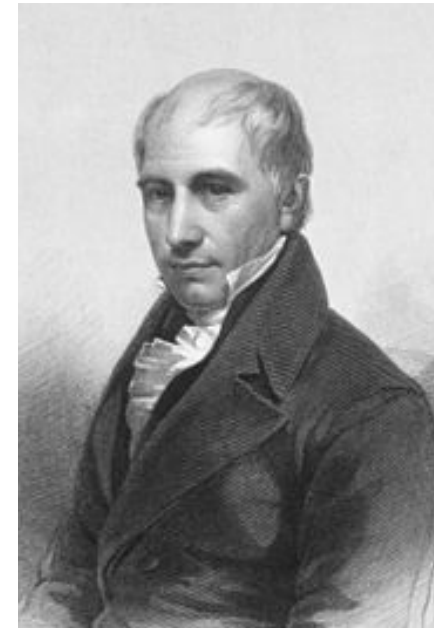
1808 Law of partial pressures $p = p_1 + p_2 + \dots$

Dalton supported the caloric theory of heat, and how it is combined in chemistry and gas theory. He proposed that specific heat of gases is inversely proportional to atomic weight.



Thomas Thomson 1773-1852

Publicized in a chemistry book Dalton's atomic theory.



Gay-Lussac 1778-1850

1806 If a gas expands without work, its temperature does not change.

1808 Gases combine chemically at fixed ratios. Exploded oxygen and hydrogen at various ratios and concluded that water is a combination of two hydrogens and one oxygen atom.

Dalton refused to accept these results since he did not know the difference between atoms and molecules.



Amedeo Avogadro 1776 -1856

1811 Avogadro claims that at constant temperature and pressure all gases include the same number of molecules per unit volume.

Avogadro called atoms – elementary molecules, and to compounds integral molecules. The law was not accepted for 50 years.

1860 Stanislao Cannizzaro showed that Avogadro's law is the solution to atomic and molecular weights.

1865 Josef Loschmidt estimated the number of molecules in 1 Mole from the kinetic theory of gases, and called it Avogadro's number:
 $= 6.02252 \times 10^{23}$

1909 Baptiste Perrin estimated Avogadro's number from Brownian motion.

Avogadro's number = 1 Faraday (charge of 1 Mole of electrons) / Milikan's charge of one electron.

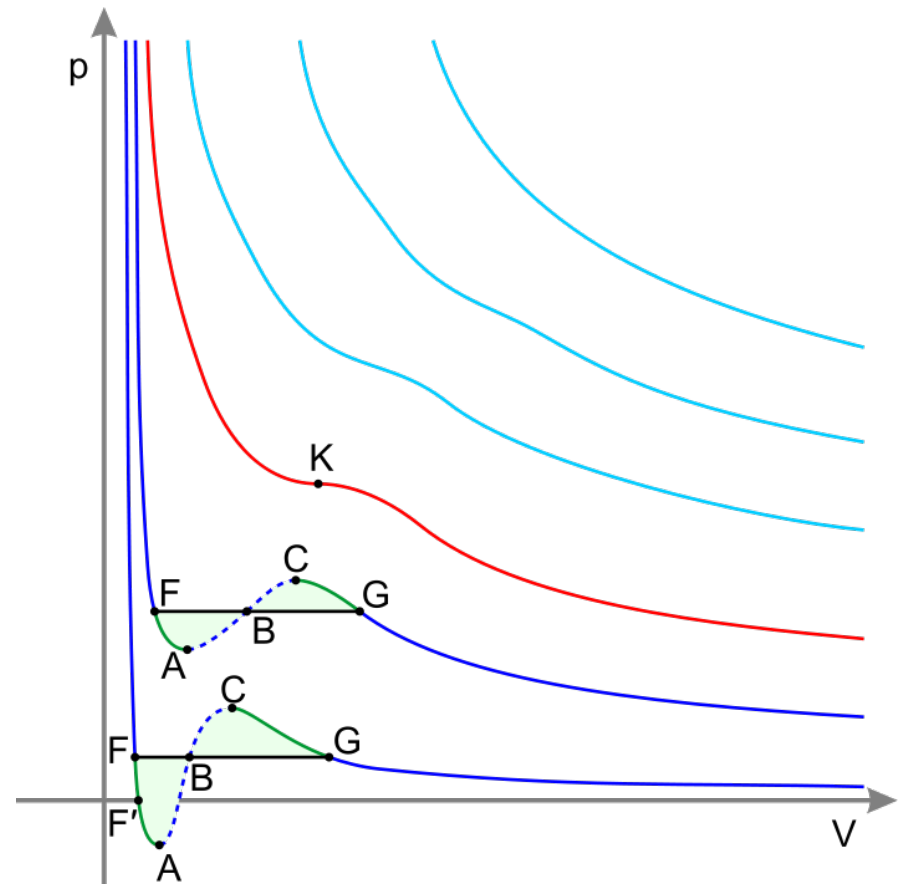
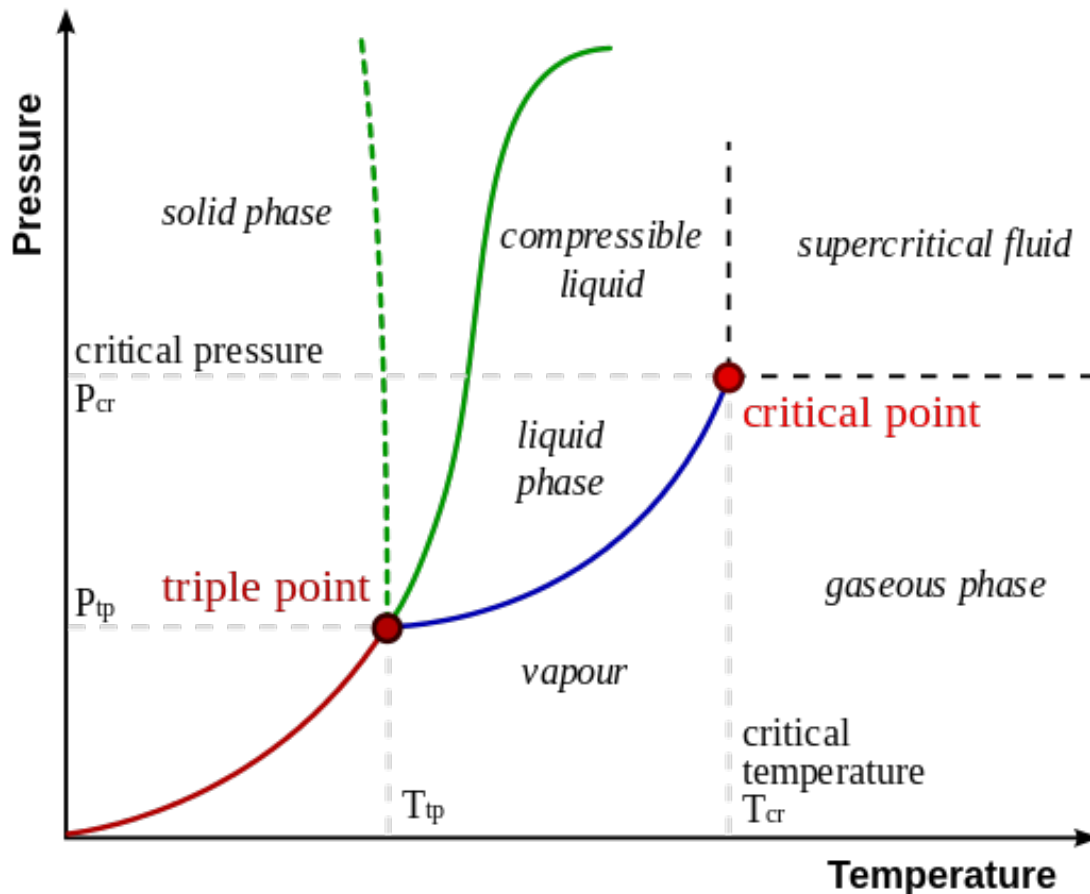


Thomas Andrew 1813 –1885

1861 Showed that Boyle's law fails to hold for CO_2 at low temperatures. In regions near the isothermal line, volume change does not cause pressure change due to the liquid-gas Equilibrium. Found the critical-point and triple-point (see **van der Waals, Clausius-Clapeyron** later).

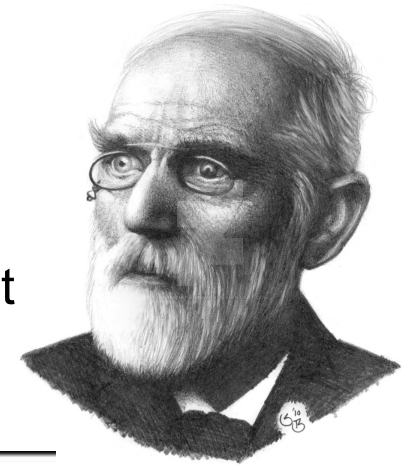


*Yours most sincerely
Thomas Andrew.*

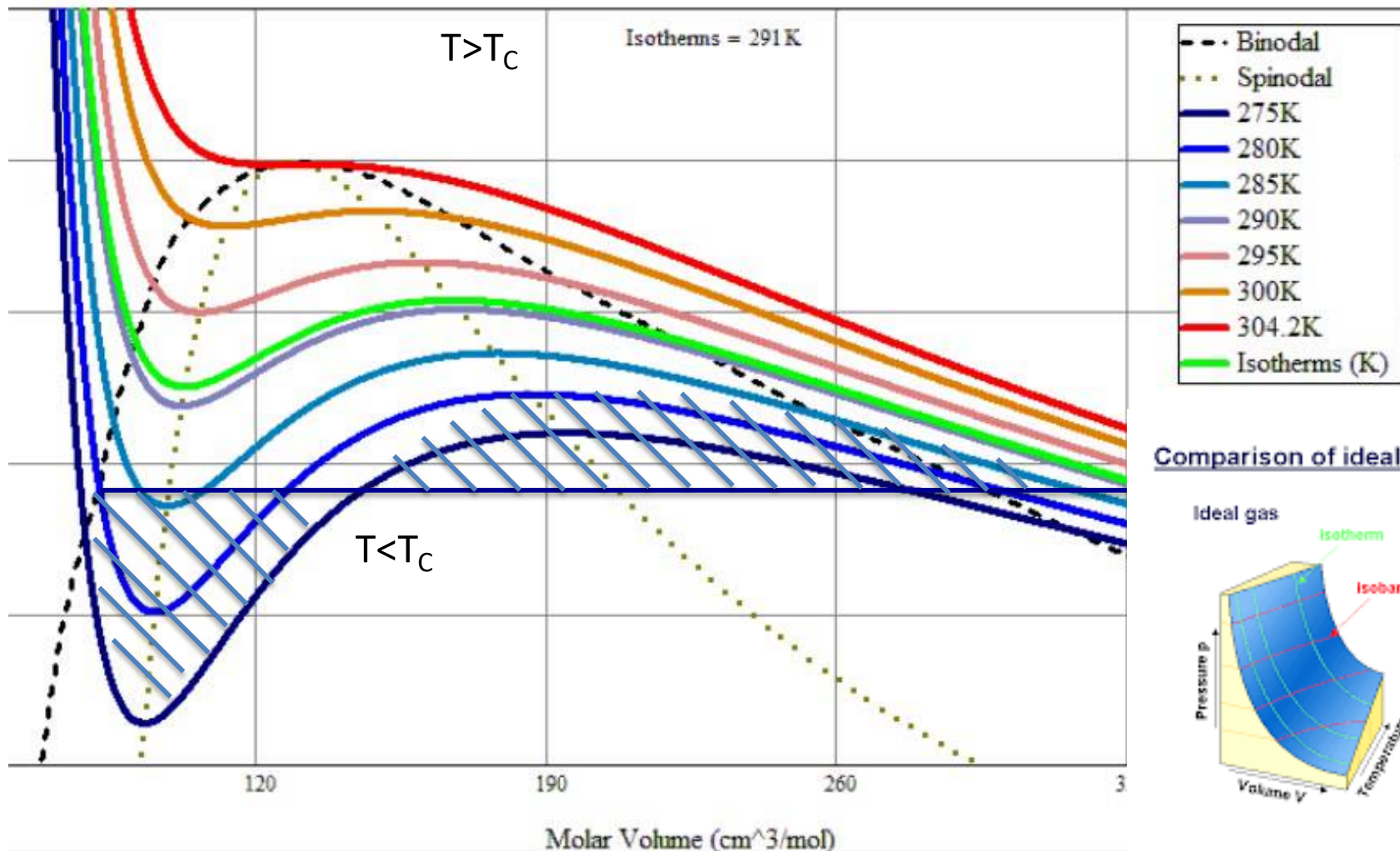


Nobel 1910 Johannes Diderik van der Waals 1837 –1923

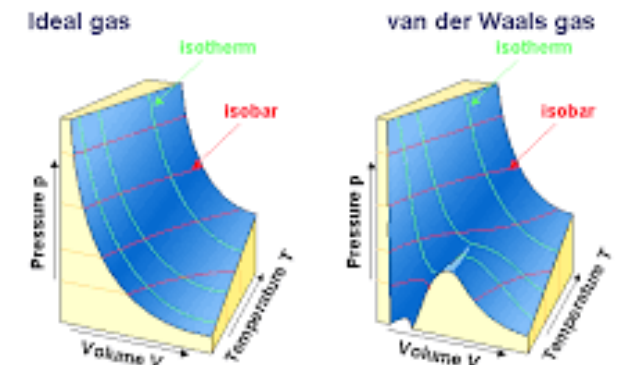
1873 Non-ideal gas behavior is due to attraction between molecules. Cause cooling upon expansion (refrigerators), and heating upon Compression (e.g. Bicycle pump heating). Van der Waals forces repel at long distances and attract close by molecules. Correction to $PV = \text{const}$ Below critical temperature T_c : $(P + a / V_m^2)(V_m - b) = RT$



Carbon Dioxide Phase Envelope : van der Waals Equation-Of-State



Comparison of ideal and van der Waals gas



William Henry 1774 –1836

1801 Henry's law: Gas solubility in liquid is proportional to pressure.
Vapor pressure of liquids at boiling point equals atmospheric pressure,
Therefore boiling temperature dependence on mountain height.

Q: Water container in a room with volume of 4000 liters. How much
Water will evaporate at 25°C given water vapor pressure of 23.8 mm
mercury. **A:** 1 atmosphere = 760 mm.

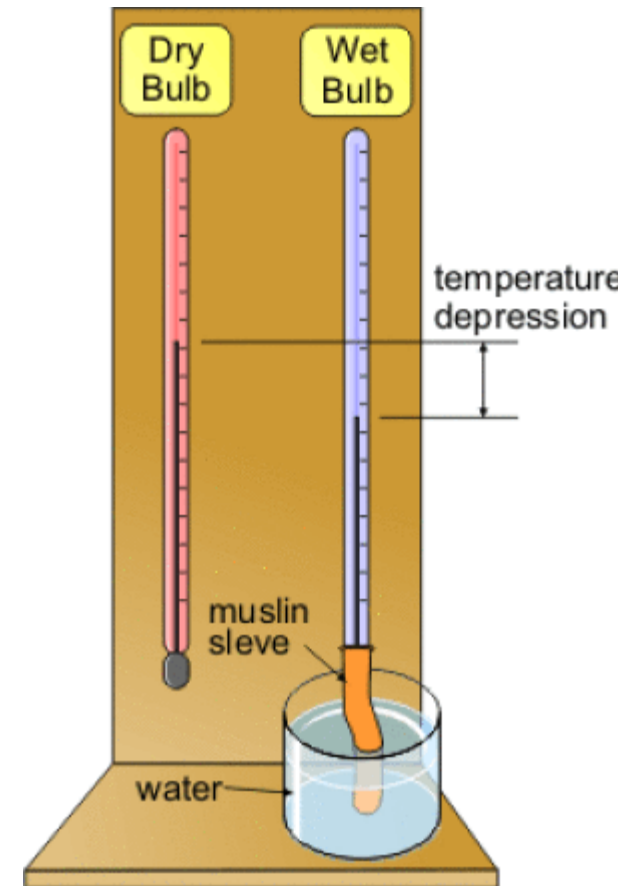
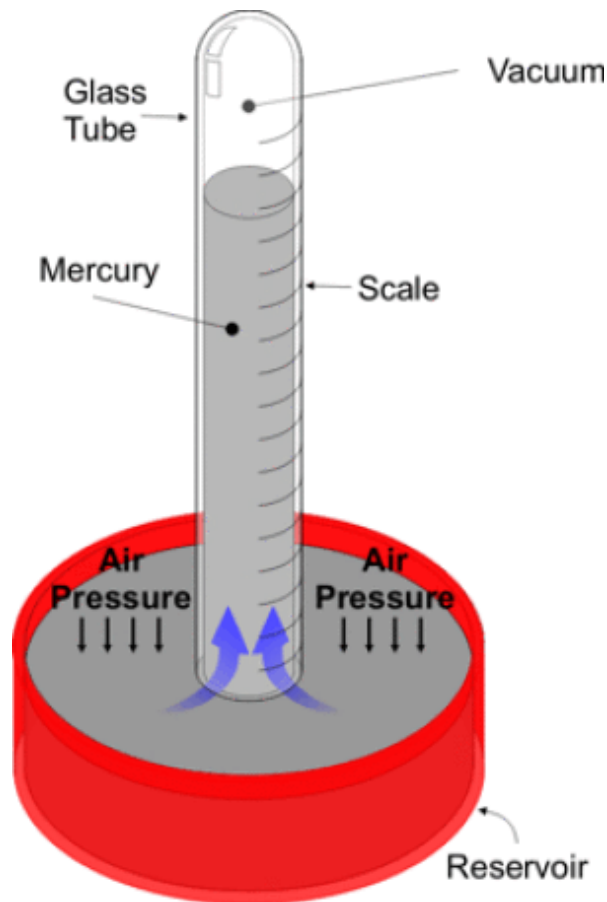
$$n = PV/RT = 23.8/760 * 4000 / 0.082057 \text{ liter atmosphere/mole/Kelvin} / 298 \text{ }^{\circ}\text{K}$$

$$N = 54.4 \text{ moles of water}$$

$$\text{WEIGHT OF WATER} = n * \text{MW} = 54.4 * 18.01 = 980 \text{ gr}$$



Hair hygrometer,
Differential temperature water
evaporation hygrometer,
and Mercury barometer.



THERMODYNAMICS

η

Nicolas Léonard Sadi Carnot 1796 –1832 France

Studied in École Polytechnique in Paris, where Poisson, Ampere, Gay Lusac and others studied. Was a soldier who left the army after Napoleon's defeat, suffered from mania, and died of cholera at the age of 36.

1803 Wrote a paper about geometric transformations: 'geometric motions'

1825 Carnot write a book about steam engines. Their efficiency was very low, and he asked: can efficiency be increase by replacing steam with another material. At that year energy conservation law was published, the 1st law of thermodynamics was published 10 years later, and the 2nd law 20 years later.

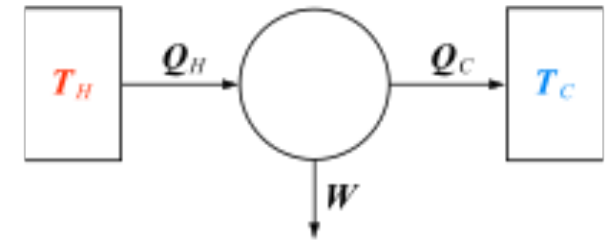
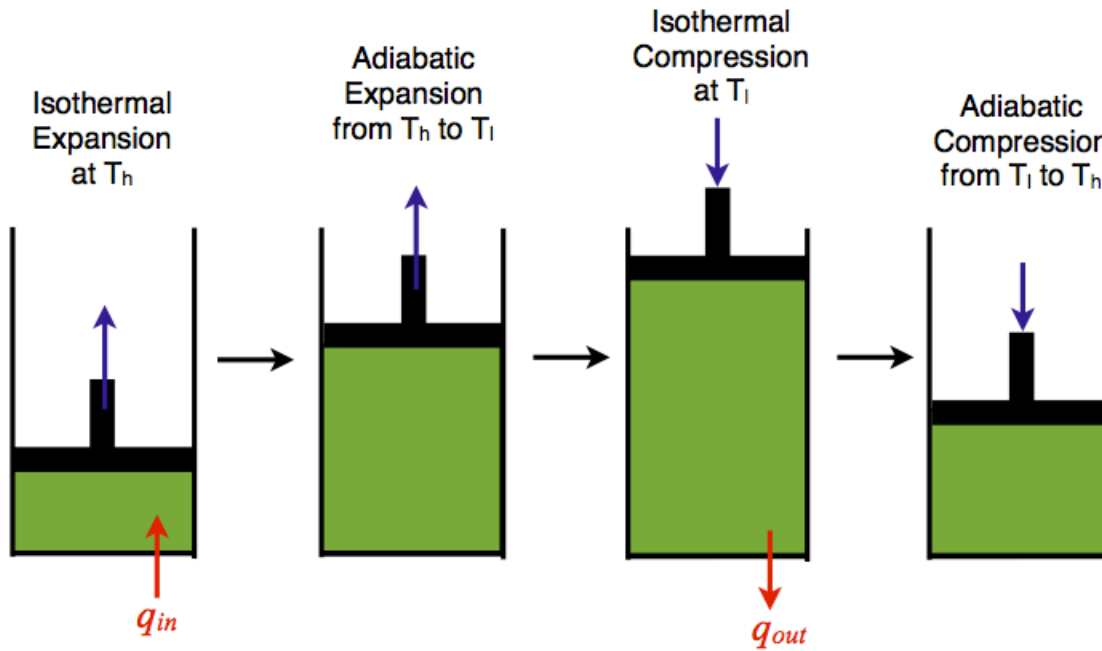
He described in his book the “Carnot cycle”: an abstract ideal machine working between two heat reservoirs with no heat or friction losses. He showed that its efficiency is proportional only to the temperature difference between the reservoirs divided by the absolute temperature in degrees Kelvin: $(T_1 - T_2)/T_1$.

He also discussed lack of reversibility, which lead to the 2nd law, and proposed internal combustion engine that will achieve high efficiency due to the high temperature.

Carnot elevated theoretical methods in thermodynamics and physics in general. On one hand physicists were at ease with materialistic models (heat-caloric, electrodynamics-aether), **Mach** was the most verbal, on the other hand repeated conflicts demonstrated the limitations of these models in prediction of results. Therefore **Boltzmann, Hertz & Planck** supported theories and gedunken experiments as guides for planning and predicting experiments.

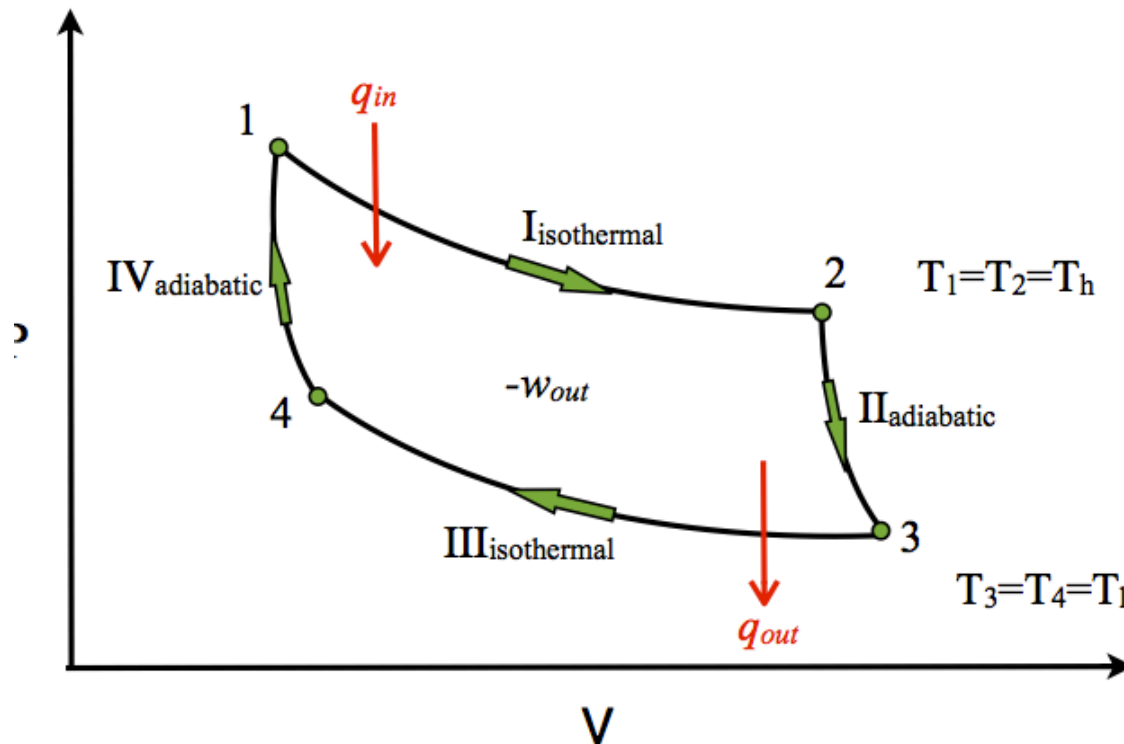


Carnot cycle: 4 beats.



$$PV=nRT$$

$$\text{Work} = \int PdV$$



$$\text{efficiency} = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

HISTORY OF THE STEAM ENGINE:

10-70 Heron of Alexandria – Steam engine made of heated container with two steam exit nozzle that turned the container.

Leonardo: A cannon made of heated bore into which water were injected.

1551 Taqi al-Din turned a turbine by steam jet.

Several inventors followed this design.



Thomas Savery 1650–1715

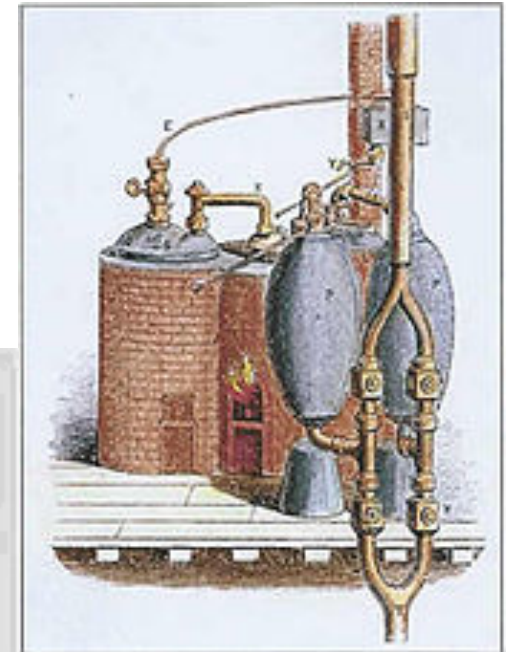
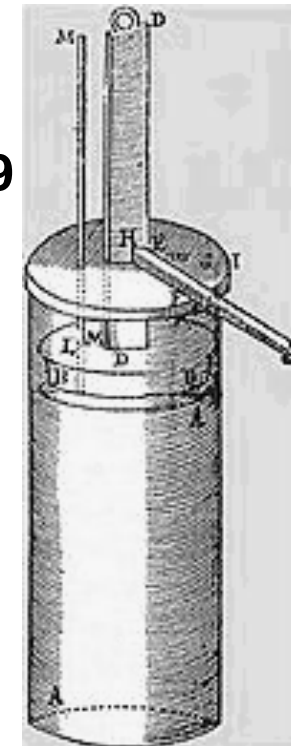
1698 “fire pump” for pumps and sawmills –Valves and 2 steam containers, no moving parts. Steam condense in the water cooled container and pumped water, e.g. from a mine.

Denis Papin 1647 – 1712

Built a pressure can and piston that could do mechanical work. He traveled from France to England to meet Boyle.

Thomas Newcomen 1664-1729

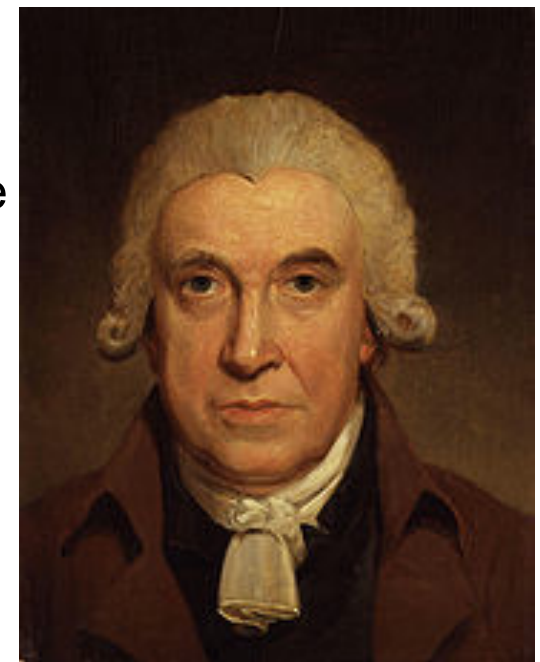
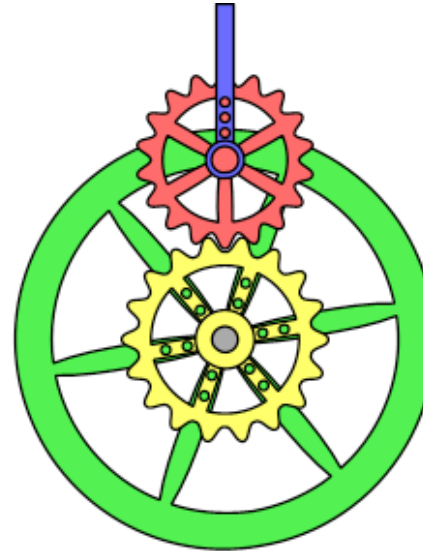
1712 Designed a motorized water pump with piston and valves. Used in coal mines.



James Watt 1736-1819

1765 Understood that the low efficiency of the Newcomen engine was due to the cooling of the cylinder that condensed the steam and created under-pressure to pump water, but also caused most of the steam in the next cycle to condense before closing the valve. His solution was separating the power from the condensing cylinders. His next problem was piston sealing to the cylinders so that steam leakage is minimized without excessive friction.

After his improvements the engine was linked to rotating wheel to convert linear to circular motion:

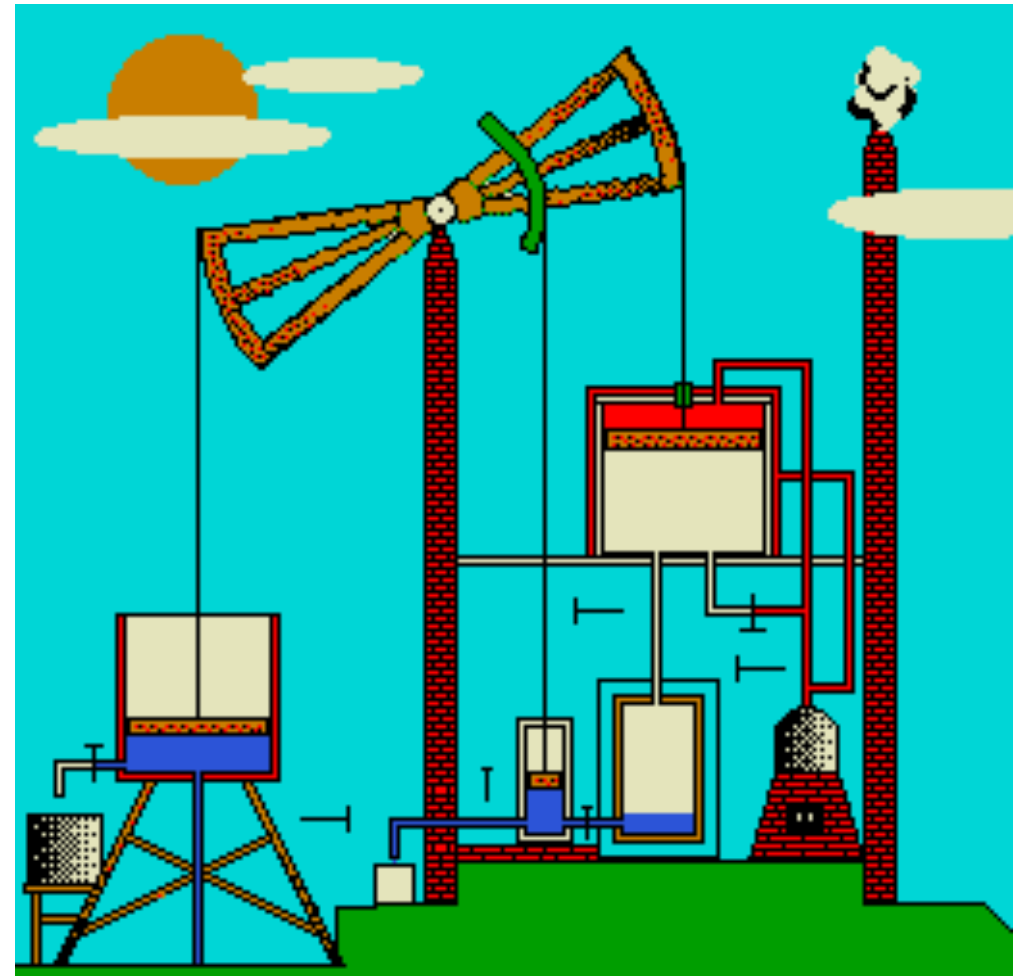
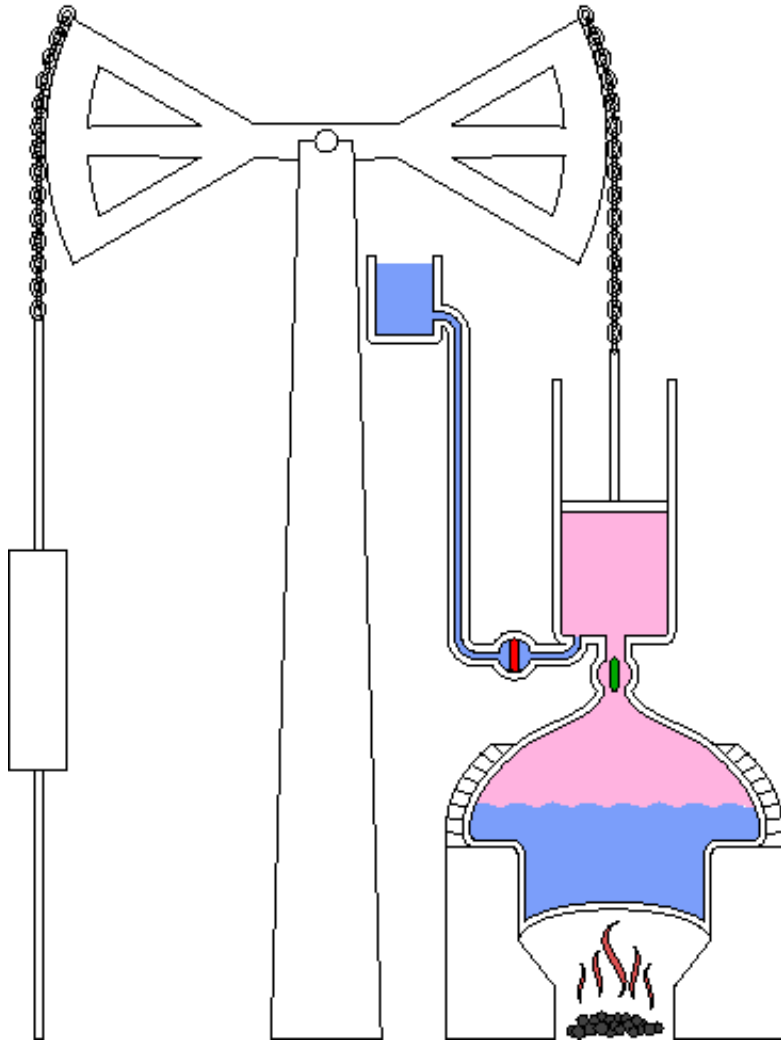


Richard Trevith 1771-1842

1800 Due to Carnot law of efficiency – attempted to build engines where force was created by high-pressure and not by low pressure condensation. The engines were smaller and faster, but tended to explode... Yet they prepared for the train engines.



Animated Newcomen steam engine (left) and Watt's improvement



Water pump

Two cylinder engine

Ivan Polzunov 1728 –1766

1880 Steam engine with two power cylinders – smoother motion

John Finch 1743-1798

1788 Built a steam boat for regular service on the Delaware river between Philadelphia and Burlington.

Robert Fulton 1765-1815

1807 Built peddle-wheel steamboats for commercial lines on the Mississippi river.



Robert Stephenson 1803 –1859

Trains using the already existing rails built for horse-driven carriages.

THE INDUSTRIAL REVOLUTION

Motivating factors:

Spinning mills

Looms programmed by punch cards

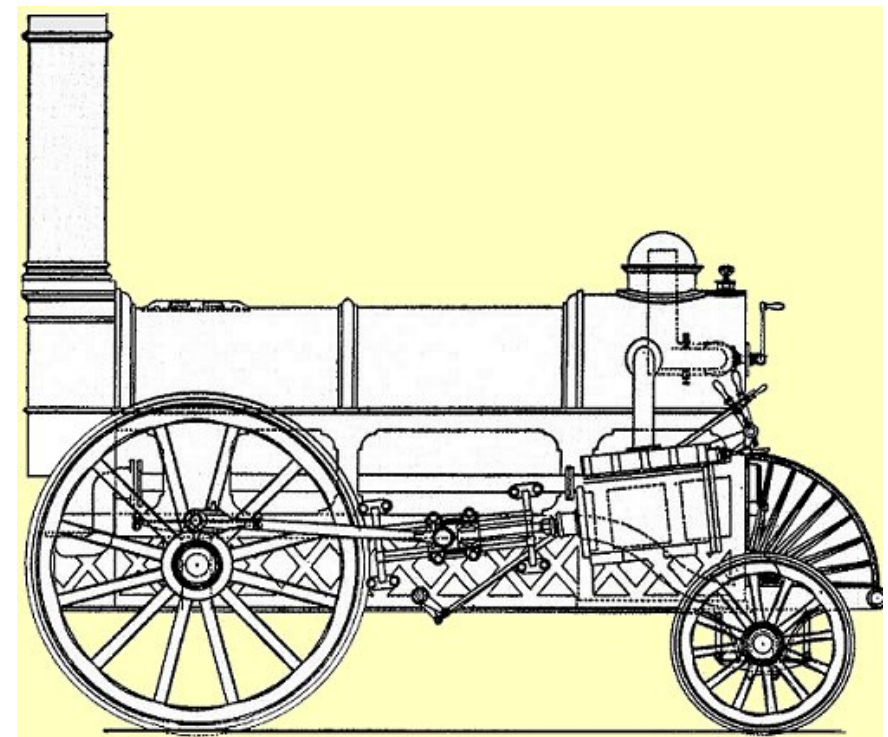
Steam engines

Steel and other metal manufacturing capability

Artificial light

Coal mines

Transportation (channels, trains)



Thomas Young 1773 –1829

1806 Formulated the kinetic theory, and the concept of energy.



James Prescott Joule 1818 –1889

Came from English beer brewers family.

1845 The mechanical equivalence of thermal energy (heat).

Was described independently by **Julius Robert Mayer**

Joule built a device where a weight rotated a vane in water.

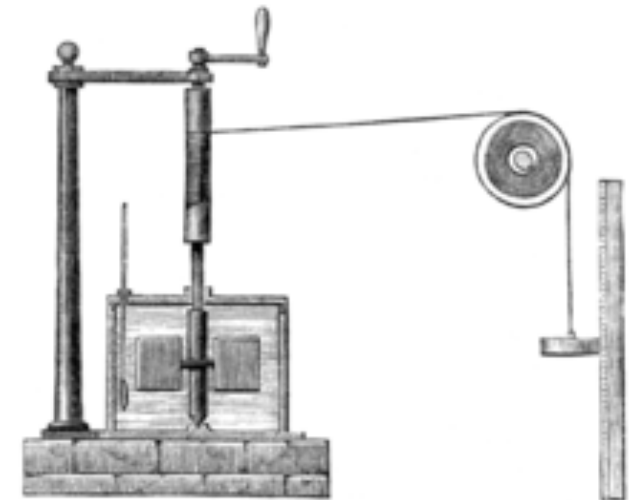
Its friction caused water temperature to rise. Conservation of mechanical energy was thus extended to heat+mechanics, forwarding the 1st law of thermodynamics, and burying the caloric theory of heat (“caloric liquid flow from hot to cold”).

Joule described the kinetic theory of gases (although he assumed rotational energy and not linear to molecules).

During his honeymoon in France he tried to measure temperature difference of water coming down a waterfall.



Energy unit is named after Joule.



Hermann Ludwig Ferdinand von Helmholtz 1821 –1894 Germany

The eye, color vision, metabolism in muscles (believed that muscles use vital energy), hearing and sound (built a resonator to produce defined steady tones at controlled intensities).

1847 Energy conservation law. Separated free energy from chemical energy.

Gibbs-Helmholtz equation:

$H=E-TS$ Free energy = internal energy – entropy times temperature

Conservation of free energy.



William Thomson, 1st Baron Kelvin or – Lord Kelvin 1824 –1907

1848 Absolute zero temperature – atomic motion is frozen.

Absolute temperature scale after his name:

$$\text{Degrees kelvin} = \text{Degrees Celsius} + 273$$

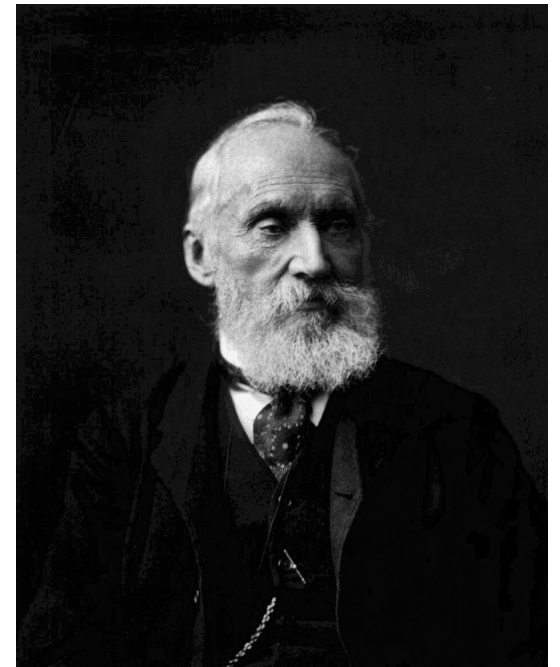
Following Joule's publication of the mechanical equivalence of mechanical work, he claimed that heat cannot be converted to work.

Joule-Thomson effect: cooling of gas, flowing through an orifice.

Formulation of the 2nd law of thermodynamics: The total entropy of a system can only rise. 3rd law of thermodynamics: The entropy of a system approach a constant at absolute zero temperature.

Kelvin advanced the transatlantic telegraph line, won nobility from Queen Victoria, and was the vice chairman of Eastman-Kodak company.

He calculated that we have 400 years of oxygen supply in the atmosphere before we all dye choking...



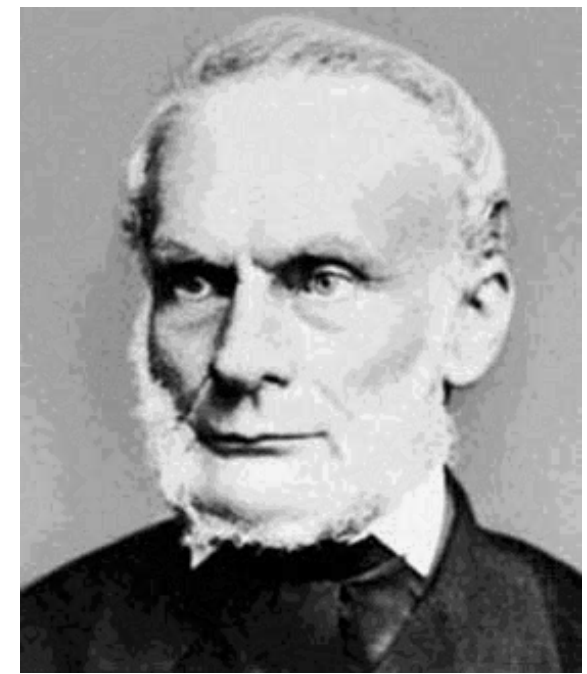
Rudolf Julius Emanuel Clausius 1822 –1888

1850 The 1st law of thermodynamics: total energy in a closed system is constant (yet it can transform between heat and Mechanical energy).

Mechanical theory of heat. Mean-free-path of gas molecules (mean distance between collisions).

Clausius found a conflict between energy conservation and Carnot cycle, which he solved by defining Entropy and formulating the 2nd and 3rd laws of thermodynamics:

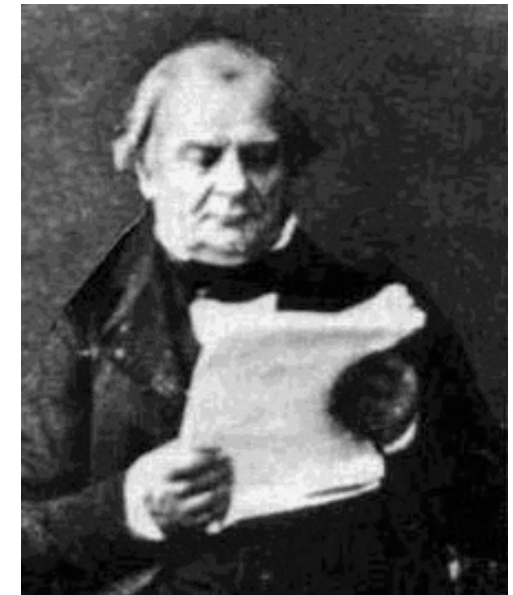
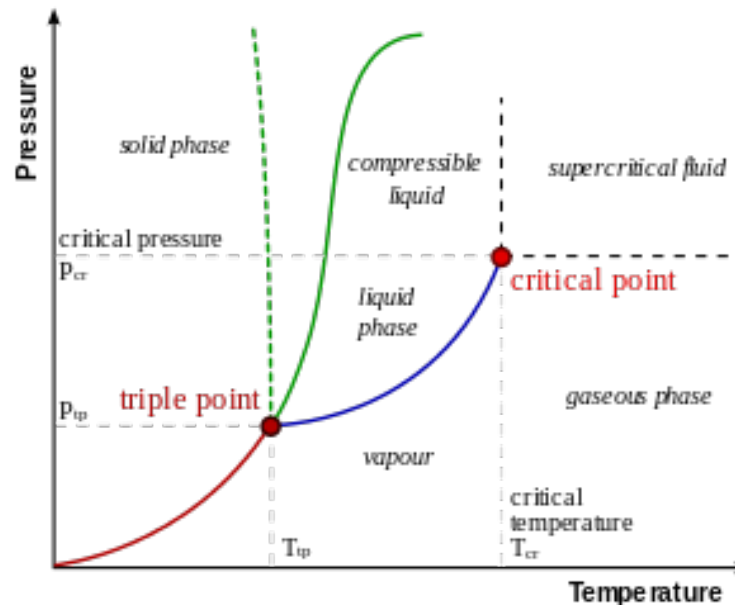
Entropy cannot decrease in a closed system: temporal arrow and irreversibility in physics..



Benoît Paul Émile Clapeyron 1799 –1864

Clausius-Clapeyron equation: pressure-temperature relation along phase transition border (liquid-gas):

$$\frac{dP}{dT} = \frac{L}{T \Delta v} = \frac{\Delta s}{\Delta v},$$

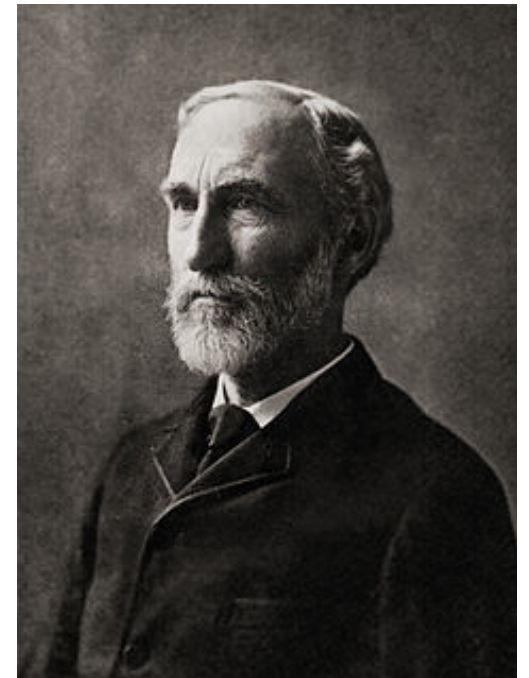
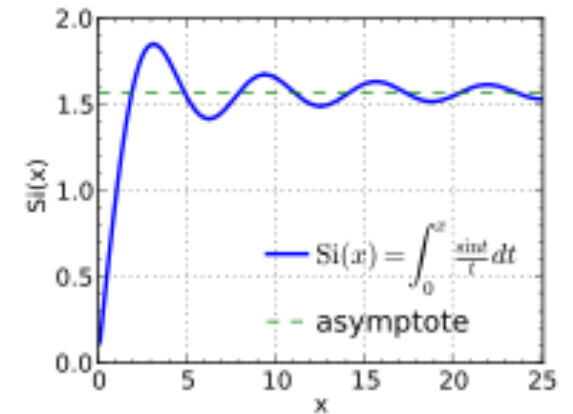


Josiah Willard Gibbs 1839 –1903

1876 Founded chemical thermodynamics – Gibbs free energy and chemical reaction theory.

“Wiggles” in the sine transform of a step function. (see figure)

Vector algebra (replaced quaternion algebra).



Ludwig Boltzmann 1844 –1906

1877 Statistical definition of entropy.

Debated with **Poincare**: “is time reversible”. Poincare proved that in mechanical systems time is reversible. Boltzmann entered entropy and showed that time is not reversible.

$$\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial x} + a \frac{\partial f}{\partial v} = \frac{\partial f}{\partial t} \Big|_c$$

Boltzmann's equation:

Describe changes in particle distribution function, f .

1872 Boltzmann claimed that the second law of thermodynamics and entropy rise can only be understood in large populations, and not from tracking the path of a few particles. Large populations “evolve” and entropy is statistical, thus there is only a small probability for “extreme” states. Defined function E equivalent to Clausius entropy.



Sir William Crookes 1832-1919

1875 Developed a light vane as a radiometer. **Maxwell** thought that radiation pressure is the force driving the vane, but when higher vacuum was achieved in the glass the motion slowed down. That brought the correct mechanism: the black side is more heated and cause gas molecules to move faster, collide with the surface and push the vane to rotate. **Einstein** calculated the effect and fitted experiments. Crookes' vacuum tube was the enabling technology of particle physics .

2009 such vane was manufactured when both sides of the wings were coated by the same crystalline nano-gold that is a good absorber, but one surface was concave the other side convex. This setting rotated by light...



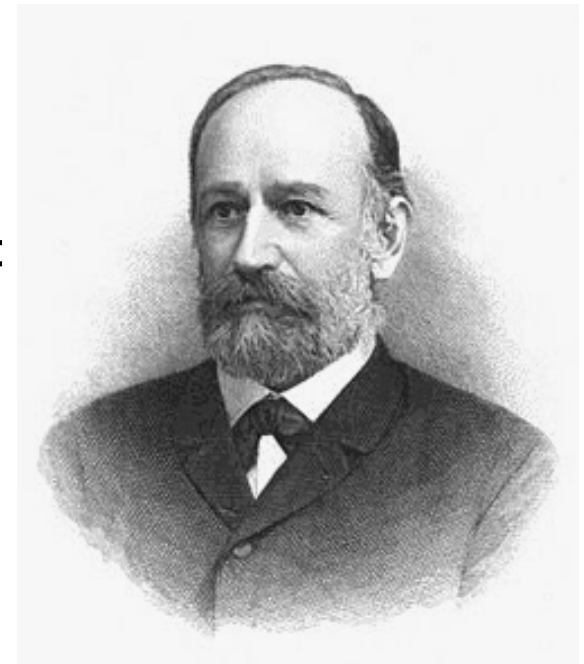
Josef Stefan 1835–1893

Stefan combined Maxwell's equation for thermodynamics – Stefan-Boltzmann law. He showed that radiated energy from a hot body is proportional to fourth power of the body temperature:

$$J = \sigma T^4$$

The radiated energy spectrum from black body played a central role in the development of quantum mechanics.

1883 Electromagnetic waves create pressure on a surface at reflection. Used the vane erroneously as a proof of radiation pressure. In fact the pressure from light reflected off the polished side should have been larger than from the black side that absorbs the light.



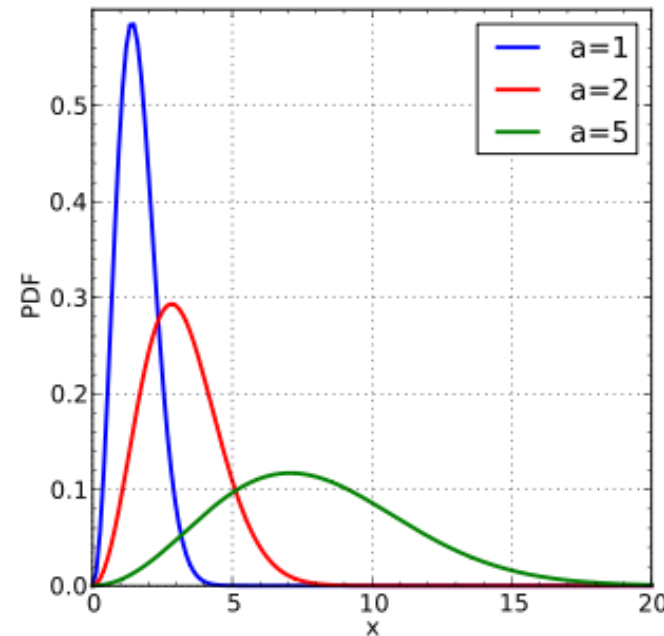
James Clerk Maxwell 1831 –1879 Scotland

1867 Dynamic theory of gases

Velocity distribution of gas molecules

Maxwell-Boltzmann distribution.

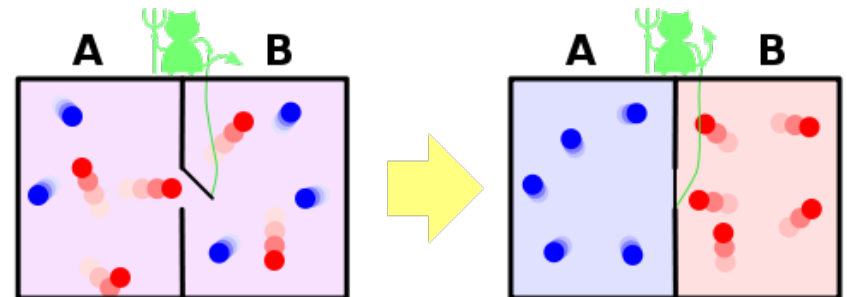
$$f(v) = \sqrt{\left(\frac{m}{2\pi kT}\right)^3} 4\pi v^2 e^{-\frac{mv^2}{2kT}},$$



Maxwell attempted to dispute Boltzmann's entropy laws.

Maxwell's demon: Senses atoms speed, and opens a gate between two chambers so that the faster molecules will concentrate at the right chamber. Eventually the right chamber will be hotter – conflicting thermodynamical laws ???

1872 Explained by the fact that it is impossible to measure the speed of particles without changing it.



Walther Hermann Nernst 1864 – 1941 Nobel 1920

Osmotic pressure –membrane impermeable to ions, but not to water molecules

1897 Invented incandescent lamp with ceramic filament. sold to Westinghouse and replaced Edison's carbon filament. **Irving Langmuir** his student developed the tungsten lamp used until recently.

1903 A source of Infrared radiation: filament from rare metal oxides: Nernst glower.

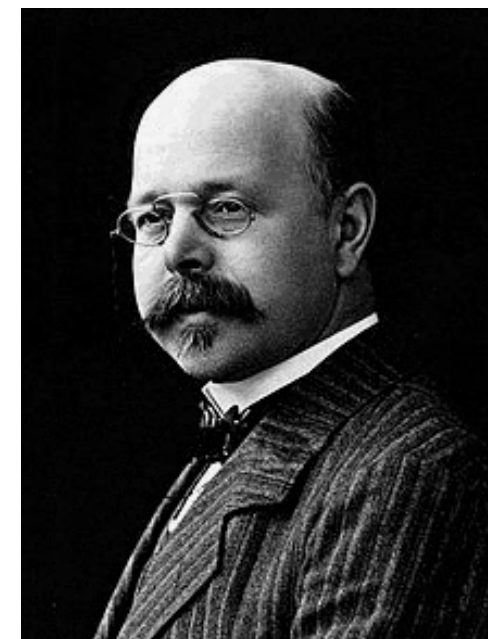
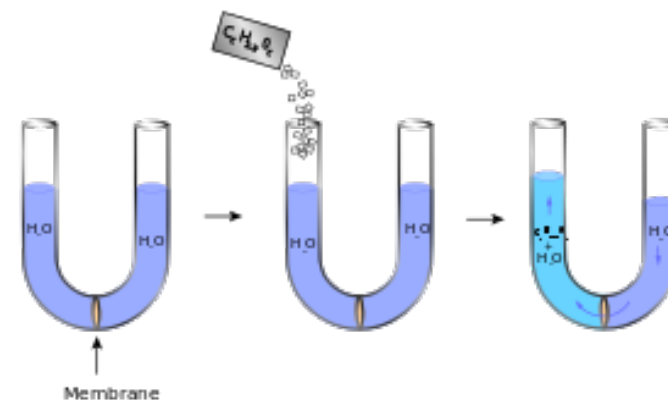
1905 The 3rd law of thermodynamics – approach to absolute zero, measured free energy and chemical equilibrium.

1914 Visited **Einstein** in Zurich after reading his papers, and invited him to take position in Kaiser Wilhelm institute at Humboldt University. He donated money to free Einstein from teaching.

1918 Chain reactions – the idea was about chemical reactions, but was realized for nuclear reactions.

1930 Electronic piano – with Bechstein piano manufacturer.

Resisted the Nazis – which terminated his academic career.



TIME POINTS IN THERMODYNAMICS

Jean Baptiste Joseph Fourier 1768-1830

1807 Solved problems of solids expansion when heated –
Used Fourier analysis



Sir John Leslie 1766 –1832

1810 Froze water in a cooling system



Siméon-Denis Poisson 1781-1840

1811 The mathematical theory of heat, based on Fourier

Amedeo Avogadro 1776 –1856

1811 Avogadro's law – all gases at similar temperature, volume and pressure contain the same number of molecules.



Jöns Jakob Berzelius 1779-1848

1811 Electric and chemical forces are the same. Atoms are charged.

Humphry Davy 1778 –1829

1812 Wrote a chemistry book, where he added rotational motion (and angular momentum) to the kinetic degrees of freedom.



François Delaroche 1775–1813 and Jacques-Étienne Bérard 1789-1869

1812 Measured specific heat of a large number of gases that matched Poisson's predictions, confirmed the caloric and Carnot's theories, and encouraged development of thermodynamics. They erroneously reported about decrease of the specific heat of air with increasing pressure.

They won the prize of the French Academy of Sciences.

Peter Ewart 1767 –1842

1813 Dealt with energy conservation in a publication that influenced **Dalton** and **Joule**.

Pierre-Louis Dulong 1785-1838 and Alexis Thérèse Petit 1791-1820

1819 Measured specific heat at constant pressure at a wide range of temperatures for metals. Demonstrated that specific heat times atomic mass is a constant. Law of Dulong and Petit: Specific heat of all atoms is identical.

John Herapath 1790 –1868

1820 Deduced constants from the kinetic theory of gases: heat is motion, not a liquid (caloric). Attributed temperature erroneously to momentum and not kinetic energy. His paper was rejected, and accepted a year later, yet except by Joule, was grossly ignore. Nevertheless, from 1821 on, the kinetic theory of gases dismissed the caloric theory.

Thomas Johann Seebeck 1770-1831

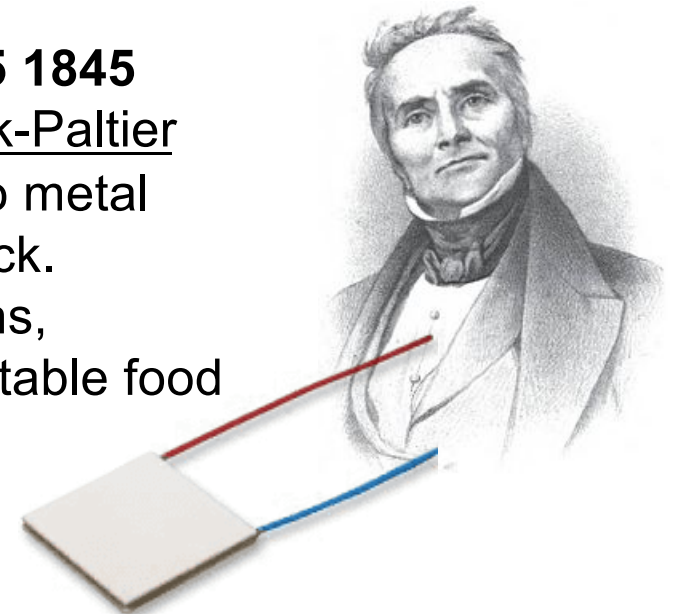
1820 Discovered generation of electric potential from temperature difference between two metals connected in a junction – thermocouple and Thermoelectric effect.

Aside from the important technology to measure temperature, the effect contributed to the crystallization of the concept of energy and its various embodiments in mechanics, heat and electricity.



Jean Charles Athanase Peltier 1785 1845

Discovered independently the thermoelectric effect: Seebeck-Paltier Effect: Heating or cooling, depend on current direction in two metal contact. The reciprocal to the thermoelectric effect of Seebeck. Today efficient Paltier coolers, produced from silicon junctions, are widely used to cool CPU processors, CCD cameras, portable food coolers in cars and more.



Charles Cagniard de la Tour 1777-1859

1822 Found that phase transition from gas to liquid depends on pressure and temperature, and discovered the critical point.

Pierre-Simon Laplace 1749-1827

1822 Published several papers opposing Newton's idea that gases are created by repulsion between molecules.

Marc Séguin 1786-1875

1822 Wrote to Herschel to support energy conservation and the kinetic theory.

Siméon Denis Poisson 1781-1840

1823 Developed a gas theory where repulsion between atoms comes from „caloric atmosphere“ around atoms.

1824 Invented the magnetic scalar potential function and density of poles on a surface and in a volume. Calculated the magnetic field at the center of a hollow magnetic metal.

Thomas Graham 1805-1869

Graham's law: Diffusion of two gases into each other – spontaneous mixing of infinitesimal volumes of the two gases in contact, at rates inversely proportional to the square root of their densities.

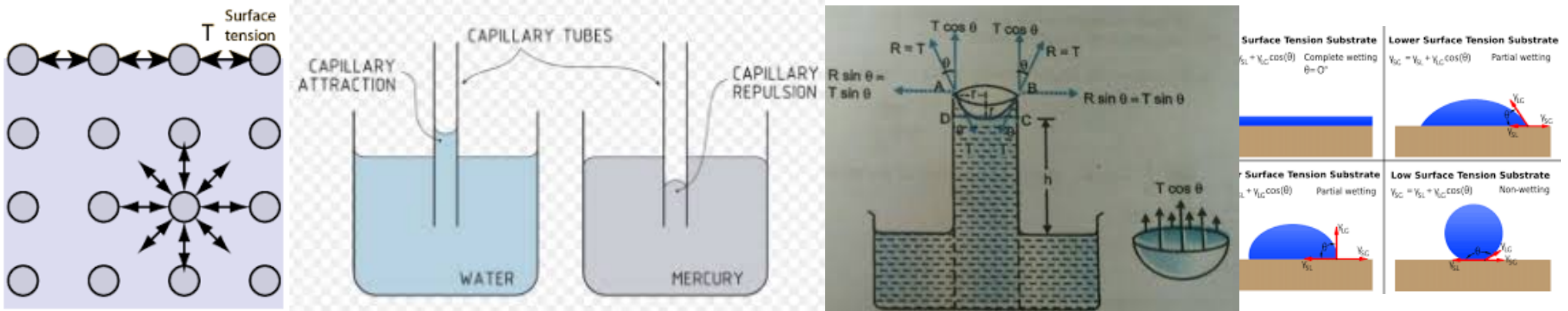
He also noted that gases can be separated by diffusion. This was the method of separation of uranium isotopes 235 and 238 using centrifuges in the Manhattan project.

Franz Ernst Neumann 1798-1895

1831 Extended specific heat (inversely proportional to atomic weight) from gases to solids. The specific heat of alloys is the sum of its components.

Carl Friedrich Gauss 1777-1855

1830 Developed the expression for surface tension based on all forces between liquid molecules at the interface with air. (see Liquids in the following slides under “Laplace”)



Macedonio Melloni 1798-1854

1830 Thermocouple, generates electric potential at temperature difference, thus when calibrated becomes a thermometer.

1831 Demonstrated that black-body radiation can be reflected, refracted and polarized like light.

Émile Clapeyron 1799-1864

1834 Following experiments with steam engines, formulated the second law of thermodynamics. Propagated Carnot's results.

Clausius Clapeyron law see above.

von Suerman 1783-1862

1837 Low air pressure experiments confirm Clapeyron version of Carnot's equation.

James Prescott Joule 1818-1889

1841 Joule demonstrated that conservation of energy in electric circuits include current, heat and chemical transmutation.

1843 Without knowing about Mayer's work, he measured the thermal equivalent of mechanical work. Energy conservation includes heat. Defined latent heat in phase transitions (such as ice to water to vapor) as the internal energy between molecules. Published **1847**.

Energy unit is named after him.

Julius Robert von Mayer 1814-1878

1841 Mayer, an amateur scientists, claimed that work and heat are equivalent. The link between heat and work – the 1st law of thermodynamics and energy conservation.

ENERGY is a concept lacking visible materialistic meaning, and was not accepted easily.

1842 Sent a paper about energy conservation that was not accepted for publication.

William Thomson (Lord Kelvin) 1824-1907

1843 published conservation of energy.

1842 Solved heat flow problems in uniform materials.

William Robert Grove 1811-1896

1842 Demonstrated decomposition of molecules in heat, e.g. steam to hydrogen and oxygen, and composition back upon cooling: chemical energy.

1846 Summarized the general theory of energy conservation.

John James Waterston 1811-1883

1844 Published, without author name, thoughts about soul functions, with comment about the kinetic theory of gases including energy equipartition and mean free path between collisions. The work was ignored.

Karl-Hermann Knoblauch 1820 –1895

1846 Published a paper about radiation of heat.

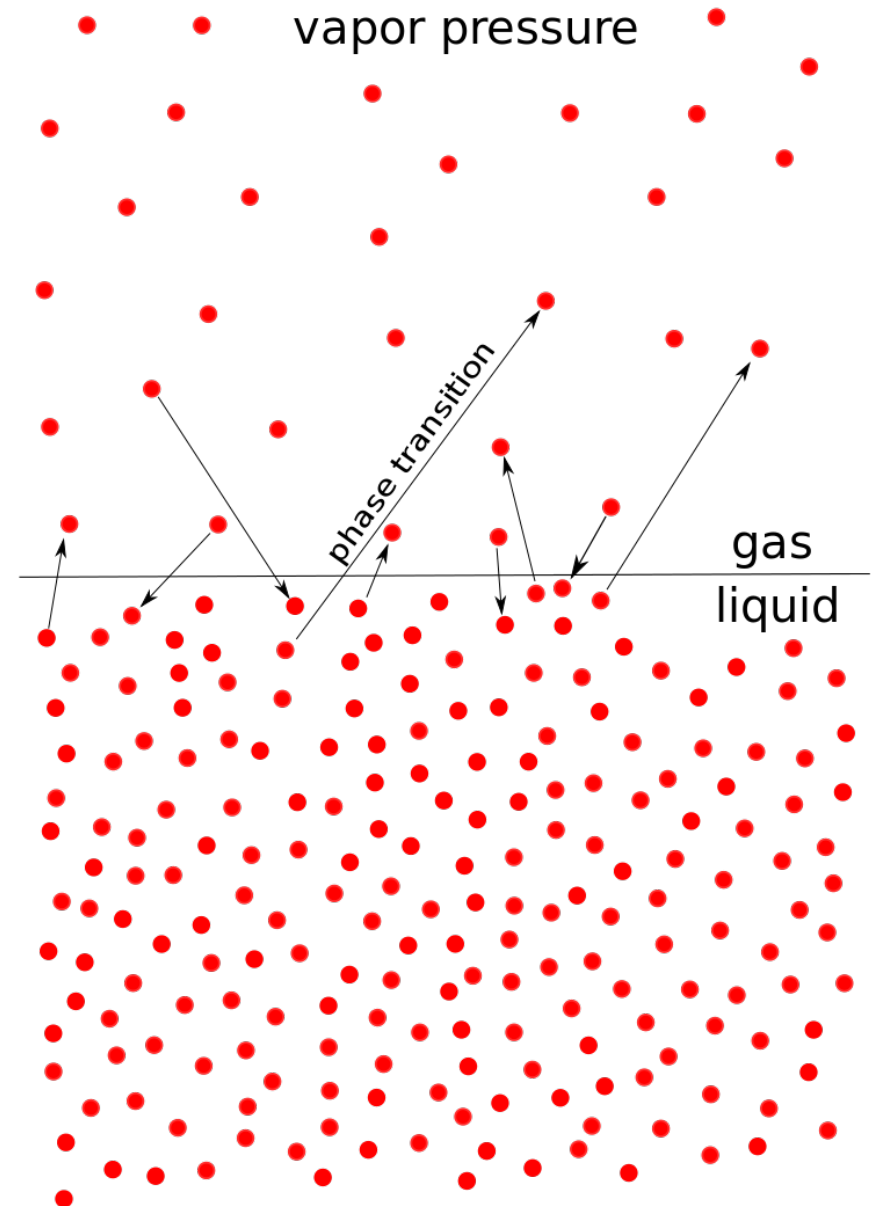
Hermann Ludwig Ferdinand von Helmholtz 1821-1894

1847 Independent from Joule, wrote a mathematical formulation to the law of energy conservation and the 1st law of thermodynamics. In his paper about “conservation of forces“ he stated that kinetic and potential mechanical energies can be converted into heat. According to **Rumport, Mayer & Joule** all energy forms can be converted to chemical, electric and magnetic energies. The world consist of materials and forces. His publication was responded with suspicions, and his paper was not accepted for publication.

Lambert Heinrich von Babo 1818 –1899

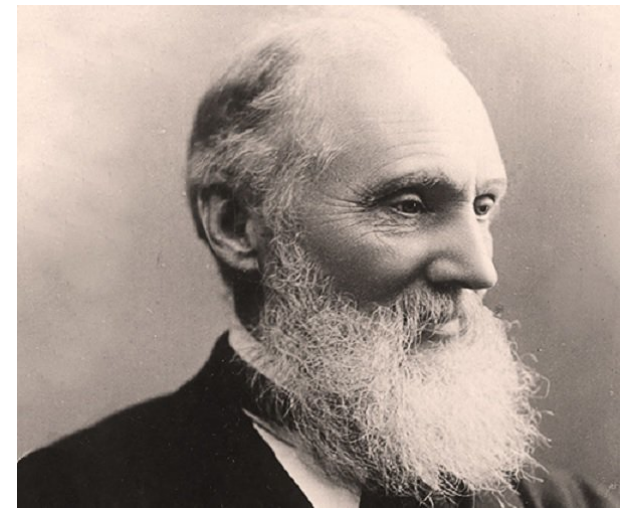
1847 Dissolving materials in liquids (e.g. salt in water), reduces the vapor pressure of the liquid proportionally to the concentration of the dissolved material.

This can be understood from the Kinetic theory, see picture.



William Thomson (Lord Kelvin) 1824-1907

1848 Rediscovered the absolute zero and extended it from gases to all materials. 149 years after **Amontons and Charles** laws extrapolated to the temperature where volume and pressure of gases diminished, Kelvin, based on Carnot's cycle, proposed that energy of molecules diminish at the absolute zero. Carnot's cycle has zero efficiency at the absolute zero temperature.



1892 The British parliament resolution: "Kelvin temperature Scale" (0°K — 273°C).

James Prescott Joule 1818-1889

A lecture based on the kinetic theory of **Herapath**. Quantitative results are published at **1851** and distributed throughout the scientific community by **Clausius** at **1857**.

Rudolf Clausius 1822-1888, Lord Kelvin 1824-1907

1850-1 The 2nd law of thermodynamics.

John William Draper 1811-1882

1847 Discovered that all materials start to irradiate red at 525°C, and at increasing temperature the color shifts to white.

James Thomson – Kelvin 1822-1892

1849 Relying on Carnot, he calculated the freezing point of water under pressure. Kelvin coined the name “Thermodynamics” when he lectured about Carnot. He rejected the caloric theory.

William John Macquorn Rankine 1820-1872

1849 Calculated the relation between vapor pressure and temperature.

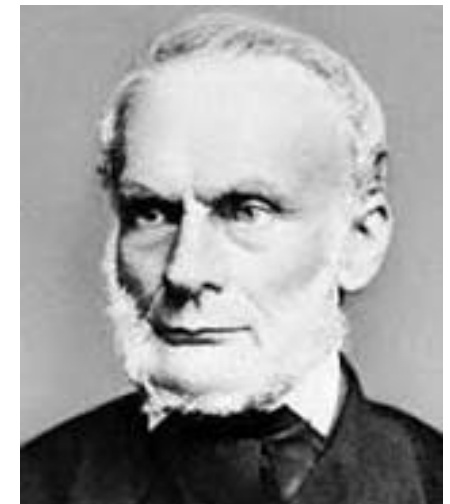
1850 Applied his turbulence theory to the temperature-pressure-density of gases and latent heat of evaporation and liquidation. Predicted that the specific heat of saturated steam is apparently negative, due to partial liquidation.

Rudolph Julius Emanuel Clausius 1822-1888

1850 Formulated clearly, for the first time, the two laws of thermodynamics. Extended Carnot’s principles to entropy – degree of system order. The 2nd law states that entropy can only rise: natural law that things age and deteriorate... Heat flow from high to lower temperature. Gas molecules move randomly at equal kinetic energies.

1851 Thomson formulate the 2nd law differently.

1870 Proved scalar virial theorem linking the temporal average of the kinetic energy in multiparticle systems to the forces acting on it.



Joule & Thomson (Kelvin) 1824-1907

1852 Demonstrated gas cooling by fast expansion – Joule-Thomson effect.

Henri-Victor Regnault 1810-1878

1852 Measured deviations from Boyle's law at low temperatures. Extrapolated the behavior to -273°C , the absolute zero.

Hendrik Roozeboom 1854-1907

1854 Concluded from measurements the law of phases, later theoretically deduced by Gibbs.

Hermann Ludwig Ferdinand von Helmholtz 1821-1894

1854 Proposed a thermal death of the universe.

Rudolf Julius Emanuel Clausius 1822 –1888

1854 Established Clausius theory for dQ/T , not yet called entropy.

1857 An extended paper about the kinetic theory of gases, the kinetic theory of heat and the statistical distribution of motion between particles.

1858 Mean free path emerge from the kinetic model.

William John Macquorn Rankine 1820-1872

1854 Presented the thermodynamic function to be called entropy.

Karl Krönig 1822-1879

1856 Published a paper about the kinetic theory describing gas molecules moving in straight lines between collisions, possibly followed reading Waterston's works.

Rudolf Julius Emanuel Clausius 1822 –1888

1857 Clausius equation for non-ideal gas:

$$RT = \left(P + \frac{a}{T(V_m + c)^2} \right) (V_m - b)$$

Similar to Van der Waals correction.

Attributed energies to velocities as well as rotational and vibrational motions.

Physical considerations to support Avogadro's law.

Based on distribution of velocities he explained evaporation from liquid-gas interface.

1862 Entropy.

1865 Entropy and the 2nd law. Applied Carnot's theory to obtain the modern definition of entropy and the two laws

$$\Delta S = \oint \frac{\delta Q}{T} \leq 0$$

Of thermodynamics (without Caloric).

Gustav Kirchhoff 1824-1887

1859 Showed that based on the 2nd law black body radiation spectrum depends only on temperature, and not on the emitting material.

Sir Joseph Swan 1828-1914

1860 Incandescent light bulb with carbon filament.

James Clerk Maxwell 1831-1879

1860 Gas viscosity is independent on pressure or density

1877 Discovered that in gas mixture the density in a centrifuge for each gas is independent on other gases – makes it possible to enrich heavier gases in mixtures, the basis of heavy Uranium isotopes enrichment for the atomic bomb.

John Tyndall 1820-1893

1863 Heat as a model for motion – publicized Maxwell's idea of heat.

Diamagnetism

Henri Becquerel 1852-1908

1864 Proposed optical pyrometer based on spectrum of black body radiation.

Hugh Longbourne Callendar 1863–1930 & M. S. Van Dusen

1885 Platinum wire resistance thermometer.

Henri-Louis Le Chatelier 1850-1936

1892 Built the first optical pyrometer – temperatures of hot objects that cannot be touched physically.

Josef Loschmidt's 1821-1895

1865 Applied Maxwell's kinetic theory of gases to estimate Avogadro's number of gas molecules and gas viscosity.

1876 Criticized Boltzmann's H theorem since it contradicted reversibility, although the physical laws at the basis of the kinetic theory were time reversible, Loschmidt's reversibility paradox.

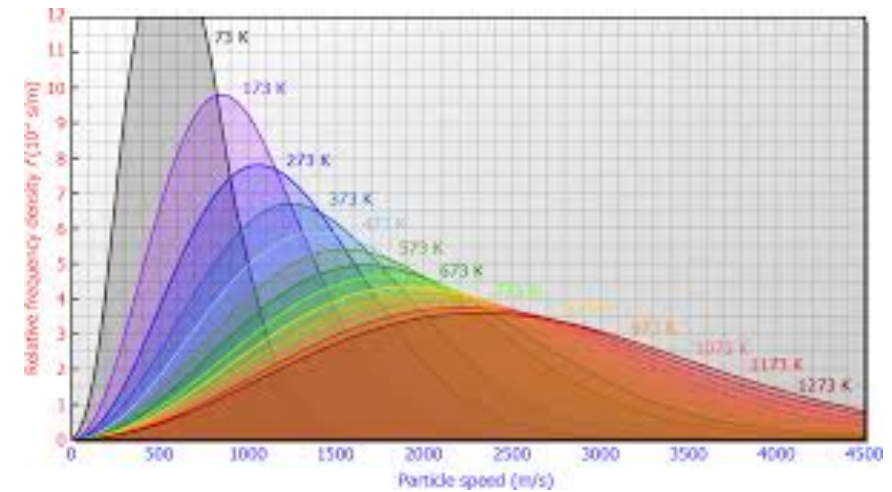
Ludwig Boltzmann 1844-1906

1868 Extended Maxwell's kinetic theory of gases: Boltzmann distribution of kinetic energies between colliding gas molecules according to probability theory and combinatorial analysis. The Gaussian Boltzmann distribution is the basis of statistical mechanics.

1872 Boltzmann formulated time-depended equations for the distribution functions in phase space. Published his H-theorem: in isolated system entropy increases. Used discrete energy levels with energy differences approaching zero. The publication raised a lot of opposition.

1877 The link between entropy and probability: entropy is the logarithm of a volume in phase space filled by system states. Statistical mechanics version of the 2nd law.

1896 Developed the kinetic theory of gases, yielding correct values when averaged on many systems: The ergodic assumption.



Boltzmann, Gibbs

1871-89 Development of statistical mechanics.

Josiah Willard Gibbs 1839-1903

1873 A graphical method to thermodynamics of liquids.

1873 The basic equation relating change of entropy and internal energy

$$dU = TdS - PdV$$

Thomson (Kelvin) 1824-1907

1874 Presented officially the 2nd law of thermodynamics.

Max Planck 1858-1947

1879 Resisted the idea that the 2nd law depends on the observer or his information, which brings in irreversibility.

Josiah Willard Gibbs 1839-1903

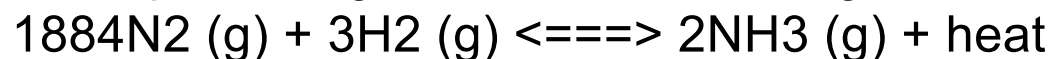
1876 Published first part of a paper on equilibrium in heterogeneous systems – phase transitions, statistical ensembles, free energy as a force motive for chemical reactions, and chemical thermodynamics.

1878 Published the second part.

1883 Coined the term “statistical mechanics” to implement the kinetic theory in thermodynamics.

Henri-Louis Le Chatelier 1850-1936

1884 Le Chatelier's principle defines a change in a system at equilibrium responding to external perturbation so as to reduce its effect. The law was first formulated for gases and change in pressure or temperature, but extended to chemical reactions. For example, Haber process of producing Ammonia from nitrogen and hydrogen:



Addition of hydrogen “pushes” the system equilibrium right, heat – left, and taking Ammonia out – right

Ernst Zermelo 1871-1953

1896 After Josef Loschmidt criticized Boltzmann's increase of entropy due to lack of time reversibility that exists microscopically (or entropy decrease), Zermelo the mathematician presented a paradox based on Poincare, who studied the 3-body problem, and proved from conservation laws that although the problem does not have an analytical solution, the system turns back to itself in phase space (space and time) with epsilonic proximity.

1890 He proved the above for n-body systems: "Poincaré recurrence time", which means that also entropy returns to its initial value.

Boltzmann's answer: entropy rise is statistical, that is averaged on an ensemble of systems possible states. Only for a minute part of the cases for a short time there will be lower entropies.

Michael Faraday 1791-1867

1823 Discovered liquidization of chlorine gas by electrolysis at room temperature (due to pressure).

Karl Paul Gottfried von Linde 1842-1934

1881 Linde built the first practical refrigerator with liquid Ammonia.

James Dewar 1842-1923

1892 Invented the vacuum-isolated silver coated glass container, the Dewar.

1898 Used it to liquify hydrogen.

Louis-Paul Cailletet 1832-1913 & Raoul Pictet 1846-1929

1896 After 100 years of trying, liquidated oxygen.

Max Planck 1858-1947

1898 Planck, possibly due to Boltzmann's criticism, adopted the kinetic theory of gases, and dismisses irreversible radiation processes.

Emile Hilaire Amagat 1841-1915

1899 Published extensive experiments in high pressured gases.

LIQUIDS

HYDRODYNAMICS – MECHANICS OF LIQUIDS

The advances in mathematics, mainly differential equations and their applications to solve time- and space-dependent problems, provided the platform to study quantitatively the behavior of liquids.

First measurable variables defining liquid states were used in dynamic problems. Pressure in flowing liquids, velocity profiles of liquids flow in pipes and between plates, and densities, showed unexpected properties, such as pressure drop in Venturi's pipe. In order to understand these properties the laws of motion for liquids were based on conservation of mass and continuity rules for every incremental "element of volume" in a flowing liquid, as well as the forces and pressures applied on these incremental volumes. The application of Newton's mechanical laws to such volume elements defined the differential equations that provided solutions to the effects of frictional boundaries, external pressures etc.

The mathematical developments related to these differential equations had decisive influence on electrodynamics, primarily understood as occurring in the "liquid aether".

FLUID MECHANICS – Time Points

Intuitive understanding of the properties of liquids and air was implicated in the design of arrows, boats and irrigation systems starting at ancient times.

287-212 BC Archimedes discovered the laws of floatation. Liquid exerts equal forces at all directions. Archimedes screw was a pump relying on liquid properties.

120 BC In Ptolemy Alexandria siphones and double-valve water compression pumps were developed by **Hero & Ctesibius**. A pumping wheel with buckets was common in Egypt for irrigation, and valves were used to facilitate the sinking of the buckets into the Nile water.

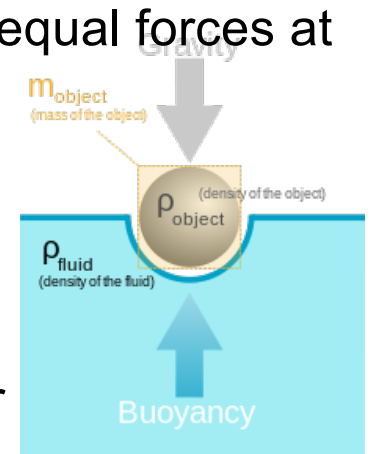
103-40 BC Sextus Julius Frontinus senator in Rome, planned the water supply system, a mandatory facility to the expansion of the Empire capital. He understood that the amount of water flowing from a bucket depends on both diameter of the opening and its depth below water level.

Al-Khazini 1115–1130 Abu Rayhan Biruni 973–1048 Developed experimental methods to study liquids. Biruni detected the difference in density of sweat and salted ocean waters, and hot versus cold water.

Banu Musa brothers, 9th century, & Al-Jazari 1206 Books of inventions including hydraulic systems with feedback control, water pumps with two conjugated cylinders, one open while the other is closed.

1452-1519 Leonardo da Vinci described capilarity effect

1564-1642 Galileo Galilee described liquid dynamics, fall of objects inside liquids, siphons, water flow in rivers and inside pipes.



17th century

1608-1647 Evangelista Torricelli (Galileo's student)

1643 Torricelli's law – pressure at a point depends only on the height (in fact weight) of the liquid above the point. Experimentally confirmed by **Raffaello Magiotti, 1648**.

1629 Castelli studied flow of water in channels and inside pipes.

Edme Mariotte 1620-1684

Designed the impressive sprinkles and fountains system in Versailles gardens.

Blaise Pascal 1623-1662

Pulled water from a tower. Found that one cannot pull to more than 10 meters height. Mercury in a sealed tube creates vacuum above its column.

Domenico Guglielmini 1655–1710

Friction between water and the channel boundaries or the pipe walls.

Isaac Newton 1642-1727

Defined shear force and stress in solids and liquids, and described flow from a small hole. Studied waves in liquids.

18th century

Henri de Pitot 1695-1771

Pitot's pipe – Created sub-pressure perpendicular to flow direction.

Daniel Bernoulli 1700-1782

Bernoulli's principle – At increasing flow speed pressure drops. Silon.

Leonard Euler 1707-1783

Continuity equations in viscous liquids.

Jean de Rond d'Alembert 1717-1783

Refraction in liquids, d'Alembert's paradox: zero force on a ball in zero viscosity liquid.

Antoine de Chézy 1718-1798

Hydrology engineer. Formulated the equation of flow in channels and pipes.

Jean Charles Borda 1733-1799

Marine engineer. Improved water wheels and pumps. Applied flow lines to navigation.

Joseph-Louis Lagrange 1736-1813

Extended hydrostatics to hydrodynamics. Forces applied by a flowing liquid on bodies.

Giovanni Battista Venturi 1746-1822

Venturi's law, Venturi's pipe.

Pierre-Simon Laplace 1749-1827

Laplace's equation – continuity equation for liquid dynamics.

19th century (see details in following slides)

In addition to the contribution of differential equations for vector fields (liquid flow vectors), which was applied also in electrodynamics and later in quantum mechanics, the physics of liquids became of great importance for applications and engineering: Water flow in rivers and channels applied for shipping and transportation, friction of various boat profiles, water (and later oil) diffusion through soils to pumped wells, turbulence (boats and aircrafts) and vortices in pipes.

Augustin Louis de Cauchy 1789-1857

Cauchy-Riemann equation of vector field of liquid flow – wave propagation in liquids.

Hermann von Helmholtz 1821-1894

1858 Studied turbulence in liquid flow.

Gaspard Riche de Prony 1755–1839

Collected studies on water flow and compared experiments to theoretical equations.

Johann Albert Eytelwein 1764-1848

1801 Collected studies on water flow in pipes and reservoirs and collision with solids. Water wheel has maximum efficiency when its peripheral velocity is half of the water jet speed.

Jean Nicolas Pierre Hachette 1769-1834

1816-7 Water flow through holes in containers.

Andreas Rudolf Harlacher

1872-5 Water flow in rivers: theory and later measurements for rivers in Europe, America, India and Burma.

Adolf Eugen Fick 1829-1901

1855 The two Fick laws for gas diffusion or diffusion of dissolved solid in liquid:

I. Flow, J , is proportional to gradient of concentrations:
$$J = -D \frac{d\varphi}{dx}$$

II. Change of concentration in time follow the diffusion equation:
$$\frac{\partial \varphi}{\partial t} = D \frac{\partial^2 \varphi}{\partial x^2}$$

Gotthilf H. Ludwig Hagen 1797-1884

Coined the name “hydrodynamics”. Water engineering. Found, independently of Poiseuille, the law of flow in pipes.

Pierre-Simon Laplace 1749-1827 & Thomas Young 1773–1829

1805 Laplace & Young capillarity equation, connecting the effect with surface tension and wetting angle of liquid droplet on glass surface.

Carl Friedrich Gauss 1777-1855

1830 wrote the differential equation for capillarity.

Henri Philibert Darcy 1803-1858

Flow in porous media (such as soil and sand layers). Important for rates of pumping water and oil from wells.

Julius Weisbach 1806-1871

Darcy-Weisbach equation for Flow in porous media. Built Dijon's water supply system.

William Froude 1810-1879

Studied water friction in boats.

Robert Manning 1816-1897

Water flow in open channels.

George Gabriel Stokes 1819-1903 Ireland

Claude Louis Marie Navier 1785-1836

Stokes-Navier equation for speed of falling ball in viscous liquid.

Ernst Mach 1838-1916

Mach velocity – in units of sound velocity. Shock waves. Ultrasonic boom.

Lord Rayleigh-John William Strutt 1842-1919

Instability of jets. Rayleigh-Plesset equation for collapse of bubbles.

William Thomson (Lord Kelvin) 1824-1907

A theory that atoms are turbulents in the aether. The theory was not considered correct, but attraction between two turbulents drove much interest. However, vortex theory was forgotten and rediscovered several times in new contexts (chaos):

Walter Gröbli 1852-1903

1877 Solved in his thesis three point vortices on the plane.

John Lighton Synge 1897 1995

1949 Rediscovered the vertex problems.

Evgeny A. Novikov

1975 Chaotic behavior of four vertices.

Hassan Aref 1950-2011

1979 Chaotic motion of particles in four vertex system.

Horace Lamb 1849–1934

1894 Published the book “hydrodynamics”.

Vincez Strouhal 1850-1922

Hypersonic. Waves moving in turbulence. Strouhal's number for vibrations in liquids.

Edgar Buckingham 1867-1940

Gas diffusion in soil, and dependence on humidity and capillarity.

Moritz Weber 1871-1951

Weber number for flow of two non-mixable liquids such as oil and water. Yields a limit on bubble generation. Surface tension in liquid-gas or liquid-liquid interfaces.

Ludwig Prandtl 1875-1953

Aerodynamics of airplane wings – elevation and drift. Described flowing liquid layers next to a wall.

Lewis Ferry Moody 1880-1953

Moody's diagram: dependence of flow on roughness of pipe surface.

Theodor von Karman 1881-1963

Supersonic and hypersonic air flow. Flow exceeding speed of sound. Helicopters, wind tunnels, rockets, solid fuel.

Paul Richard Heinrich Blasius 1883-1970

Blasius theorem for drifting solids in flow. Drift of boundary layers in liquids. Laminar and turbulent flow.

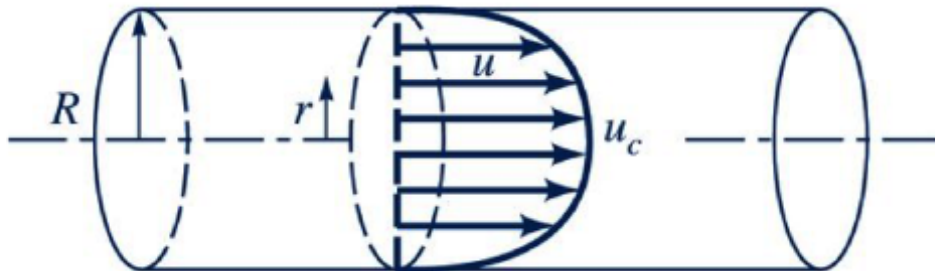
Jean Louis Poiseuille 1799-1869

Hagen-Poiseuille law of liquid flow in pipes with circular cross section..

3. In Poiseuille flow (laminar pipe flow), the velocity profile is parabolic, as described by the equation

$$u = u_c \left(1 - \left(\frac{r}{R} \right)^2 \right)$$

where u_c is the centerline velocity, r is the radial location in the pipe, and R is the radius of the pipe (see figure).



Hagen-Poiseuille equation

Jean Louis Marie Poiseuille 1797- 1869 French

Gotthilf Heinrich Ludwig Hagen 1797 –1884

Poiseuille was interested in blood flow in veins and arteries.

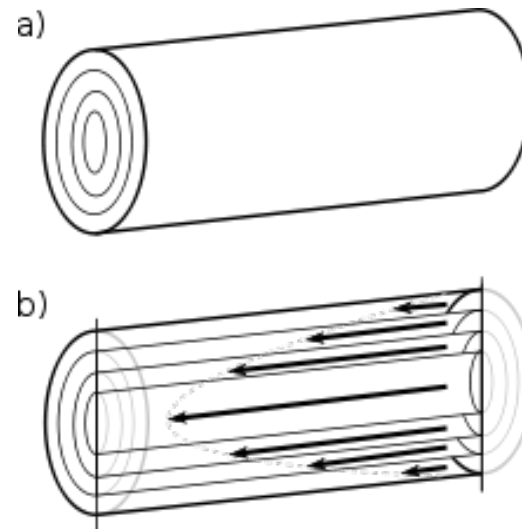
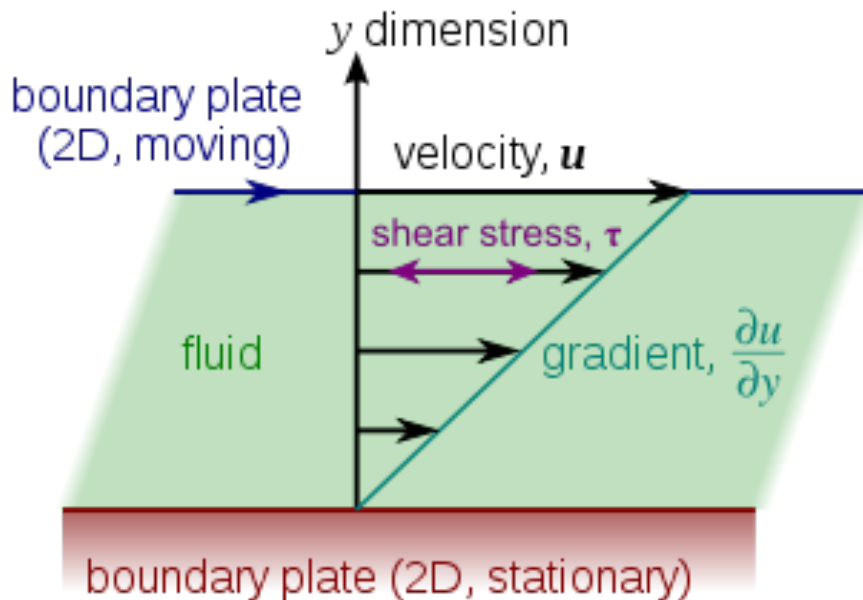
Hagen-Poiseuille equation: pressure drop ΔP for laminar flow of Q volume units per second in a pipe length L , radius r and liquid viscosity μ :

$$\Delta P = \frac{8\mu LQ}{\pi r^4}$$

The unit of viscosity, Poise, is named after him.

Viscosity is measured from the force F needed to move a planar surface of area A in velocity u , where liquid layer height y separates the moving from stable surface (see figure below):

$$F = \mu A \frac{u}{y}.$$



1855 Oceanographer. Wrote “The Physical geography of the sea”. From many records of ship trails he composed charts of winds and ocean currents. Migration of whales as icebergs-free paths made him search for a sailing path from the Atlantic to the Pacific oceans surrounding south America. He mapped depth of oceans, preparing the foundation for laying the telegraph cable.

[illegible]

Pierre Louis Georges Dubuat 1734–1809

Understood that frictional forces in flowing liquids within itself and the walls balance gravitational forces to get constant speed.

George Gabriel Stokes (1819-1903) Irland

1843 Stokes finds the force acting on a ball falling in viscous liquid – details in next slide.

Viscosity of liquids per density is assigned in Stokes units:
 $\text{Stokes} = \text{Poise} / \text{fluid-density (gr/cc)}$

Stokes have other important contributions in mathematics (Stokes equation), and in fluorescence (Stokes shift, see there).



George Gabriel Stokes (1819-1903) Ireland

1843 Stokes found the force acting on a ball of radius R falling at speed V in viscous liquid, Stokes law:

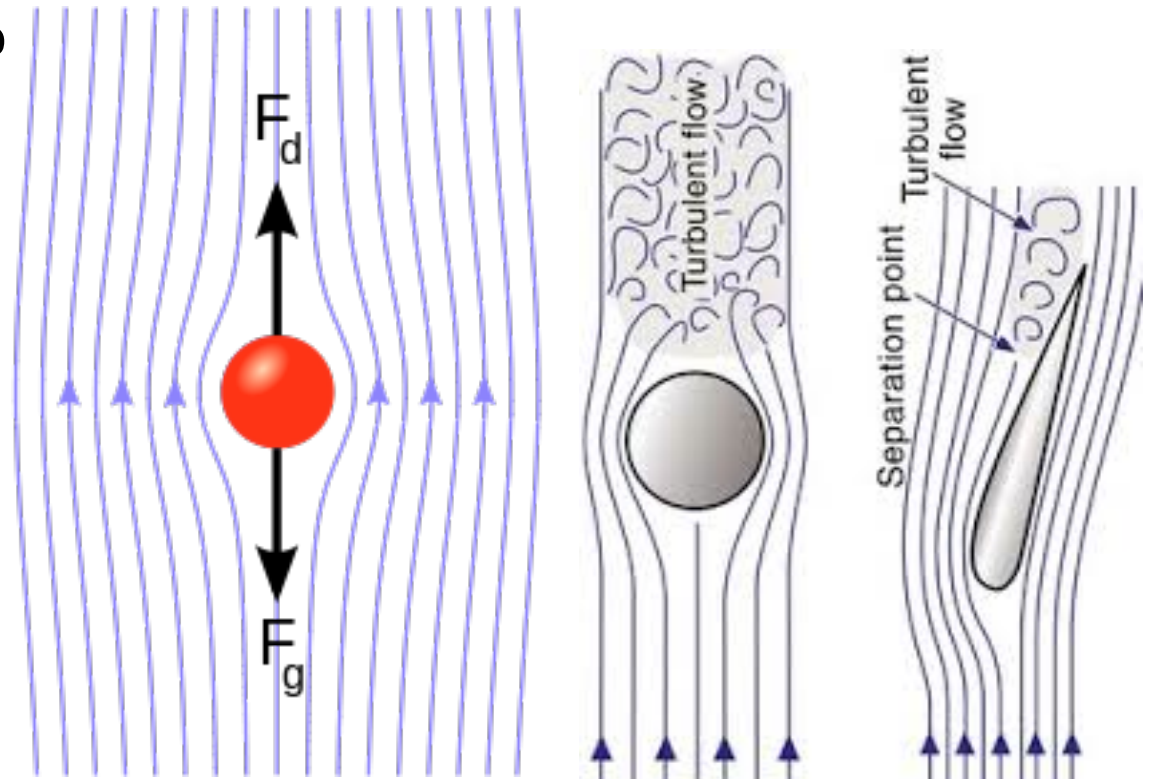
If we let the ball fall, it will reach a final speed V where its Weight and floatation balance the liquid viscosity friction.

$$F_d = 6\pi \mu R V$$

$$V = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2$$

If we pull the ball very fast, turbulence will be created behind, and the force needed to draw the ball exceeds Stokes law. The profile of airplane wings is designed to prevent such turbulence despite the high speed.

1850 Stokes equation is cited by Kelvin. Stokes presented his solution as a part of examination for Smith prize nomination. Maxwell, who was also examined, solved the problem, but published it in Stokes name.



Osborne Reynolds 1842–1912



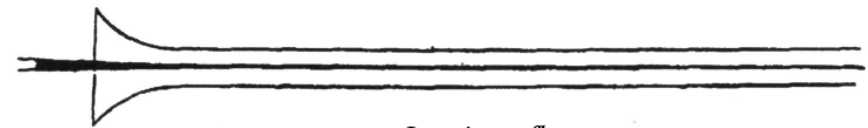
1883 Studied behavior of turbulent flow, and presented “Reynolds number” for transition from laminar to turbulent flow, and Connected with viscous force gradients. The idea was proposed by **Stokes, 1851**, but **Arnold Somerfield**, who publicized the concept, called it after Reynolds. The number is dimensionless, since it is the ratio of the inertial force (mass*acceleration) to the frictional forces (viscosity*velocity gradient*area): $R_e = \rho u L / \mu = u L / \nu$

$$R_e = \frac{(\rho L^3) \left(\frac{v}{t}\right)}{\mu \left(\frac{v}{L}\right) L^2} = \frac{(\rho L^3) \left(\frac{1}{t}\right)}{\mu \left(\frac{1}{L}\right) L^2} = \frac{(\rho L^2) \left(\frac{1}{t}\right)}{\mu} = \frac{(\rho) \left(\frac{L}{t}\right) (L)}{\mu} = \frac{\rho v L}{\mu} = \frac{v L}{\nu}$$

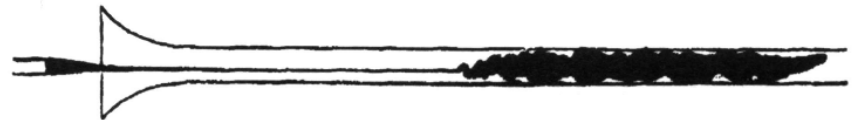
Where:

ρ Liquid density
 u Liquid velocity with respect to the body
 L Typical length dimension
 μ Dynamic viscosity of the liquid
 $\mu/\rho = \nu$ Kinematic viscosity of the liquid

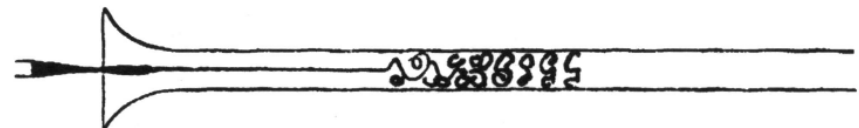
Transition from laminar to turbulent flow happen around Reynold numbers of about 1000



Laminar flow

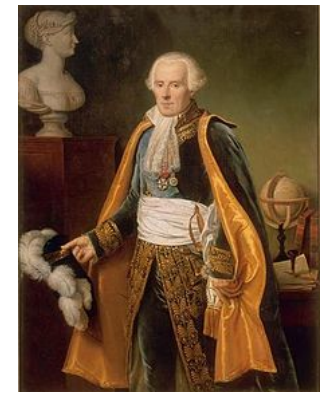


Turbulent flow



Turbulent flow (observed with an electric spark)

Pierre-Simon Laplace 1749-1827



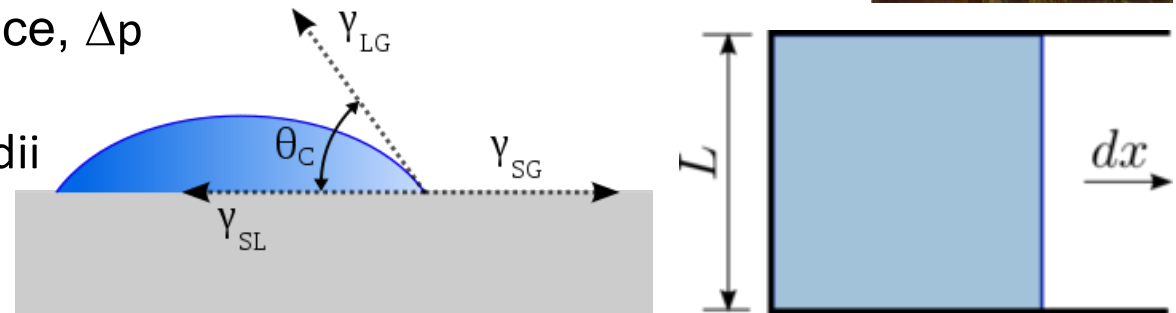
1805 Theory of liquid capilarity and contact angle of droplet with surfaces.
Surface tension (force per unit length extending surface area)
 Is related to the contact angle θ_c energy of liquid-solid surface contact per unit area.

Pressure difference at liquid-air interface, Δp
 cause liquid rise in a capillary

H surface curvature, R_1, R_2 principal radii
 (at perpendicular directions)

a capillary radius.

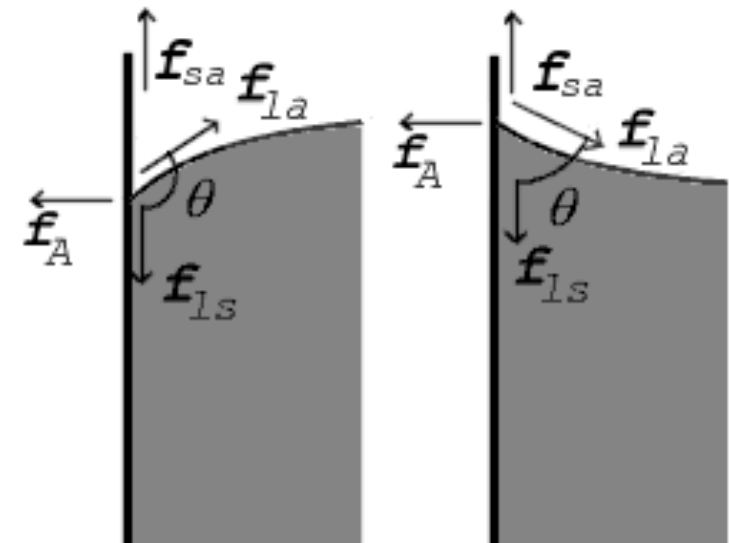
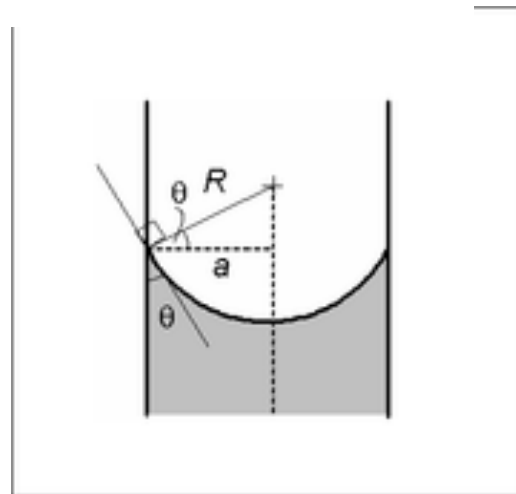
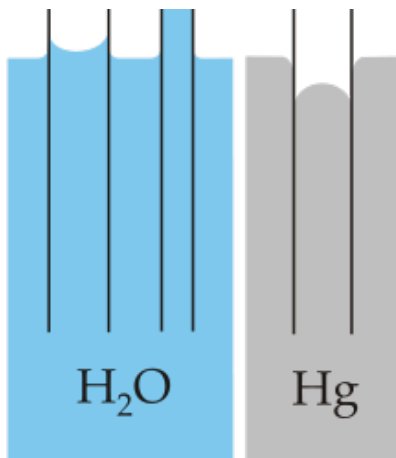
θ contact angle



$$\begin{aligned}\Delta p &= -\gamma \bar{\nabla} \cdot \hat{n} \\ &= 2\gamma H \\ &= \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)\end{aligned}$$

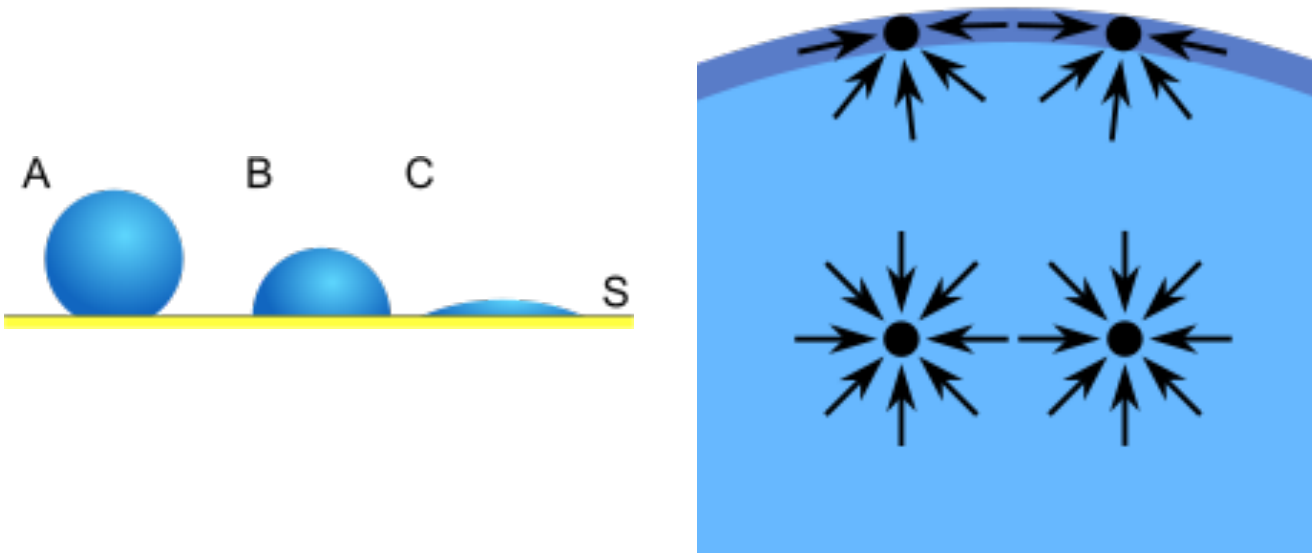
$$\gamma(1 + \cos \theta_c) = \Delta W_{SLV}$$

$$\Delta p = \frac{2\gamma \cos \theta}{a}$$



Joseph Antoine Ferdinand Plateau 1801-1883

1873 Demonstrated experimentally that liquid interfaces at equilibrium create curvature to minimize surface energy.



He was known for animations of movies. He invented an early stroboscopic device, the "phenakistiscope", the first device to give the illusion of a moving image.



John Scott Russell 1808-1882

1843 While planning horse-pulled barges for transportation of goods via the English channel system, Russell discovered "solitons": waves propagating from an arrested barge, and they did not decay nor changed shape. He used a water tank to measure speeds of such waves as it dependence on amplitude and channel depth. Interestingly, two such solitons do not interfere, but each soliton pass the other "ignoring" each other. His finding was accepted suspiciously. Theoretical explanation was given by Lord **Rayleigh** at **1876**.

Solitons are important in fiber optics.

LIGHT & ELECTRICITY

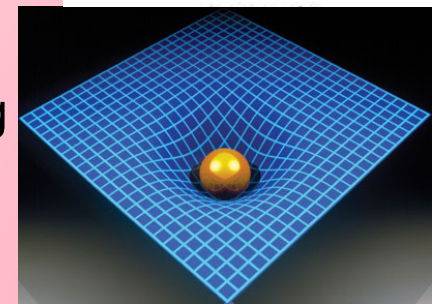
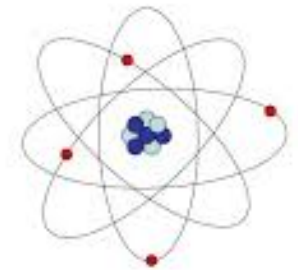
ELECTROMAGNETISM

This field of science is undoubtedly the crown of achievements of the 19th century. It is rooted strongly into the mathematics of the previous centuries, notably differential equations, and paved the way to the 20th century quantum mechanics.

The timeline of electromagnetics is amazingly similar to a previous evolution in science: the fall of geocentric theories and the acceptance of heliocentric models. But this time, the fight for scientific progress was not against the church, but with the very old tradition of aether filled world, started by the Greeks, and constantly updated by modern theories such as the elastic properties of media, propagation of waves in liquids and solids, and the twisted adaptation of aether theory to experiments showing light propagating in vacuum, polarization of light (inconsistent with aether longitudinal waves) reflection, refraction, diffraction, interference and birefringence. Attribution of bizarre properties to Aether not found before in materials were needed. It was only at the end of the century that electricity, magnetism and light were unified in Maxwell's equations, a description that eventually got rid of the aether and of Newton's particle theory of light. Light particles (photons) soon came back at the beginning of the 20th century, where Quantum mechanics combined wave and particle properties to matter.

It is interesting that even at the 20th century scientists turned to visual and materialistic models to understand and explain emerging theories. Quantum mechanics solved all experimental finding with the wave equation of electrons, but the electron orbitals around the atom are the logo of nuclear physics. Also, general relativity is modeled by a stretched rubber sheet distorted by mass...

Last, the motion-independent Speed of light planted the seeds to relativity.



Thomas Young 1773 –1829

1801 Proposed that light hitting the retina create vibrations which frequencies excite differentially nerve cells by color.

1801 The wave nature of light, demonstrated by interference. dark areas were superposition of opposite light phases. Young applied glasses of different refraction indices (e.g. crown flint sassafras) to correct lens chromatic aberration.

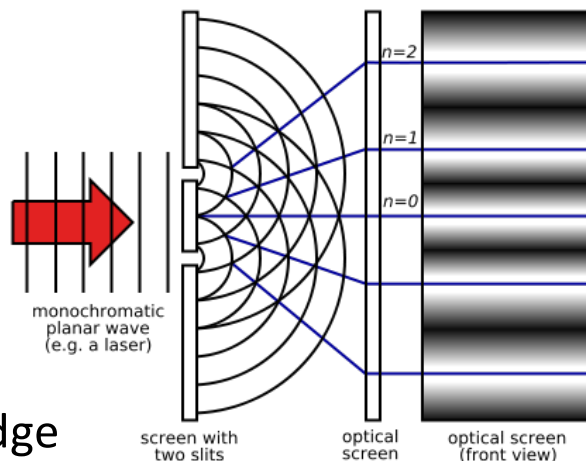
1803 Showed interference pattern at shadows from sharp edges. These phenomena enforced the wave nature of light, but since the light wave was thought to be longitudinal, the effect of double refraction in none isotropic crystals could not be explained, and **Newton's** light particle theory persisted.

1805 Splitting and recombining light, Young performed interference between two slits, that he explained by the wave nature of light, and declined the light particles of **Newton**.

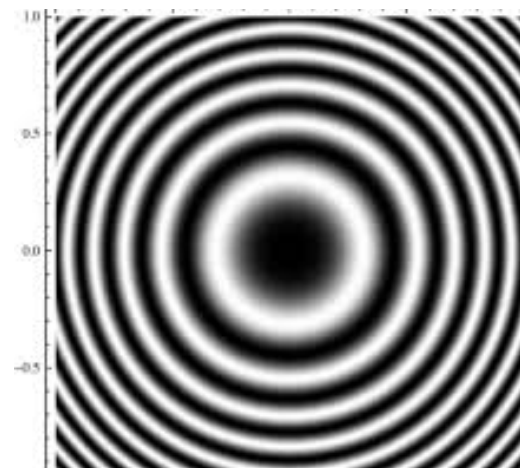
1807 Coined the term “Energy” in a lecture about heat causing kinetic motion of particles (Bernoulli's kinetic theory).



Sharp edge



Two slits



pinhole

1809 Young: Light is a transversal wave. Such wave cannot propagate in liquids (aether). He believed that light falling on the retina excites three color receptors: **Young-Helmholtz** theory.

He also involved astigmatism in vision.

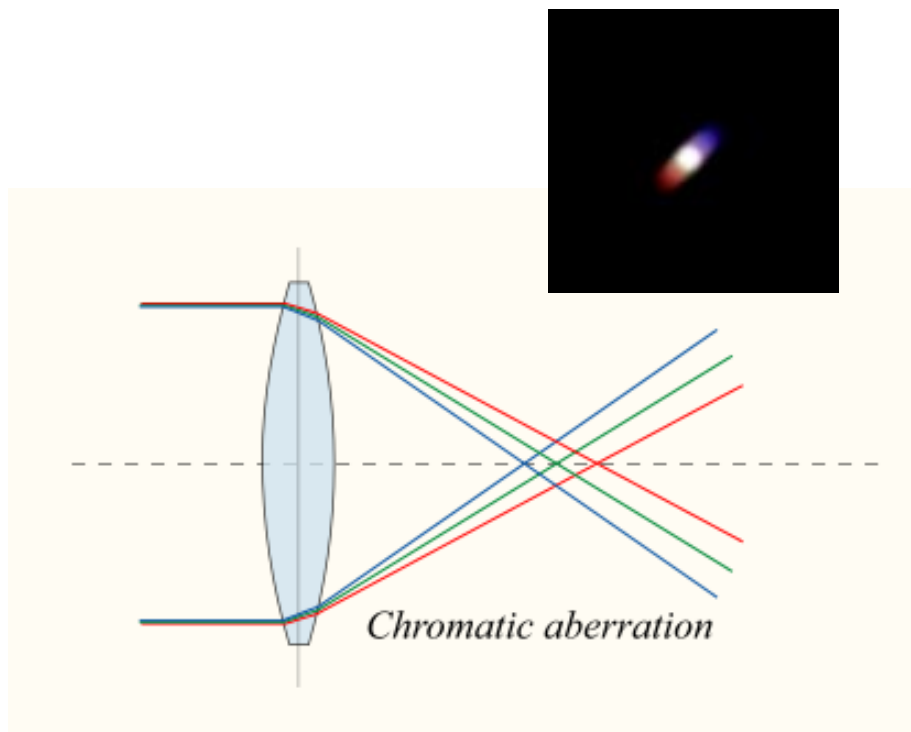
Joseph Jackson Lister 1786-1869

1830 Built aberration corrected lenses and microscopes.

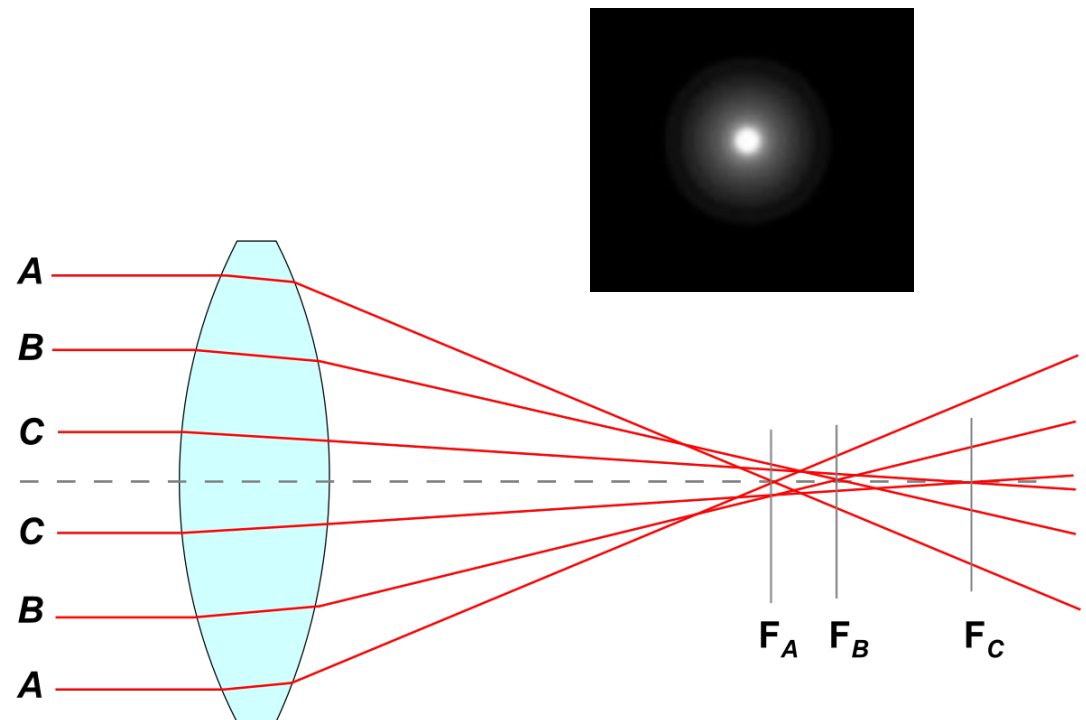
Lens aberration

In the small angle (Gaussian rays) approximation ($\sin\alpha=\alpha$) and for thin lenses, the law of similar triangles implies that all rays exerted from a point will reach a point after refraction by lenses. However in real lenses they do not reach a geometrical point, generating various type of aberrations: spherical, on the optical axis for paraxial rays (at large angles with the axis), field aberration, off the optical axis, and chromatic aberrations – focus dependence on ray colors (due to glass refractive index change with color).

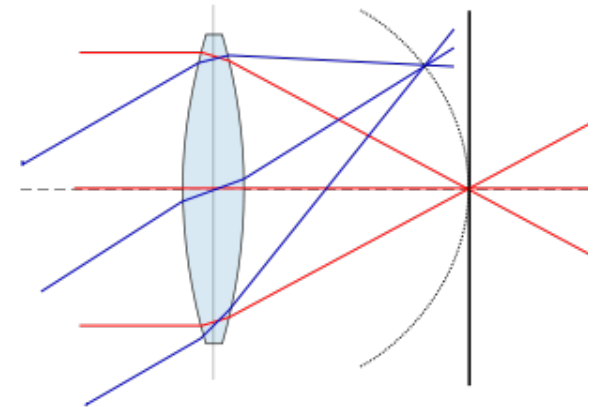
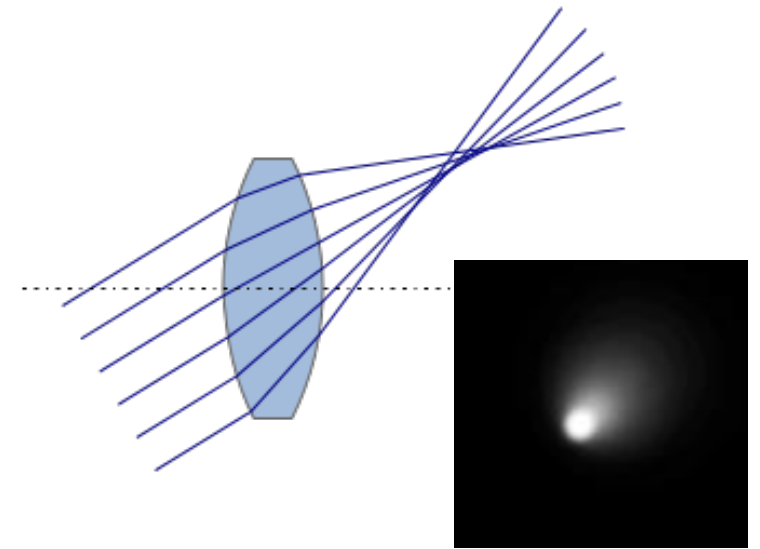
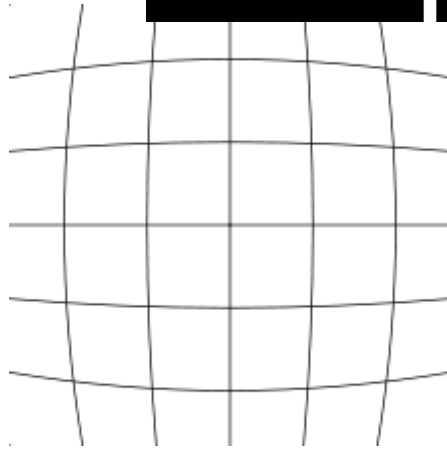
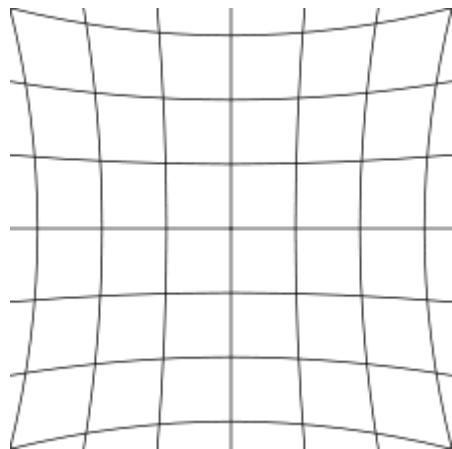
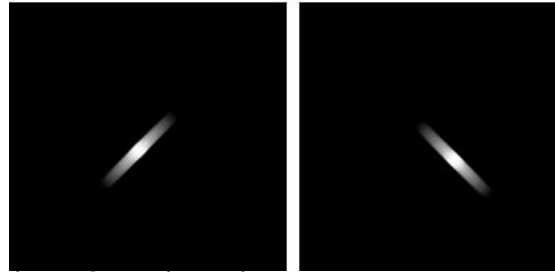
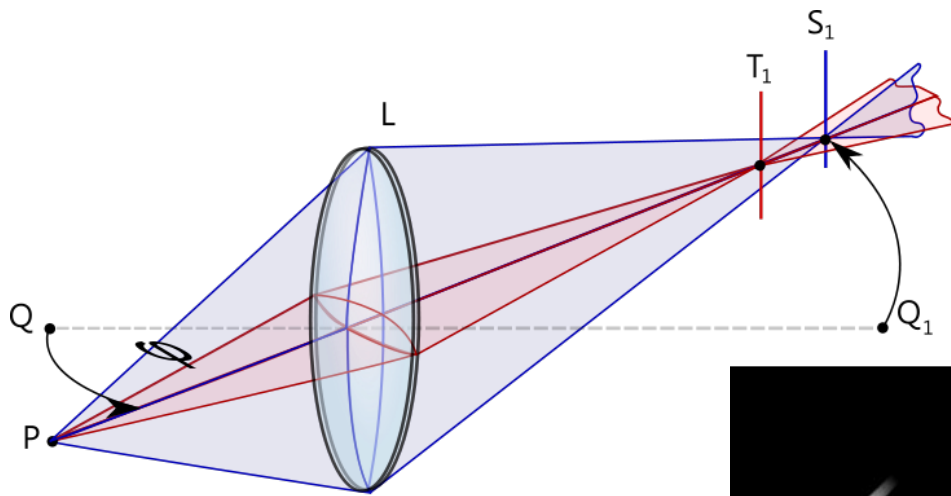
Chromatic aberration



Spherical aberration



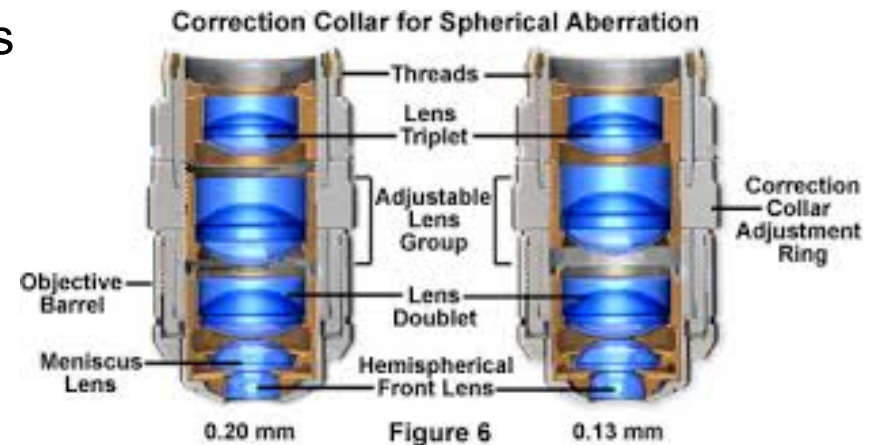
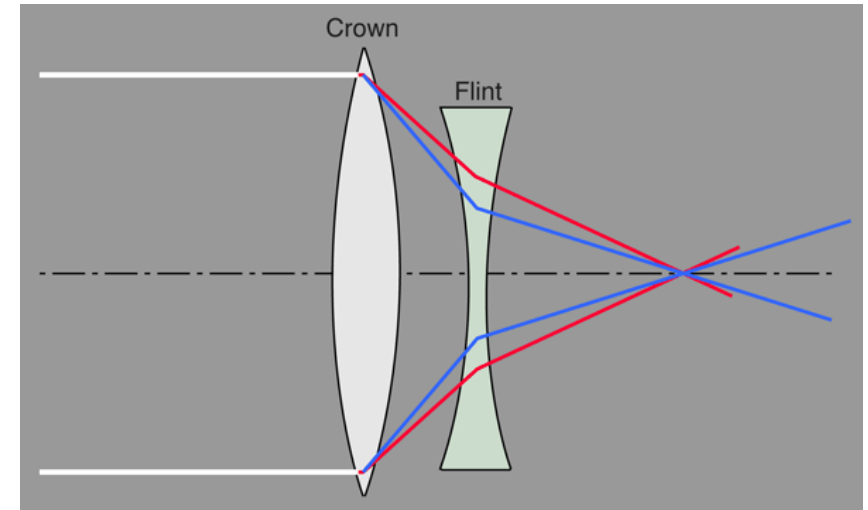
Field aberration are for sources emerging off the optical axis. Other aberration types are astigmatism (different focus for vertical and horizontal rays, common in vision and corrected by cylindrical glasses), Coma, field distortions (barrel and pincussion types that increase with distance from the axis).



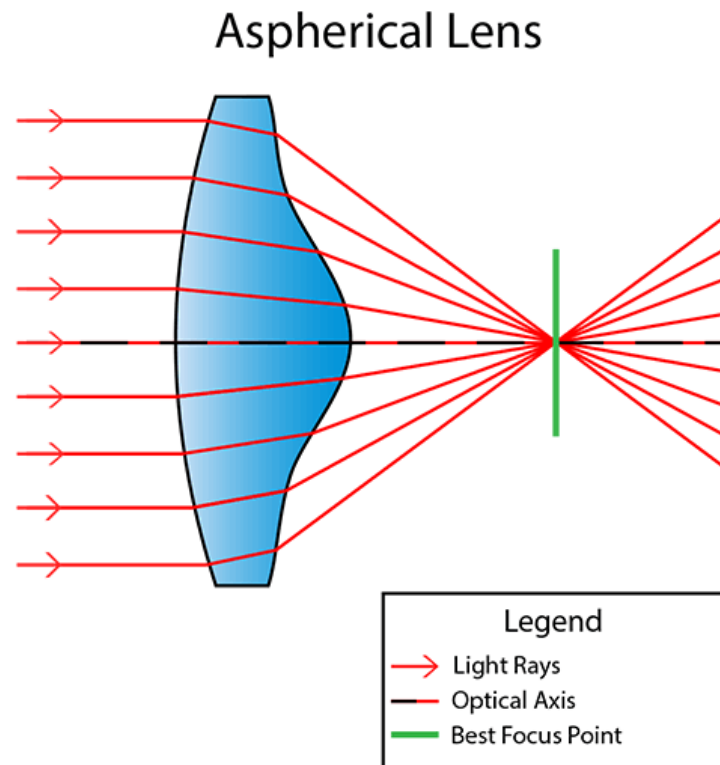
During 400 years microscope builders struggled with aberrations.

For example, doublets, composed of two lenses, concave and convex with different refractive indices reduce chromatic aberration.

Increasing the number of lenses in the designed objectives provides degrees of freedom for the minimization of aberration. Modern high Magnification objectives contain up to 13 lenses. Abbe, the founder of Zeiss microscopes, employed hundreds of Facit calculator operators who ray traced through his designed objectives using Snell's law and reduce their aberration by trial and error till they reached the diffraction limit. Same strategy was in camera lenses (telescopic and wide angle) and In zoom lenses, making them cumbersome and heavy.



In the last decade cellphone cameras (and other applications such as fiber optics) motivated development of aspherical lenses, “printed” in plastics of high refractive indices ($n=1.6-1.8$, also used to reduce weight of high diopter eyeglasses, and in the manufacturing of multifocal eye glasses) replacing the expensive lens polishing by diamond machining of molds and “printing” lenses in quantities. The aspheres achieve low aberration with a small number of lenses (often one lens).



Sir John Leslie 1766-1832

1804 Discovered that radiation of heat and light are similar, and matte black surfaces irradiates heat better than glossy surfaces: black body radiation.

Étienne Louis Malus 1775-1812

1808 Measured polarization in reflected light as a function of incident angle (see Fresnel equations). Malus law – intensity of light passing through two polarizers. Announced a competition for explaining the double refraction, and won the prize.

1810. Denied the possibility that light wave may have two polarizations...

François Jean Dominique Arago 1786-1853

1811 Discovered quartz crystal cuts that change light polarization.

1816 Arago, a collaborator to **Fresnel**, criticized Young demonstrating to him that differently polarized light beams do not interfere. Young proposed that light is a transversal wave, not longitudinal wave. When this idea reached Fresnel at 1818 he understood how to solve difficulties in light theory. 6 years later, Newton's particle theory of light was announced dead (until Einstein's explanation of the photoelectric effect ...).

Jean-Baptiste Biot 1774-1862

1811 Showed that Arago's crystals rotate the plane of polarization.

Pierre-Simon Laplace 1749-1827

1808 Explained double refraction based on particles light theory – although Young denied this explanation.

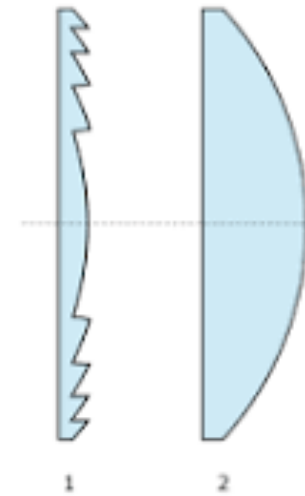
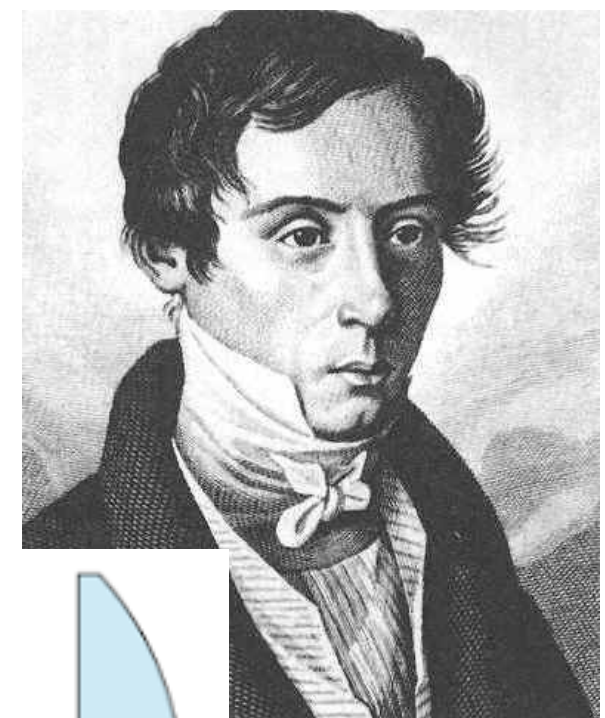
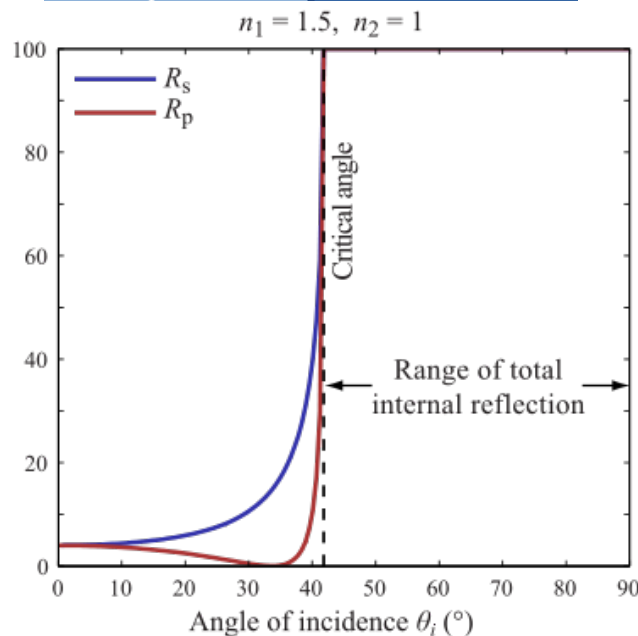
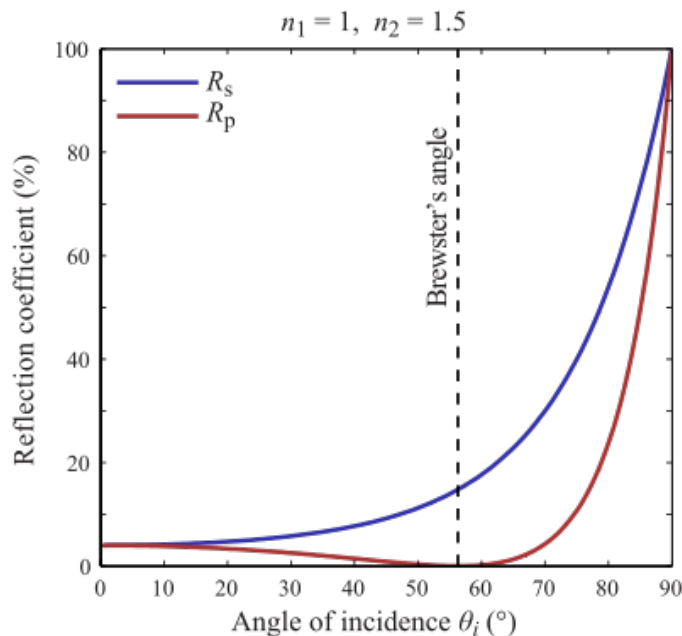
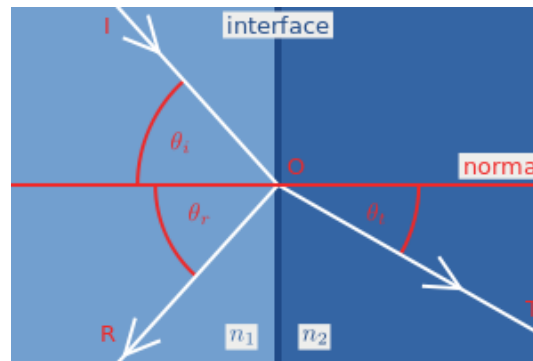
1813 Showed that the electric force close to a conductor is perpendicular to its surface.

Augustin-Jean Fresnel 1788 -1827

Showed that in reflection and refraction, intensity of light in and perpendicular to the plane of the rays depend on angle. Fresnel equations. They are derived from the continuity of the electric and magnetic fields of light wave at the reflecting and refracting interface.

A special case: Brewster angle, (see following)

Fresnel invented lighthouse focusing lens. Today one can buy magnifying plastic Sheet based on Fresnel lens.



Joseph von Fraunhofer 1787-1826

1814 Built a spectroscope with the sun as light source interrupted by a slit and a prism to disperse the rainbow colors. He also observed discrete black lines at set positions in sunlight spectrum: Fraunhofer lines.



Augustin Jean Fresnel 1788-1827

1814 Wave theory of light – interference.

1816 Explained interference and diffraction by the wave theory of light.

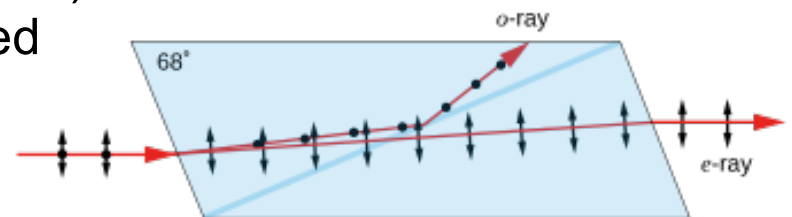
The French academy favored **Newton's** light particle theory, and offered a prize for explaining light diffraction. To their dismay, Fresnel won the prize for his wave theory explanation, following **Huygens**.

Fresnel & Dominique François Arago 1786-1853

1816 Together demonstrated that light rays with perpendicular polarizations do not interfere – Proving light is a transversal wave, inserting the last nail in the coffin of the aether theory.

William Nicol 1770-1851

1828 Built "Nicol prism" from two glued CaCO_3 (calcite) calcium carbonate crystals. It is a polarizer that helped studies about polarized light properties.



Augustin Jean Fresnel 1788-1827

1818 Poisson predicted that the center of interference pattern in the shadow of a ring would have a bright spot: „Poisson-Arago spot“. But Fresnel found a dark spot.

Arago eventually showed a bright center spot. The reason was correction of aberration using a doublet lens with two different refractive indices.

1821 Published laws of reflection and refraction of light from air into a medium. Linearly polarized light becomes elliptically polarized.

1825 Phenomenological explanation to optical activity and circular birefringence.

Showed that combination of two light beams of opposite polarizations propagating at different speeds explain rotation of the plane of polarization.

1827 Published a decade of studies about light, explaining diffraction, interference, polarization, birefringence and Fresnel's sine and tangent laws of light transfer between transparent media of different refraction index.

William Hyde Wollaston 1766-1828

1801 Established the equivalence of galvanic and frictional (resistive) electricity.

1821 Explained the attracting force between two wires with electric currents that **Ampere** discovered by assuming cylindrical symmetry.

David Brewster 1781-1868

1815 Found the angle that reflected light is fully polarized – Brewster angle.

He also discovered that there are ionic crystals that are uni-axial and bi-axial. While in the first crystal kind it is possible to accept longitudinal light wave theory, it is not possible for bi-axial crystals due to birefringence.

1816 Discovered birefringence in crystals stressed by pressure. Invented the kaleidoscope.



John Robison 1739-1805

1801 Encyclopedia Britannica published a summary of the electrostatic theory according to **Aepinus & Coulomb**.

1822 Published a device for measuring electric forces which he developed at 1770

John Herschel 1792-1871 (son of the astronomer William)

1820 Crystals that rotate light polarization in opposite directions have different structure of helical nature. He studied color blindness and developed photography.

Siméon Denis Poisson 1781-1842 France

probability, Poisson random variable, Poisson approximation, Poisson process

1811 Poisson's equation: vector notation -

$$\nabla^2 \phi = -4\pi\rho$$

in cartesian coordinates:

$$\nabla^2 \Psi = \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} = -\frac{\rho_e}{\epsilon\epsilon_0}$$

Expresses the electric potential created by charges ρ

Reminder: the potential around a single charge q at $r=0$ is: $\phi = 1/4\pi\epsilon_0 q/r$

Poisson's equation cannot be evaluated at the origin $r=0$, but can be computed at any desired small circle around it, and use Stokes' theorem for any point inside the circle (see following).

Poisson considered the electric field as a liquid.

1812 Developed a (wrong) model for electricity, explaining that the charge in a capacitor spreads on its surfaces to diminish the force inside it.



Gian Domenico Romagnosi 1761-1835

1802 Discovered the displacement of a magnetic needle near batteries. This finding did not draw much attention...

Hans Christian Ørsted 1777-1851 Denmark

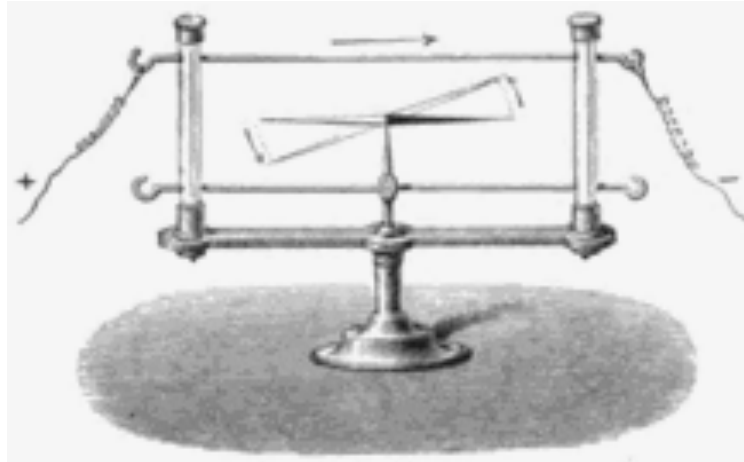
Was a close friend to **Hans Christiam Andersen**.

1820 Discovered that electric current in a wire cause displacement of a magnetic needle, and that the field around the wire has cylindrical symmetry. Explained the magnet as loops of current perpendicular to its axis.

The unit of magnetic induction is called after Ørsted.

1825 Isolated Aluminum by electrolysis.

Ørsted proposed the Telegraph.



André Marie Ampere 1775-1836

1820 A week after hearing Ørsted discovery he showed that two parallel wires carrying electric current in same direction repel each other, and opposite direction- attract.

1822 Published an assumption that all magnetism is originated from electric currents.

1825 Published all his experiments on magnetism, with equations that Maxwell described as one of the most important achievements of science. Ampere's formulae calculated the contribution of a current element to magnetic field, adding a term to Biot-Savart's equation with a zero integral over a current loop. Yet the latter formula was preferred over Ampere's, although it was more sophisticated...



Jean-Baptiste Biot 1774-1862 & Felix Savart 1791-1841

1820 Showed that magnetic forces from wires with current decay proportional to the inverse distance, and are directed perpendicular to it. This was a prove of the electromagnetic interactions. **Whittaker** continued this analysis.

Carl Friedrich Gauss 1777-1855

1813 Rediscovered Lagrange's divergent law that was called "Gauss law"

1833 Gauss proposed the electric telegraph.

Georg Simon Ohm 1789-1854 Germany

1827 Ohm's law: $V=IR$ Voltage drop over a conductor and the electric current through it are proportional to each other, and the proportionality coefficient is the resistance.

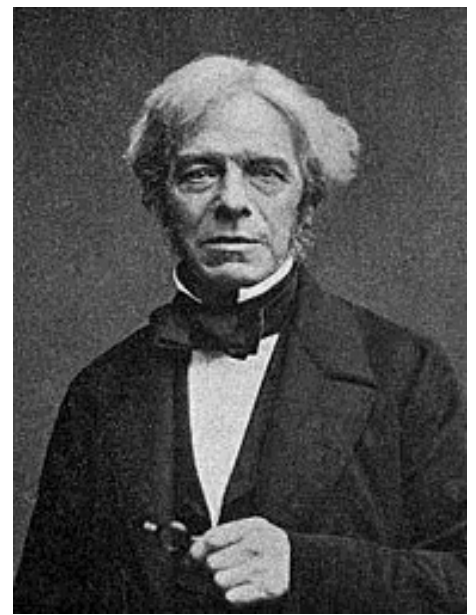


Michael Faraday 1791 –1867 England

Faraday came from a family of iron workers who moved to London to find their income as horseshoe blacksmiths. Faraday found work as a book binder, where he acquired his knowledge Reading all books that passed by him. He attended Humphry Davy's lectures and tried to publish the summary, and applied to work for Joseph Banks, the British Royal Society but was denied the job.

He was lucky when Davy's lab assistant was fired and Davy hired Faraday **1812** to replace him for 1 Guiney a week, a heated room and papers... Davy, whose vision was hurt following an explosion in his lab, took Faraday on a European trip to meet the greatest French and Italian scientists. The trip was interrupted when Napoleon, who admired scientists (even if they were English as enemies), was sent to exile. Publication of Faraday's monopolar electric motor made him famous, but rose Davy's criticism at him, maybe due to envy of his international recognition...

In England Faraday became the top experimental scientist of his time. Davy finally submitted his candidacy as the head of the Royal Society laboratory, where he concentrated his work on electricity. He understood that if electricity makes magnetism, also magnets will generate electricity. Experience taught him that stable magnets do not induce electricity, unless they move. Thus he designed the disk generator.



Following **Ørsted, Davy and Wollaston's** publications proposing to rotate copper wire loops around magnets, they approached Faraday for technical help. Faraday found a solution, and came to Wollaston when he was not home, thus published his solution without citing Wollaston. That created strong reaction, especially from Davy, causing Faraday to apologize publically and to turn into studying stainless steel alloys. Actually, Faraday was not interested in the application after solving a basic problem, and the applicable implementations of transformers, electric generators and motors, telegraph and telephone was achieved by **Henry & Bell** in America.

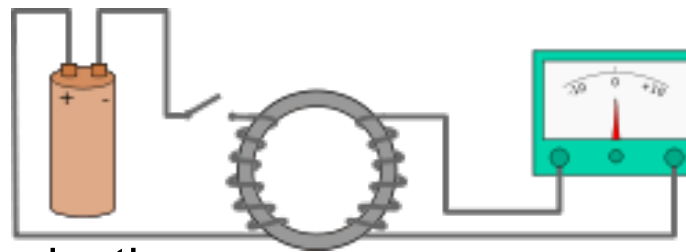
Upon the publication about emission of hydrogen and oxygen in electrolysis of water, Faraday studied the subject and published Faraday laws of electrolysis. Faraday retired to his home at 1855, getting a pension from the queen, till he died 1867.

Faraday discovered electromagnetic induction: current in one coil induces current in a close-by coil. Explained in diagrams of magnetic flux (without equations) and electricity stored in Aether.

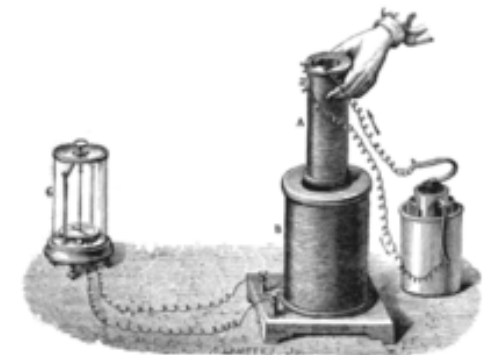
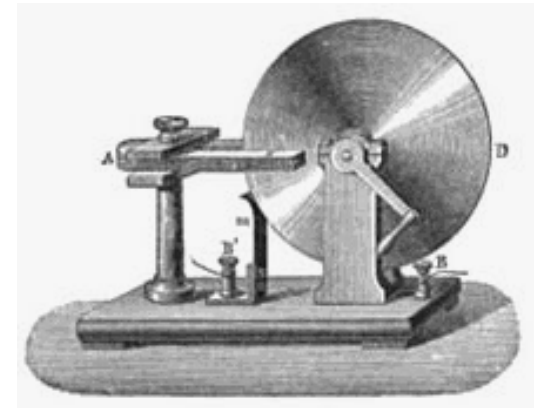
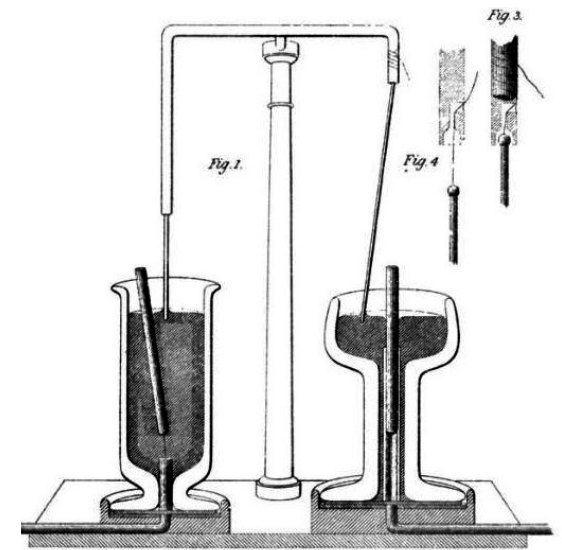
He built the first mono-polar electric motor. The cups are filled with Mercury. When electric current is drawn, the rod immersed in the mercury rotates around the fixed magnet.

Disk generator, rotating between two fixed magnets, created voltage difference between its center and periphery, that is increased at faster rotation speed.

1831 Demonstrated electric induction: when a magnet is inserted or extruded from a coil, current is induced in it. If current is drawn in one coil, it induces current in another coil.



Faraday cage: a closed conducting net isolates the inside from induction originated from outside currents.



1818 Faraday started experiments on steel alloys.

Induced voltage comes from change in magnetic flux:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

In a coil, the induced voltage is multiplied by the number of loops

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

1821 Faraday reproduced **Ørsted** experiments. Accepted **Wollaston's** electromagnetic theory – rotating pole around a wire or wire around pole: anticipated the electric motor.

In a motor, the flux change create a torque that turns the rotor.

1832-4 Published **Faraday laws of electrolysis**: ions in solution deliver or receive charges from the electrodes and are released as free atoms:

1st law: A current running through ionic solutions, the number of moles of released atoms at the electrodes is proportional to the number of electrons flowing in the electric circuit.

2nd law: The mass of material released at the electrodes is proportional to the chemical equivalent weight.

Faraday coined the terms “electrode”, “cathode” (negative) and “anode” (positive electrode), to where positive “ions” - “cations” and negative “ions” - “anions” flow respectively. Understood the relation between chemistry and electricity, and that every atom has a defined charge.

1823 Created liquid chlorine from electrolysis of the hydrochloric acid HCl , as well as other gases: H₂ O₂ SO₂ NH₃ CO₂ that he collected in tubes and often exploded...

Claude Louis Marie Henri Navier 1785-1836

1827 Published the mechanical equations for vibrations in elastic medium, that was applied to oscillations of light in aether.

F. Savery

1827 Discovered that voltage discharge from Leyden Jar magnetizes a needle forming layers of opposite polarity. That brought him to conclude that the discharge induces fast oscillations.

George Green 1793-1841

1828 Extended **Lagrange, Laplace & Poisson**'s works. Coined the name "potential" to the scalar function describing electrostatic fields. Formulated Green-Gauss theorem (the law of the divergent) without knowing about Gauss. Quoted **Priestley** for square distance dependent force, and **Franklin's** experimental work on charges in closed container screened from the outside.

Augustine Louis Cauchy 1857-1789

1828 Published work similar to **Navier** about light propagation in aether, based on elastic (not molecular) properties, therefore his equations are more general. According to Cauchy aether has constant inertia, but his elasticity depends on the medium.

Siméon Denis Poisson 1781-1840

1828 Showed that **Navier's** equations has longitudinal and transversal wave solutions. Physicists in the coming 50 years attempted to describe aether carrying longitudinal waves only.

Heinrich Lenz 1804-1865 Russian

1833 Lenz law: The direction of the induced current in a closed circuit attempts to cancel a change. It is the electromagnetic analogue of **Le Chatelier** law in chemistry (1885).

Discovered that resistance increases at higher temperatures.

Carl Jacobi 1804-1851

1834 Characterized uniformly rotating self-gravitating ellipsoids, and stated that gravity forces inside the ellipsoid comes only from inner ellipses, while outer layers gravity forces cancel out.

James MacCullagh 1809-1847 & Franz Neumann 1798-1895

1835 **Cauchy's** theorem for continuous medium is extended to crystals. Attempted to explain electromagnetism in mechanical terms.

Hippolyte Pixii 1808–1835 France

Built the first dynamo – electric generator with a magnet rotating around a conducting coil wound around an iron core.

Charles Brush 1849 –1929 America

Invented the dynamo with open coil, generating continuous electric current.
Developed arc lamp operated by the dynamo.

Michael Faraday 1791-1867 & Ányos Jedlik

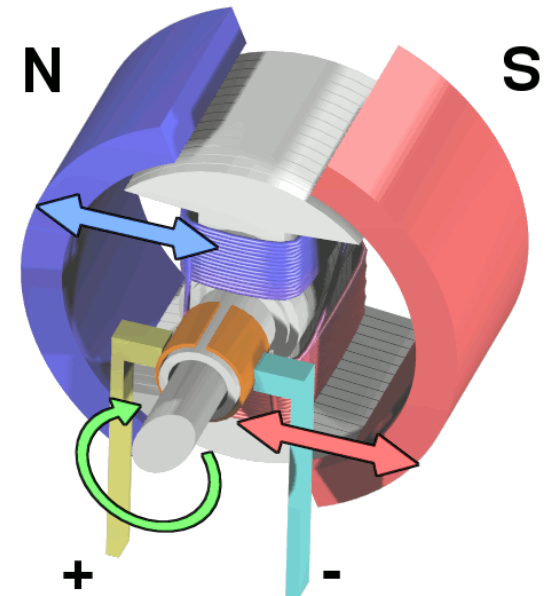
1831 Electric generator.

1834 Discovered self induction of coils.

Thomas Davenport 1802 –1851 America

1834 Invented the direct current (DC) electric motor.

Used the comutator to invert the direction of the current every half turn.



Joseph Henry 1797-1878 America

1828-9 Discovered induction independent of Faraday or Ampere. Create a strong electromagnet from copper wire loops around an iron core. This development improved the performance of electric motors that he described.

1831 Implemented an electromagnet in a recording telegraph. Invented the AC transformer, enabling long distance electricity supply. Studied metals, and founded the national weather institute that used telegraphs for reporting.

1842 Rediscovered **F. Savery's** results of decaying oscillations in electric field upon capacitor discharge.

1846 Henry was elected as the president of the Smithsonian Institute in Washington DC.

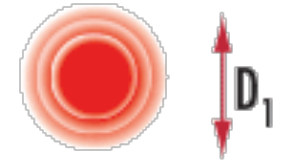
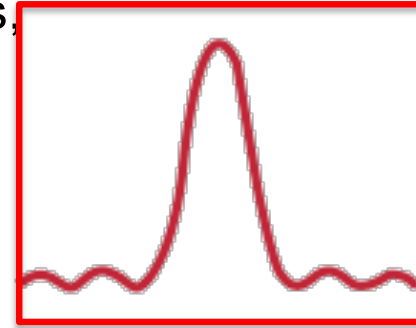


George Biddell Airy 1801-1892

1835 Computed the interference pattern from a circular pinhole. The diameter of this disk is classically the resolution limit in optical systems, notably telescopes and microscopes.

Airy designed a cylindrical eyeglass to correct astigmatism in vision.

About 30 years later Abbe designed lenses with reduced aberration that reached the theoretical resolution.



Wilhelm Eduard Weber 1804-1891

1835 Measured the magnetic field of earth.

Michael Faraday 1791-1867

1837 Dielectric constant.

Faraday built a comprehensive theory based on force lines spanning space – to replace centers that execute forces from distance.

George Green 1793-1841

1837 Treated boundary conditions in the elastic theory of the aether, replacing laws of optics with dynamic laws as the basis of the theory.

Michael Faraday 1791-1867

1838 Showed that induction of charges in isolators is analogous to induced magnetism in magnetic materials. Connected this to Poisson's equation.
Faraday discovered a dark region in arc lamp discharge near the negative electrode.

James MacCullagh 1809-1847

1839 Elastic aether without longitudinal waves, where the potential energy of distortions depend on rotation and not compression. The wave equation is identical to Maxwell's equations.

William Thomson (Lord Kelvin) 1824-1907

1839 Following MacCullagh, invented a mechanical model to rotational energy that includes balls, rods, sliding contacts and flying wheels...

Augustine Louis Cauchy 1857-1789 & George Green 1793-1841

1939 Deny the possibility of explaining longitudinal aether waves by negative compression.

Franz Neumann 1798-1895 & Matthew O'Brien 1814-1855

1842 Proposed that optical properties emerge from aether flow about material particles.

Christian Doppler 1803 –1853 Austria

1842 Proposed “Doppler effect” – Shifting light frequency towards red when the source (such as a star) moves away from us. (At that time trains were not sufficiently fast to test doppler effect on sound), then developed the theory.

Kelvin also described the effect.

The frequency shift for light-sent from a source moving away at speed v_s and detected by a receiver moving in speed v_r is:

$$f = \left(\frac{c + v_r}{c + v_s} \right) f_0$$

Doppler was the teacher of **Gregor Mendel**, the father of genetics.

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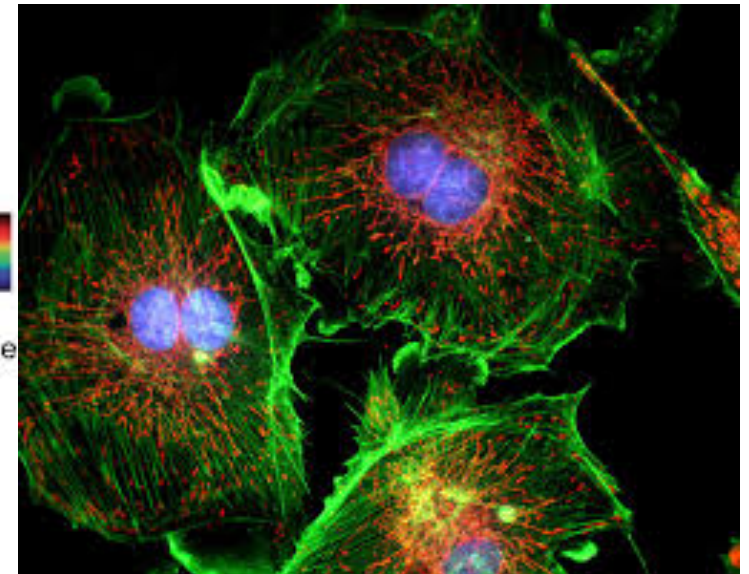
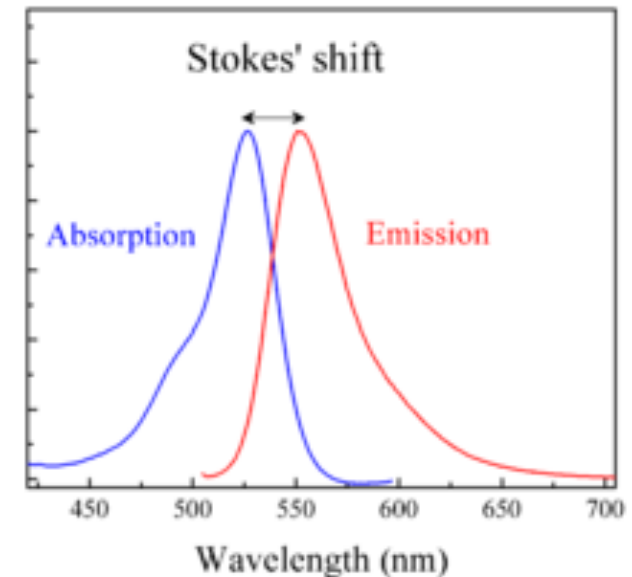
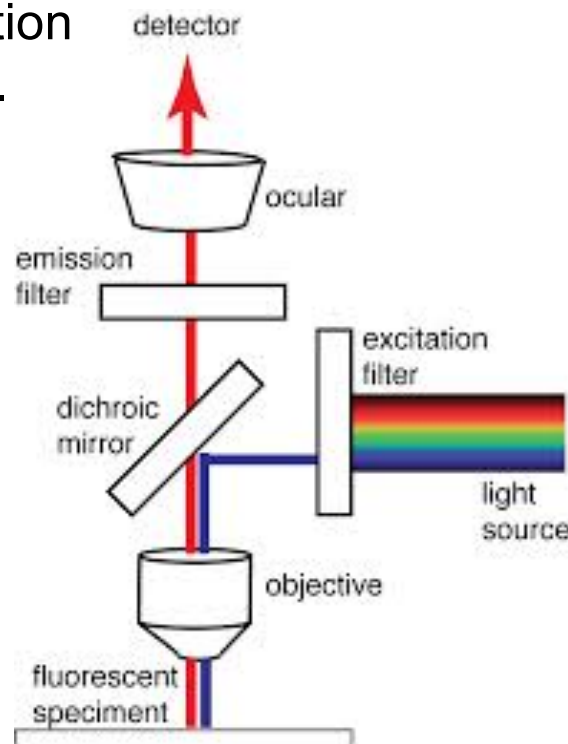
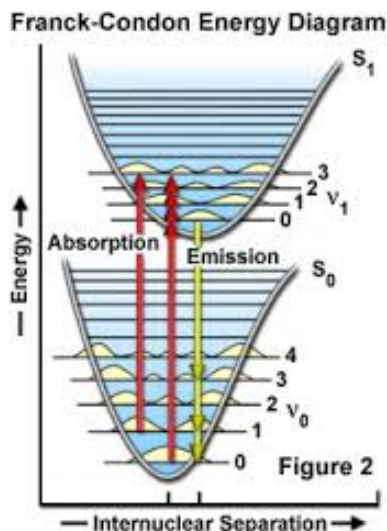


George Gabriel Stokes 1819-1903 Irland

1843 Stokes described shift between fluorescence absorption and emission spectra: Stokes shift. He characterized the effect in Uranium glass.

Modern fluorescence microscopes (see schematics below and a typical image of cells) rely on Stokes shift to block the strong fluorescence excitation light from the faint emitted fluorescence (5-6 orders of magnitude weaker).

The electron energy diagram and the transitions responsible for absorption, vibrational relaxation and emission of fluorescent light.



Michael Faraday 1791-1867

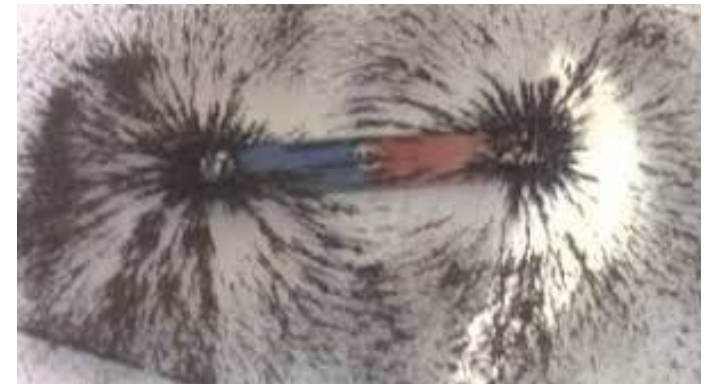
1844 Studied rotation of light polarization and its electromagnetic theories.

1845 “Faraday Rotation”: Discovered that propagation of light in materials is affected by a magnetic field: Polarization-plane is rotated when “crossing” the field lines of a magnet.

1845 In response to Thomson’s inquiry studied polarization rotation of light passing through glass plates in magnetic fields. The magnet affects polarization within the glass. Faraday developed the idea of force field lines, inspired by the organization of iron sawdust near a magnet (see picture). Maxwell followed this idea.

1846 Following his findings of magnetic effects on light, he proposed that light is a transversal electromagnetic wave. At the same year he discovered diamagnetism (i.e. in Bismuth): materials that, unlike iron, are repelled from magnets.

1860 Faraday described reducing of water freezing temperature under pressure. This also implies that freezing water density is lower (Le Chatelier law) therefore the ice in frozen lakes floats to the top, providing below the ice fish life.



William Thomson (Lord Kelvin) 1824-1907

1845 Following Faraday’s experiments he deduced that electricity and magnetism are linked.

Franz Ernst Neumann 1798-1895

1845 Used Lenz law, assuming the electro-motive force is proportional to the magnetic force in a current element, and used Ampere's considerations to get Faraday's law. He defined a potential function that derived the induced electric field – Maxwell's equation.

William Thomson (Lord Kelvin) 1824-1907

1846 Showed that the electromagnetic potential of Neumann is in fact the vector potential **A** from which the magnetic field **B** can be derived by $\underline{\mathbf{B}} = \nabla \times \underline{\mathbf{A}}$

George Biddell Airy 1801-1892

1846 Modified the elastic theory of aether according to MacCullagh in order to explain Faraday's polarization rotation due to a magnet.

Wilhelm Edward Weber 1804–1891

1846 Combined considerations of **Ampere**, **Faraday** & **Fechner** that currents contain equal amounts of positive and negative charges moving in opposite directions. His electromagnetic theory was based on velocity-dependent forces between charges. The theory is wrong, but contributed to the correct theory of **Maxwell & Lorentz**, and to a new look at gravitation by **Thomson** attempting to explain Mercury's orbit precession.

1847 Proposed that diamagnetism is Faraday's law acting on atomic-scale current loops. This is a correct theory, since ferro- and para-magnetic materials contain strong molecular currents of electron orbitals around the nuclei.



Gustav Kirchhoff 1824-1887



1848-9 Extended **Ohm's** law to “Kirchoff's laws for networks”:

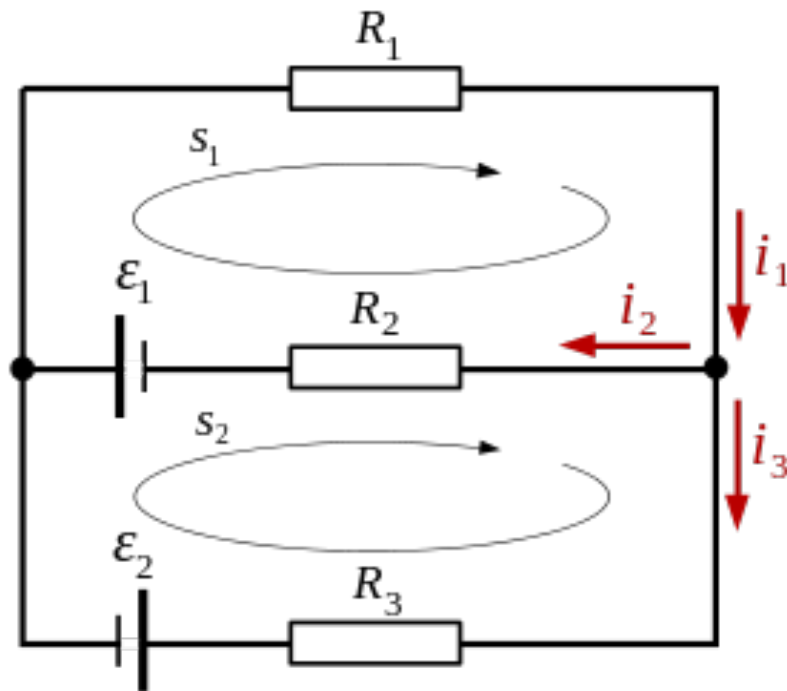
1. The sum of currents in a junction is zero.
2. The sum of voltages in any close circuit is zero.

United **Ohm's** electrostatic voltage with **Lagrange**, **Laplace** & **Poisson's** potentials.

Understood the connection of electromagnetism to light.

Proved that electric currents at equilibrium distribute so as to minimize Joule's heating.

1857 Developed the “telegraph equation” for coaxial cable, where for low resistance yields wave equation with close-to-light speed.



See fololowing:
Kirchoff's law for black body radiation

George Gabriel Stokes 1819-1903

1849 Stokes studied diffraction at the edge of opaque objects. Demonstrated that aether vibrations are perpendicular to polarization.

1852 Reached the same conclusion from polarized light scattered from the atmosphere, but this was incompatible with experiments in crystals. Some incompatibilities may be resolved if aether elasticity was equal for all materials, but the inertia should be different, and angle-dependent (therefore anisotropic in the crystal). He defined Stokes parameters of polarization.

1867 New experiments killed his own anisotropic inertia theory

August Beer 1825-1863

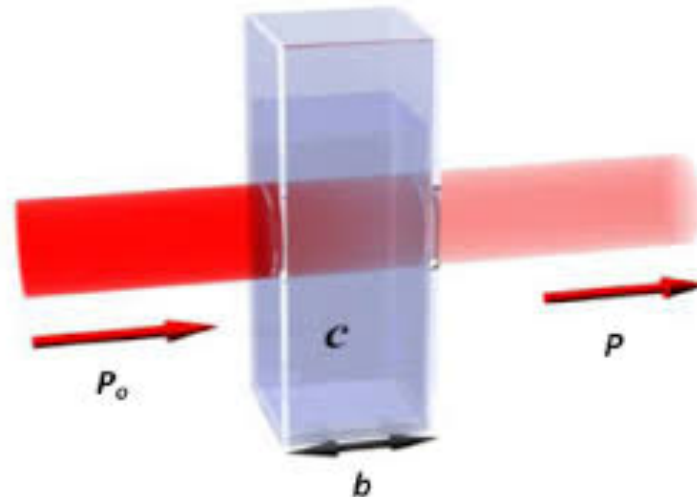
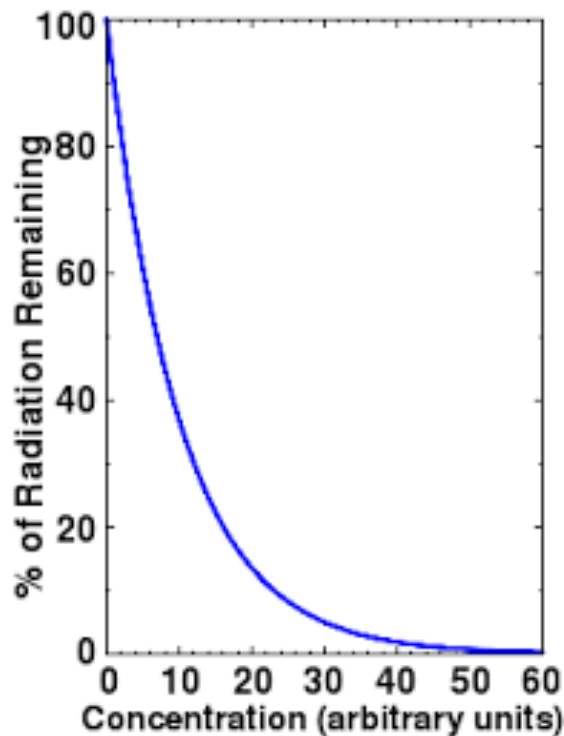
1852 Beer-Lambert law: relates light absorption with the medium it transverse through. Partially based on the works of

Pierre Bouguer 1698-1758
& Johann Heinrich Lambert 1728-1777



Spectrometry is based on Beer-Lambert law: the log-ratio of out-to-incoming light intensities in a solution of a dye is proportional to b-path length in the medium, and concentration of the dye.

$$-\log_{10}(P/P_0) = \epsilon C b$$



Hermann von Helmholtz 1821-1894

1851 Invented the ophthalmoscope – by touching the eye ball the retina blood vessels can be visualized.

1858 Corrected Young's three-color vision model– Every wavelength excites all three color receptors in the eye. That explained why there is no saturation in “pure” colors.

William Thomson (Lord Kelvin) 1824-1907

1850 Kelvin invented the concept of magnetic susceptibility, χ_m and permeability, the constants relating magnetic field to material magnetization. For diamagnets $\chi_m < 0$.

$$\mathbf{M} = \chi_m \mathbf{H}, \quad \mu = \mu_0 (1 + \chi_m)$$

1850 Formulated a theory for Seebeck & Paltier's electrothermal effect.

1853 Employed Poisson's magnetic theory to the equation of magnetic energy. He mistakenly stated that the magnetic force on electric current depend on field gradient. Developed the theory for circuits with resistance, capacitance and inductance, R,C,L, that explained **Henry & Savery's** observations.

1856 Electricity in motion is heat, and current rotational axis create magnetism.

Explained **Faraday's** rotation of polarization by rotation of the material molecules transferring the light. Following **William John Macquorn Rankin's** assumption he claimed that around a current there are spiral force-lines that bent by magnets. Later he corrected his claim, saying that change in circuit current generate magnetic field.

Wilhelm Eduard Weber 1804–1891

& Rudolph Hermann Arndt Kohlrausch 1809-1858

1856 Collaborated in the measurement of the ratio between the electrostatic (electric permeability, ϵ) and electrodynamic units (magnetic susceptibility, μ) . Found $\mu = 3.1074 \times 10^8$ – very close to the speed of light: $\mu \epsilon = 1/c^2$

This result led **Maxwell** to conclude that light is an electromagnetic phenomenon.

Bernhard Riemann 1826-1866

1861 Developed a wrong variation of Weber electromagnetic theory.

At the same year **Maxwell** presented his 4 equations that unified **Coulomb's** laws, **Ampere** and **Faraday** (induction). (see coming slides).

1867 Proposed an electric equation to replace Poisson's.

Joseph Boussinesq 1842-1929

1867 Proposed that instead of medium-dependent aether, same aether but different interaction with the medium.

Ludwig Valentin Lorenz 1829-1891 Denmark

1867 Electromagnetic theory for light based on delayed scalar and vector fields. They yield the wave equation, and Maxwell's equations can be derived from them.

1869 From his optics research and the wave equation, linked density and polarization to the refractive index of water.

Hendrik Antoon Lorentz 1853-1928 Netherland

1878-1880 Developed independently the link between density and polarization to refractive index of water: Lorentz-Lorentz equation:

n – the refractive index

N – number of molecules

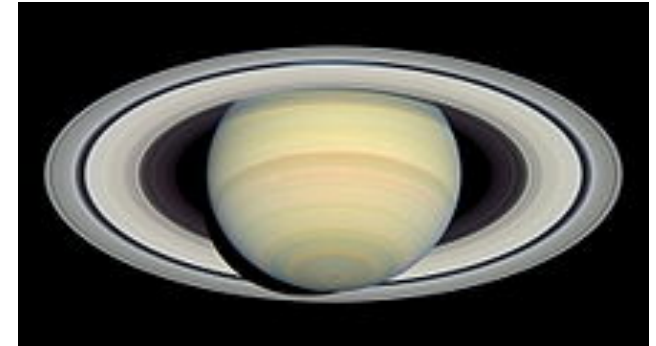
α - polarizability

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3} N \alpha,$$

James Clerk Maxwell 1831 –1879 Scotland

Theory of electromagnetism **1873**

Saturn's rings are not continuous solid or liquid since they would fall apart, but a collection of small particles, each circling in his own stable orbit. This was confirmed directly by the Voyager at **1980**.



1865 Four Maxwell's equation: Electromagnetic wave equation.

The mathematics of electromagnetism: unification of electricity, magnetism and light.

Gauss law: Charge ρ create electric potential field E :

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

Gauss law for Magnetism B

No sources (no isolated magnetic pole): $\nabla \cdot \mathbf{B} = 0$

Faraday's induction law: Changing magnetic field generate electric field

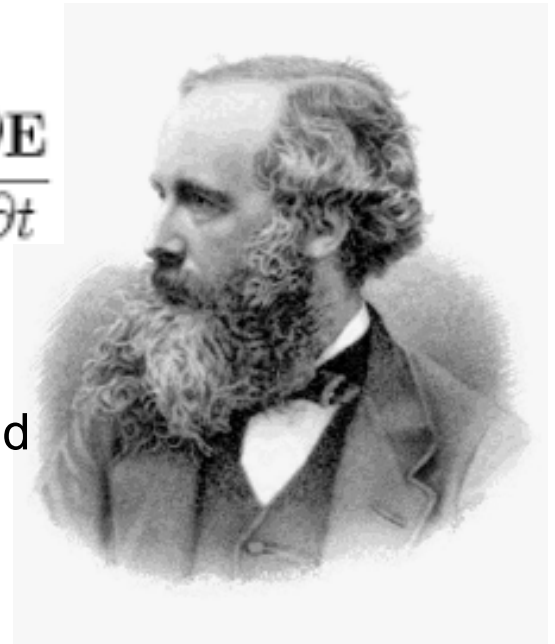
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's law: electric current (changing electric field) Create a magnetic field:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

1873 Formulated the equations in terms of scaler-Electric field and vector-Magnetic field: no aether !!! The equations solution is a wave propagating at constant, wavelength independent, speed and radiation pressure was predicted.

1868 Published "On Governors" the first significant essay on feedback.



Maxwell's equations describe all electromagnetic radiation (x-rays were discovered later). The wave equation:

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad \nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} \qquad c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 \cos(\omega t - \mathbf{k} \cdot \mathbf{r} + \phi_0) \qquad \mathbf{B}(\mathbf{r}, t) = \mathbf{B}_0 \cos(\omega t - \mathbf{k} \cdot \mathbf{r} + \phi_0)$$

$$k = |\mathbf{k}| = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

For spherical waves:

$$\mathbf{E}(\mathbf{r}, t) = \frac{1}{r} \mathbf{E}_0 \cos(\omega t - k \cdot r + \phi_0), \quad \mathbf{B}(\mathbf{r}, t) = \frac{1}{r} \mathbf{B}_0 \cos(\omega t - k \cdot r + \phi_0),$$

Maxwell claimed that if an electric charge oscillated sufficiently fast, it will irradiate light. Indeed later, electrons around the nucleus were found to emit light, and antennas irradiate radio waves with wavelength determined by the antenna length (since it determines the resonance frequency of charge oscillations).

1855 Maxwell wrote a memo combining **Faraday's** field lines with **Thomson's** mathematics using scalar and vector operators divergent and curl. $\nabla \cdot$ & $\nabla \times$

1861 Maxwell published a mechanical model of electromagnetism. Magnets are turbulence and charges are mechanical strains. The equation gives solution of waves.

1864 Dynamic theory for electromagnetism – the mechanical model was abandoned, since it could not explain reflection or refraction due to boundary conditions, but the equations stayed for scalar and vector fields.

1869 Electromagnetic fields in media with natural resonance cause refractive index to contain a diverging resonance factor.

1873 Light is an electromagnetic phenomenon. Summary of the theory as accepted at that time, and deal with strain tensors and electromagnetic momentum.

1877 Magnetic vibrations have similar properties to light, and propagate in light velocity.

Hermann von Helmholtz 1821-1894

1870 Derived reflection and refraction from Maxwell's equation with boundary conditions for continuity of the scalar field and of the perpendicular vector field at the interface. This derivation is cited in Lorenz' thesis, and relate back to **MacCullagh** theory.

Maxwell, Thomson, Kirchhoff, Bjerknes, Leahy, Fitz Gerald, Helmholtz, & Hicks

1870-1900 All worked on mechanical models of the aether to match to Maxwell's equations.

Heinrich Rudolf Hertz 1857-1894

1894 The success of Maxwell's equations made him believe in a mathematical theory organizing the physical reality, and predicting experimental results. He used **Newton, Lagrange and Hamilton** formulations. This must have been the last time they were considered correct theories.

John William Strutt, 3rd Baron Rayleigh (1842-1919) England

Nobel 1904

probability, Rayleigh's density function

1871 Calculated the angular dependence of the intensity of light scattered from particles with refractive index n and dimension smaller than the wavelength of light - $d \ll \lambda$

Rayleigh scattering

$$I = I_0 \frac{1 + \cos^2 \theta}{2R^2} \left(\frac{2\pi}{\lambda} \right)^4 \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 \left(\frac{d}{2} \right)^6$$

The total scattered intensity (integrated on all angles):

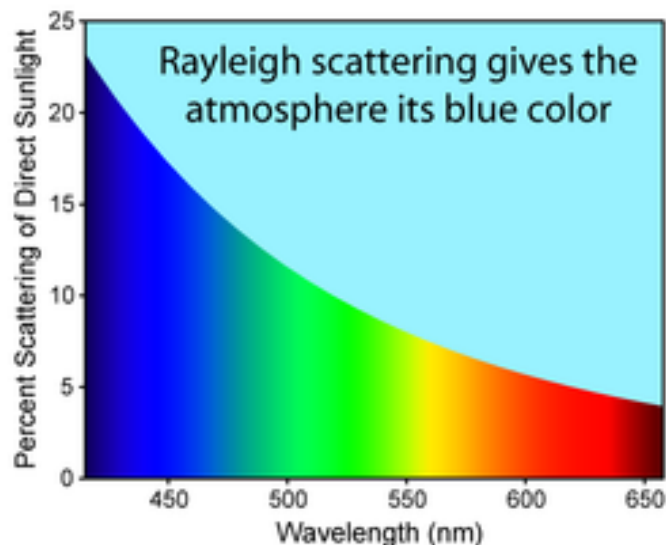
Is proportional to 6th power of the diameter, and inversely

Proportional to 4th power of the wavelength

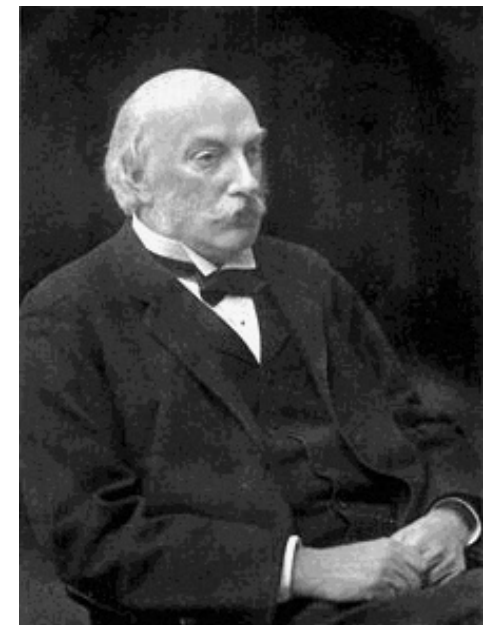
$$\sigma_s = \frac{2\pi^5 d^6}{3 \lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2$$

1874 Rayleigh fought **Boltzmann** over the irreversibility paradox of many body systems despite reversible mechanics of each particle.

1894 with **Ramsay** discovered Argon, (see chemistry).



Rayleigh scattering explains:
Why are sky blue?
Why sunsets are red?

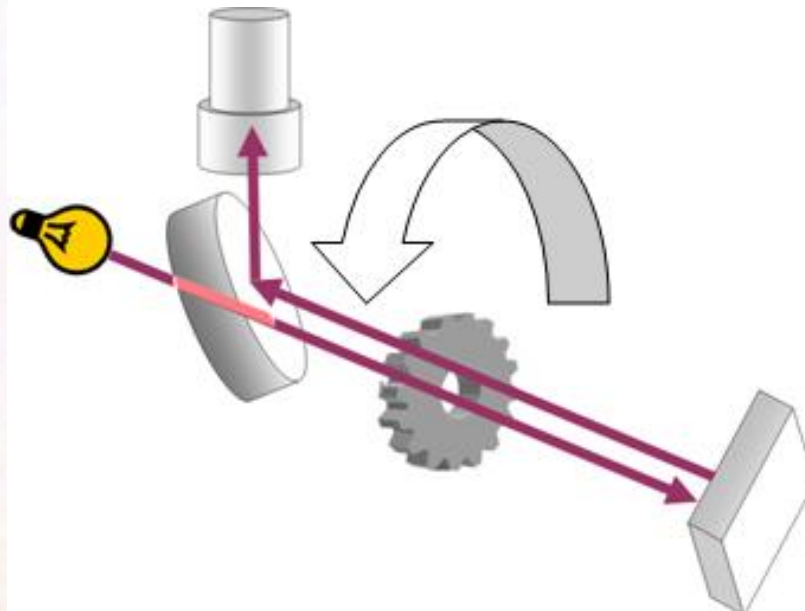


Armand Hippolyte Louis Fizeau 1819-1896 French

1848 Collaborated with Doppler to formulate Doppler effect in sound waves, and predicted the red-shift of star light. Improved photographic plates.

with **Jean-Bernard Foucault 1819-1868**

1849 Fizeau & Foucault worked on interference of light. Following Rømer's astronomic measurement of the speed of light, were first to perform such measurement on earth: Following Galileo's idea (he failed to perform the measurement) they used a teeth wheel that passed and stopped light cyclically, and a mirror at 9 km, so that when light was blocked the time of flight corresponded to half cycle time between teeth. They found $c=2900,000$ km/sec.



Armand Hippolyte Louis Fizeau 1819-1896 French

1851 Measured speed of light in flowing liquids to confirm “aether drift”, using interference between direct light and light passed through the liquid. He expected the pattern to move as the liquid started to flow, but failed to detect a shift. He improved his device using a rotating mirror, and found that the speed of light was slower inside water.



Éleuthère Élie Nicolas Mascart 1837 –1908

1872 Searched for relative motion of aether to earth by a very sensitive experiment of the rotation of the polarization in quartz crystals, and found “no eather drift”.

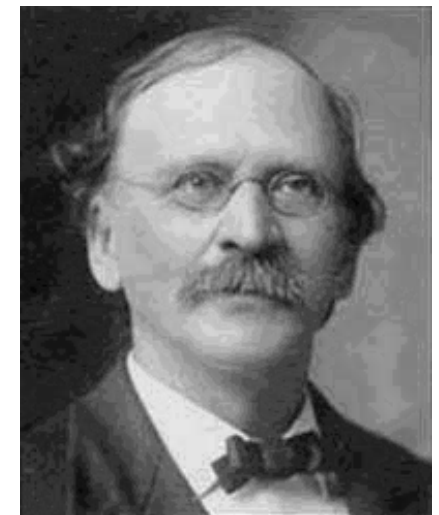
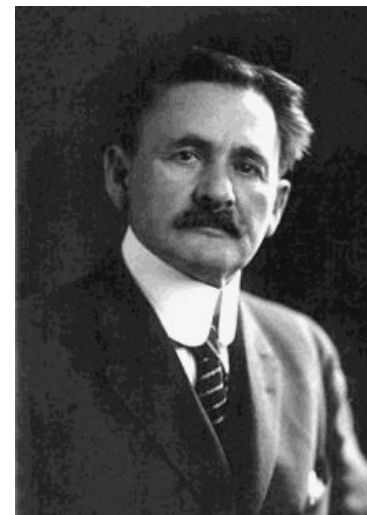
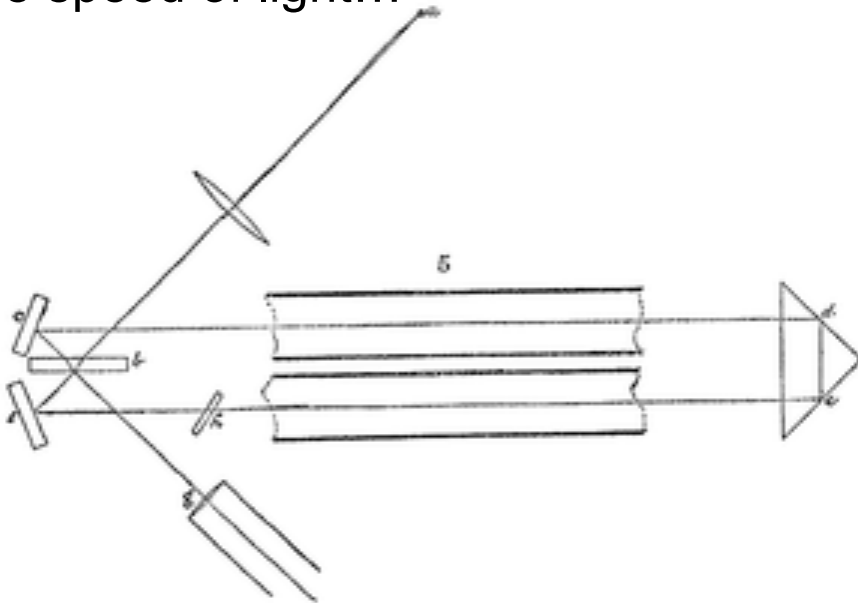
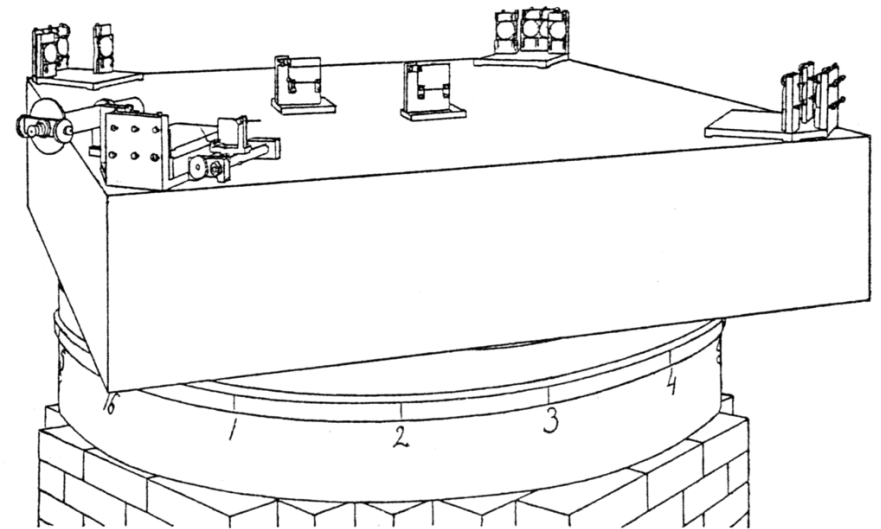
Albert A. Michelson 1852 –1931 & Edward W. Morley 1838 –1923

1882 Michelson described an interferometer: half-reflecting mirror splits and recombines the two split rays.

1886 Measured the speed of light in flowing liquid using improved technology, which they applied to measure the speed of light along and perpendicular to earth motion. The experiment was set on a marble table floating on mercury, to obtain maximum stability.

THIS IS THE MOST FAMOUS NEGATIVE RESULT EXPERIMENT, WHICH WAS THE BASIS FOR EINSTEIN'S RELATIVITY.

Their explanation tried to find an analogy to Stokes falling ball, where the speed at its surface is zero, therefore aether does not alter The speed of light...



George Francis FitzGerald 1851-1901

1889 Proposed that **Michelson-Morley**'s result can be explained by the contraction of moving bodies length at velocities close to that of light. The rationale was that forces between molecules of the body obey electromagnetic laws. This attempted to rescue **Lorentz**' theory, although they both considered the length shrinking effect hypothetical...

Albert A. Michelson 1852 –1931

1893 A standard unit of length based on the emitted red line of Cadmium.

Jules Henri Poincaré 1854 –1912

1898 Declared that simultaneous time is relative.

OPTICS

Ernst Abbe 1840-1905

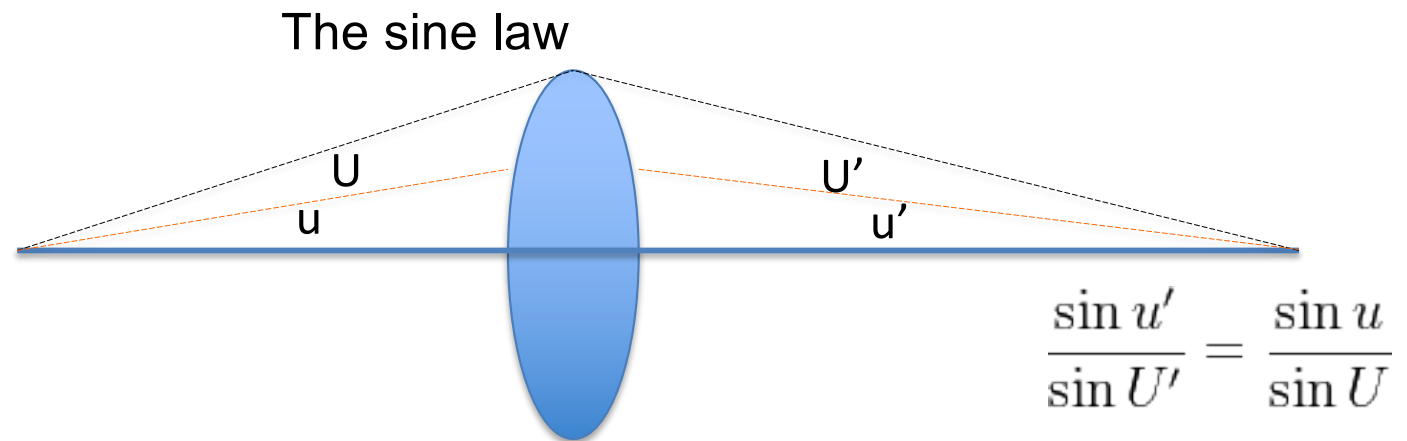
1860 The sine law – a breakthrough in lens design, applied to microscopy. Till then the design was based on trial and error approach. The sine law guarantees a sharp image for large fields.

1877 Abbe published a series of papers about microscope optics, that included the Abbe formula for resolution, d , only determined by the numerical aperture:

$$d = \lambda / 2NA .$$

Carl Zeiss company used Abbe's knowhow to produce microscopes, and takes over this market for high quality research microscopes till the late 50th of the 20th century...

The introduction of infinity corrected microscope optics by Japanese companies (Olympus) simplified the optics of research microscopes with increasing brightness.



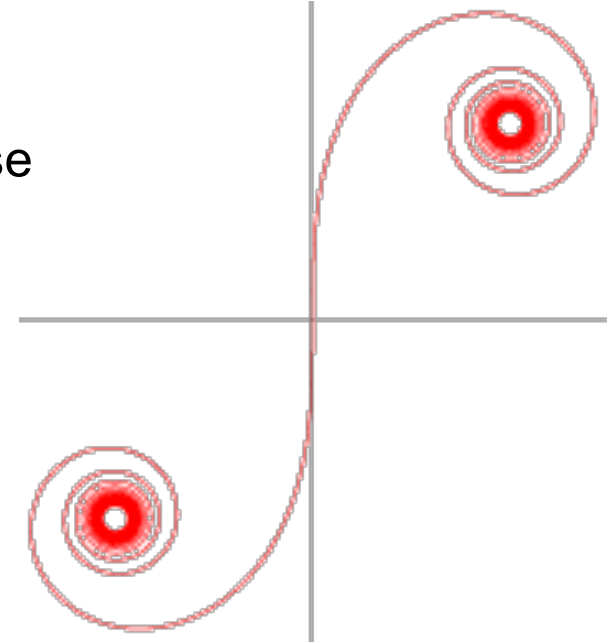
Note that for thin lenses:
 $\text{tag}(u')/\text{tag}(U') = \text{tag}(u)/\text{tag}(U)$

Marie Alfred Cornu 1841-1902

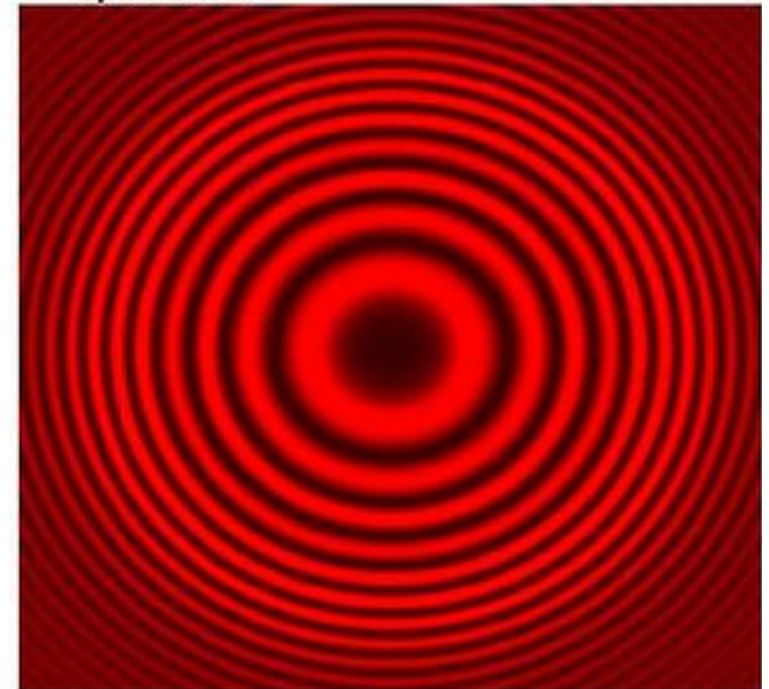
1874 Describe “Cornu’s spiral” for calculating light intensity in Fresnel interference patterns. Vector sum of intensity and phase of light contribution from a slit or disk-like source. It is a graphical presentation of the integral:

$$\psi_P \propto \int t(x, y) \exp \left(ik \frac{x^2 + y^2}{2R} \right) d\Sigma$$
$$\int_0^w \exp \left(\frac{i\pi u^2}{2} \right) du = C(w) + iS(w)$$

“Cornu’s spiral”



Fresnel diffraction of circular aperture"



Fresnel diffraction of straight edge"



John Kerr 1824-1907

1875 Discovered birefringence in some liquids under electric fields – Kerr cell.

Another demonstration of the connection of electricity to light. The effect is used today for fast polarization change of light.

Adolfo Bartoli 1851-1896

1876 Deduced existence of radiation pressure from thermal considerations: connected electromagnetism to thermodynamics.

Josef Stefan 1835–1893

1883 Reflected Electromagnetic waves create pressure on a surface.

Built a vane erroneously displayed as a proof of radiation pressure (see below).



Henry Rowland 1848-1901

1876 Induced by **Helmholtz**, he performed an experiment showing for the first time that electric current are moving charges.

Edwin Herbert Hall 1855-1938 America

1879 Hall performed an experiment proposed by **Henry Rowland** and discovered that perpendicular electric and magnetic fields create an electric field perpendicular to both: Hall effect. This effect adds a resistive contribution to **Ohm's**. The effect was only explained by quantum mechanics.

1879 Boltzmann use Hall effect to estimate speed of electric charges, assuming all have same sign and size.

Henry Rowland 1848-1901

1880 Showed that **Faraday's** polarization rotation is explained by **Maxwell's** equations+**Hall** term in **Ohm's** equation, provided displacement current that behave like resistive currents.

William Thomson (Lord Kelvin) 1824-1907

1881 Tried to confirm displacement currents, searching for magnetic effects induced by the electric field of a moving charged ball.

George Fitz Gerald 1851-1901

1881 Noted **Thomson's** mistake in ignoring the charges moving on the ball itself, that cancel the effect of displacement currents.

1883 Fitz Gerald proposed to test **Maxwell's** theory on alternating current in a circular wire (dipole antenna). But he discovered that very high frequencies are required. He obtained them later by discharging a capacitor. The birth of radio waves.

Hermann von Helmholtz 1821-1894

1881 Proposed that charged particles in atoms fit **Maxwell & Faraday**, not aether models.

John Henry Poynting 1852-1914

1884 Showed that **Maxwell's** equation predicts energy flow through vacuum.

Hendrik Antoon Lorentz 1853-1928

1892 Presented aether and electron theory combining **Maxwell's** equation with **Lorentz** force law for accelerating charge, resting aether, and incompatible with **Michelson-Morley**.

Oliver Joseph Lodge 1851-1940

1892 Performed experiments of light propagation near a rotating disk at high speed to detect effects of aether drift. No effect was measured.

Arnold Johannes Wilhelm Sommerfeld 1868-1951

1896 Solved the diffraction from a conducting half plane.

Pierre Curie 1859 –1906

1880 Pierre and **Jack**, his brother, discover the Piezoelectric effect: a crystal (such as quartz) creates electric voltage when compressed.

1881 The inverse effect: Putting voltage across a crystal cause it to shrink.

The piezoelectric effect has many applications: quartz electrometer, gramophone tip, oscillators in quartz clocks, micro-positioners (microscope objective, interferometers, adaptive mirrors in telescopes and other optical systems).

1895 Pierre discovered that ferromagnetic materials (such as iron magnet) gradually lose their magnetism upon heating, and there is no magnetism above a critical temperature: Curie point. Curie law of ferromagnetism:

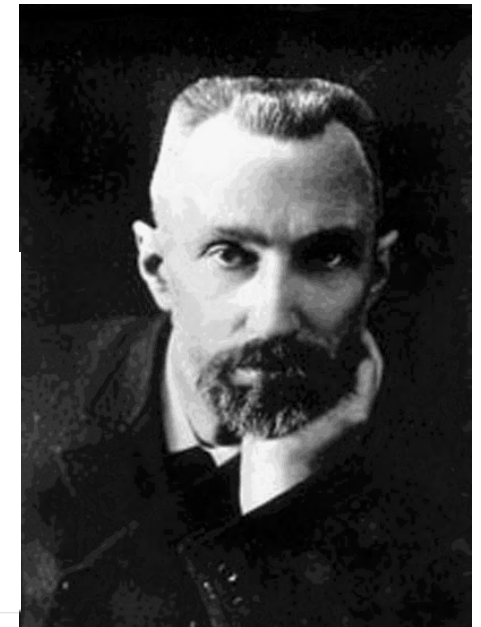
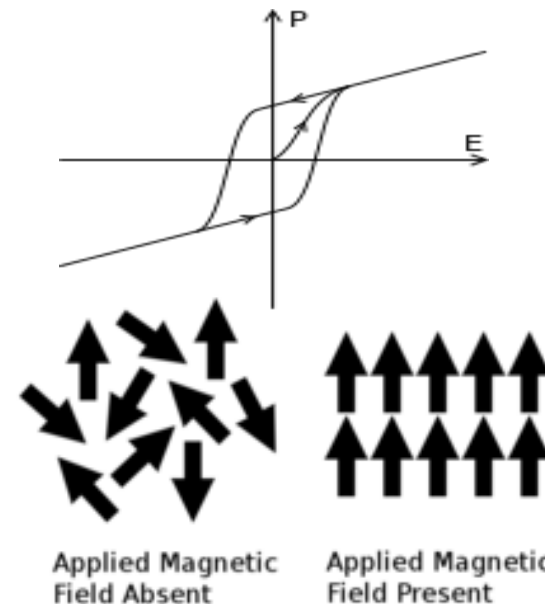
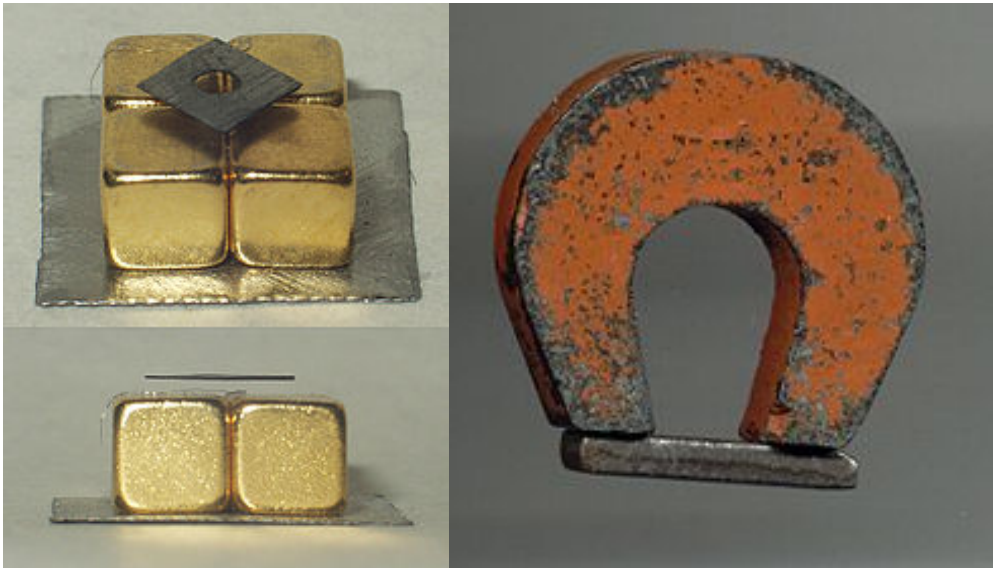
$$M = C \cdot \frac{B}{T},$$

Showed that no such temperature dependence exists for diamagnetism,

materials that align opposite to a magnetic field, but lose their magnetism when the external field is taken away. Such materials can be suspended (float) over magnets.

1895 Discovered that magnetic induction is proportional to the magnetic field strength.

Hysteresis in magnetism was studied later.



BLACK BODY RADIATION

BLACK BODY RADIATION

This chapter in 19th century physics is a vivid demonstration of how insistent scientists do not give up to “minor unexplained details” of an experimental measurement, and eventually give birth to the new era of quantum physics.

Black body is an idealized object (much like ideal gases were in thermodynamics), to which some properties should be attached according to existing laws of physics, mainly of thermodynamics. A black body can be realized closely by a hole in a cavity of a real body, and the spectral emission could be measured and compared to theoretical models.

The “ultraviolet catastrophe” was a hint that something must be wrong for short wavelengths, of atomically small dimensions. It took about 20 more years at the early 20th century, when the international collaborative effort in science formulated and agreed on a revolutionary mechanical theory.

The phenomenological equation proposed by Planck to best fit experiments evolved into a fundamental concept of quantized energy, applied both in light radiation (photoelectric effect) and in atomic structure (Bohr model of Hydrogen atom and the discrete lines of emission upon transition between electron discrete energy levels).

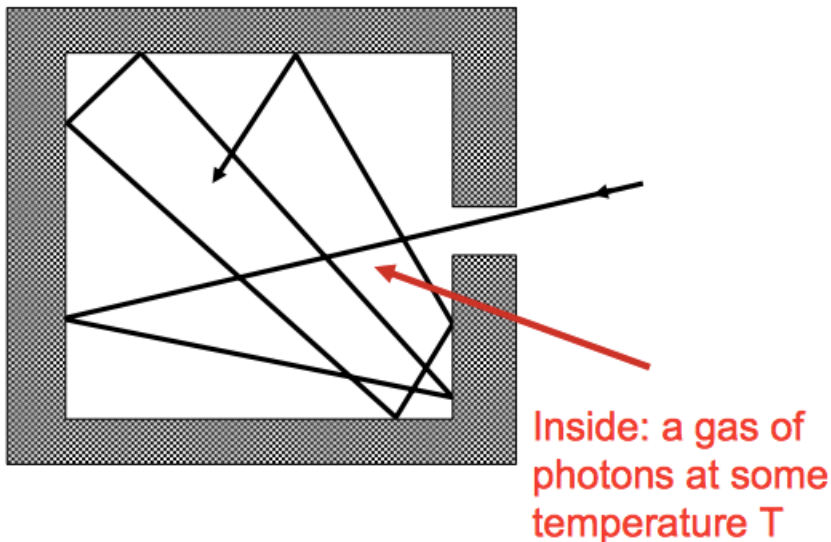
BLACK BODY RADIATION

Josef Stephan 1835-1893

1879 Proposed that the radiation from a hole is equivalent to ideal black body radiation. The reason: the gas inside the cavity equilibrated with the wall temperature, and irradiate according to its velocity distribution of thermal energies, independent on the material.

Found that the total energy radiated is proportional to the fourth power of the temperature (in Kelvin degrees):

$$j^{\star} = \sigma T^4.$$
$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} = 5.670373 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4},$$



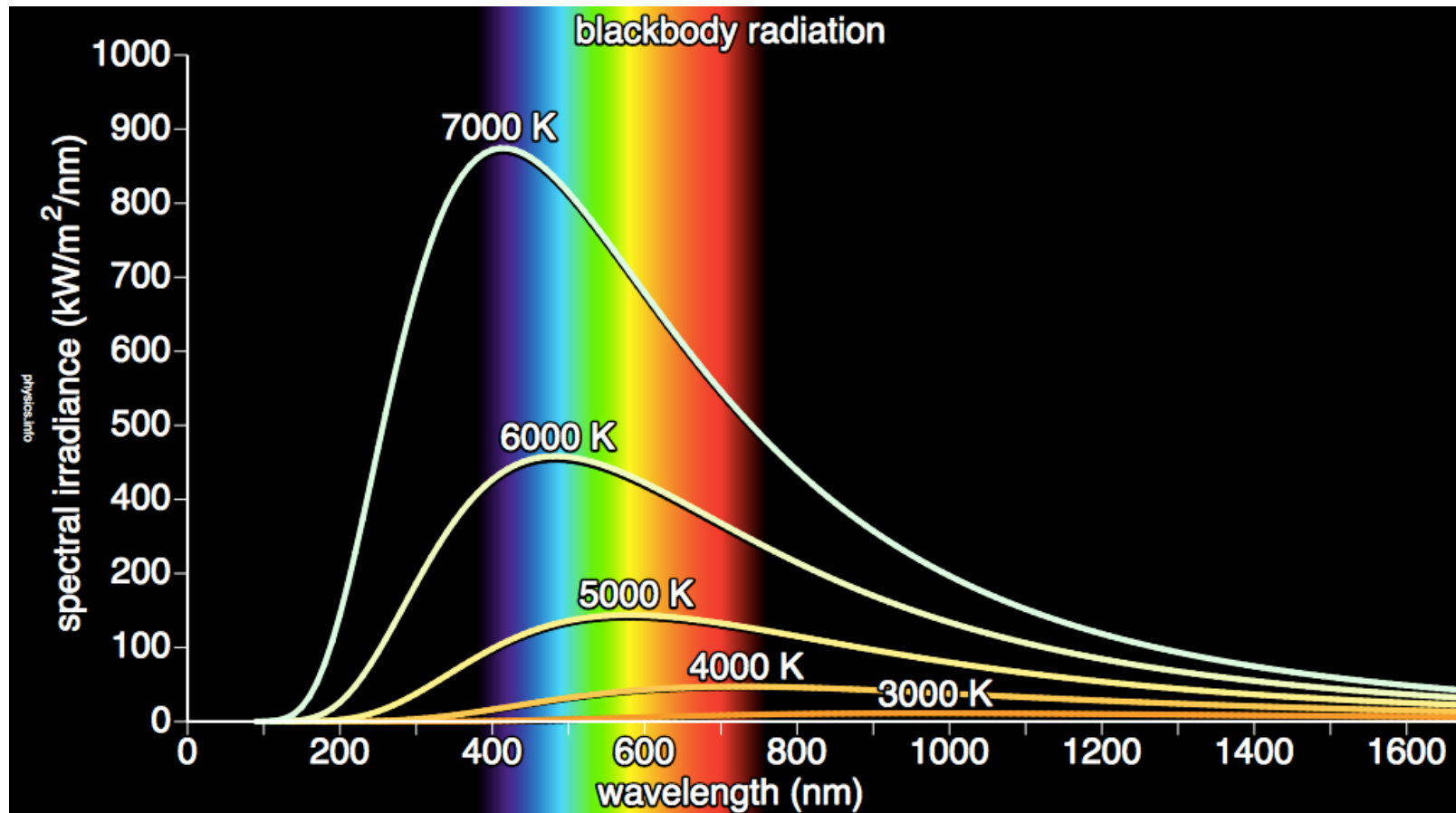
Ludwig Boltzmann 1844 –1906

1884 Developed the same law (now called Stephan-Bolzmann law) from thermodynamic considerations.

Estimated the sun temperature as 5700°K.

Wilhelm Carl Werner Otto Fritz Franz Wien 1864-1928

1893 Wien's displacement law for the spectrum of black-body radiation: The maximum radiation power is at a wavelength inversely proportional to the temperature (in Kelvin). Used a furnace with a small hole in his experiments.



The peak radiative energy vs. temperature

$$\lambda_{\text{peak}} = \frac{b}{T}$$

Gustav Kirchhoff 1824-1887

Kirchoff's law of black body radiation: independent on the material. The only dependencies are on temperature and wavelength. Introduced the name “black body”.

Lummar & Alfred Pringsheim 1850-1941

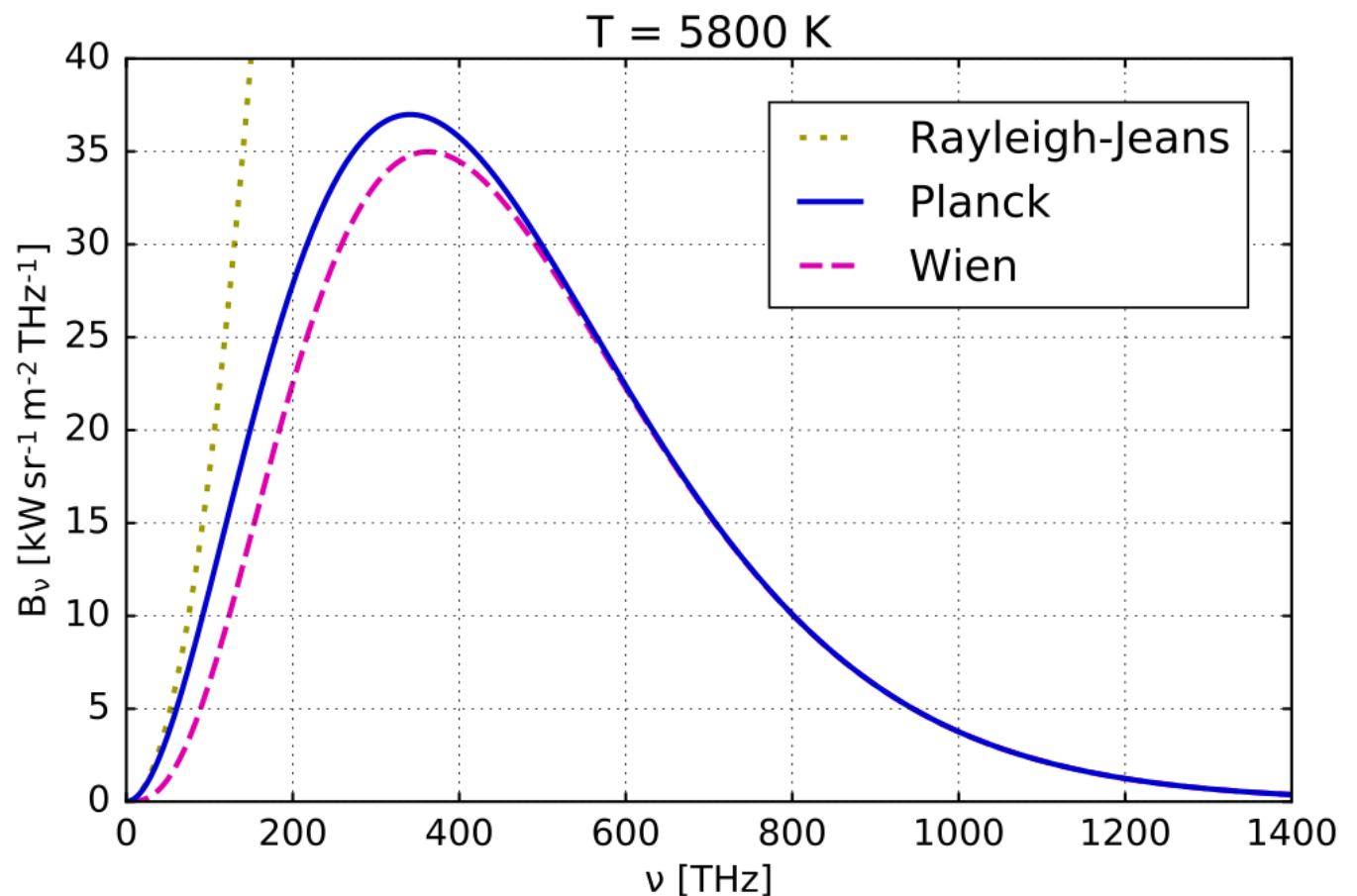
1899 Extensive spectral measurements of black body radiation. Clear mismatch with **Rayleigh-Jeans** equation, based on some theoretical considerations and fitted to experiments:

The ultraviolet catastrophe

At short wavelengths λ , of
High frequencies, ν

$$B_{\lambda}(T) = \frac{2ck_{\text{B}}T}{\lambda^4},$$

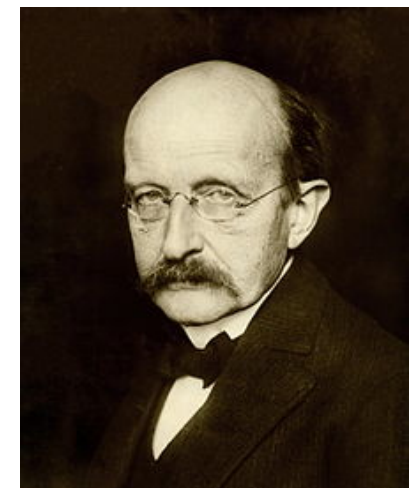
$$B_{\nu}(T) = \frac{2\nu^2 k_{\text{B}}T}{c^2}$$



Josef Stefan, Ludwig Boltzmann, John William Strutt & Wilhelm Wien

1896 All tried to find the correct equation for the spectrum radiated from a black body, finding mismatches to all models in both ultraviolet and infrared.

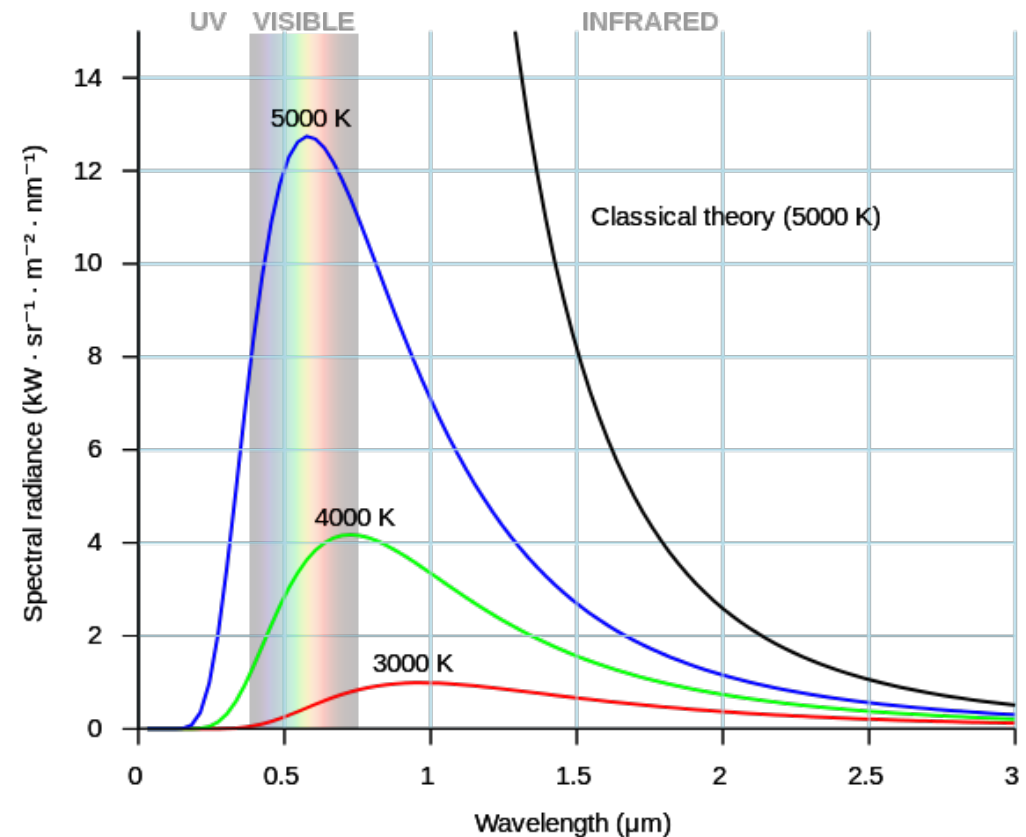
Max Karl Ernst Ludwig Planck 1858-1947



1900 Presented his equation that fit well the experimental spectra.

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1},$$

The equation was proposed as a phenomenological fitting for a wide spectral range, but became a constitutive event in the evolution of quantum mechanics, since the factor $h\nu/kT$ was soon understood as an energy quant of fundamental meaning.



See also here **Chemisty slides** for the titles:

SPECTROSCOPY AND DISCOVERY OF NEW ELEMENTS

ELECTROLYTES

STRUCTURE OF ATOMS

SUB-ATOMIC PARTICLES

A few thousand years after the Greeks debated whether matter is continuous or “atomic”, the discrete, molecular contents of all materials became well accepted, started with gases then solids and liquids. Chemistry taught us that molecules are composed of atomic elements, both for inorganic and organic compounds, and the nature of chemical bonds started to be understood after electromagnetic forces were explored.

As the atomic theory emerged from experiments with gases, the sub-atomic particles were discovered in gaseous media, this time under very low pressures in the vacuum tubes. While electric currents were proposed to consist of charged particles, their properties were only revealed when high voltages were applied to electrodes in vacuum tubes. It was then understood that atoms are stabilized by electric charge attraction forces, and energy is required to break them apart. These experiments revealed several types of rays (Alpha, Beta, Gamma) eventually sorted into positively and negatively charged subatomic particles (protons, electrons) and electromagnetic radiation (x-rays, gamma) that was created when atoms were broken in high voltages..

There was another phenomenon that contributed to the exploration of sub-atomic particles: the spontaneous energetic decomposition of radioactive elements emitting various type of radiations. These energetic and fast moving sub-atomic particles helped studying the atomic structure itself, when aimed at materials and scattered from them.

The end of the 19th century provided powerful tools for revealing the structure of atoms for 20th century atomic research,, and the new laws of quantum mechanics governing high energies and atomic-scale dimensions.

George Gabriel Stokes 1819-1903

1852 Discovered fluorescence – visible light emission from solutions exposed to ultraviolet (dispersed from sunlight).

Julius Plücker 1801-1868

1855 Transmitted electric current through a vacuum tube and caused light to be emitted.

1858 Created a shining cathode rays in a vacuum tube.

David Alter 1807-1881

1855 Described the emitted spectra from arc lamps filled with Hydrogen and other gases.

Robert Wilhelm Bunsen 1811-1899

1859 Found that every element emits its characteristic set of spectral lines. Started spectroscopy of star light using photographic plates. The first proof that the elements are common to the stars and our earth.

Explained the mechanism of action of geysers.

Gustav Robert Kirchhoff 1824-1887

Following Bunsen he found the Fraunhofer absorption (dark) lines in sunlight.

Interpreted as cold gases enveloping the sun periphery. This was again a proof that the elements in stars are the same as ours.

1860 Discovery of Cesium and Rubidium.

Anders Jonas Ångström 1814-1874

1868 Measured wavelength of spectral lines. The length unit 1 Ångstrom= 10^{-10} meter was named after him .

Johann Wilhelm Hittorf 1824-1914

1869 Cathode rays project a shadow.

Eugene Goldstein 1850-1930

1885-6 Coined the names „Cathode rays“ (electrons) and tunnel rays (Hydrogen ions or protons).

Sir William Crookes 1832-1919

1861 Discovered Thallium by spectroscopy,

1875 Developed the light vane in vacuum tube as a radiometer.

1875-9 Built “Crookes’ tube” with high vacuum (millionth of an atmosphere) and electrodes generating fluorescent radiation from accelerated electrons that hit the glass. He studied influence of electric and magnetic fields on the “cathode rays”. The tube was used by **Röntgen** and others to discover subatomic particles and short wavelength electromagnetic radiation.



Pierre Curie 1859 –1906 & Marie Sklodowska-Curie 1867-1934

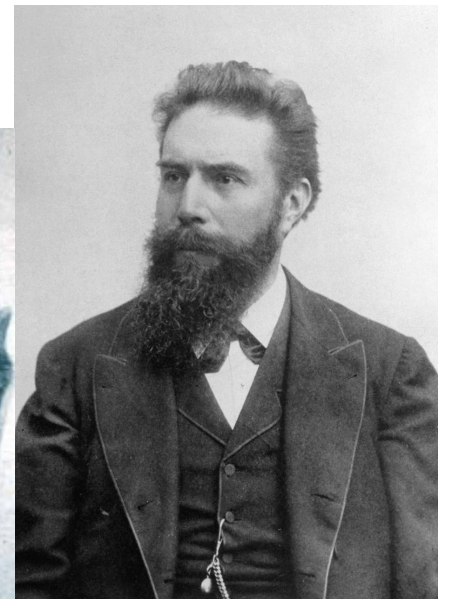
Nobel 1903

1865 Discovered radioactivity of thorium, Polonium and Radium.

Wilhelm Conrad Röntgen 1845 –1923

Nobel 1901

1895 Discovered radiation from Crookes tube that induced fluorescence in dark on a cardboard that absorbed Barium salts. He found that the radiation was highly permeable through the body, but less through bones. The radiation was emitted by decelerated charged particles in cathode radiation – Bremsstrahlung
The name: x-rays indicate the lack of knowledge about the nature of this radiation.



Franz Arthur Friedrich Schuster 1851-1934, Emil Wiechert 1861-1928 & George Gabriel Stokes 1819-1903

1896 Proposed that x-rays are short wavelength aether waves.

George Gabriel Stokes 1819-1903

1898 Proposed that Röntgen radiation is pulses emitted when electron hit the cathode.

Henri Becquerel 1852 –1908

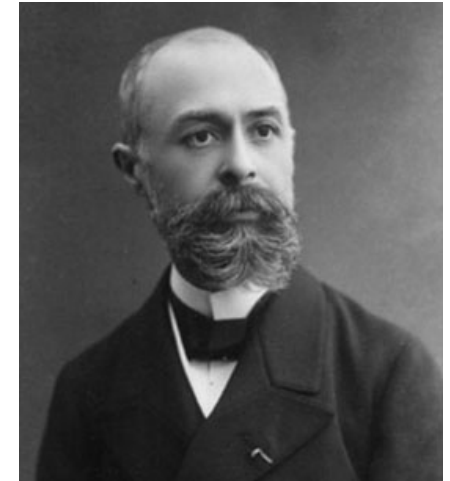
Nobel 1903 with M&P Curie

1896 Discovered that Uranium salts wrapped in black paper still cause photographic plates to become black as if exposed to light.

1899 Showed that the radiation contain charged particles that could be diverted by magnets.

1900 Measured that beta rays have charge over mass ratio equal to the electron. He used Thomson's method of accelerating the particles, then displacement by electric and magnetic fields.

The conclusion: Beta rays are electron beams.



Joseph John (J.J.) Thomson 1856-1940



1894 Found that the speed of cathode rays is much smaller than speed of light.

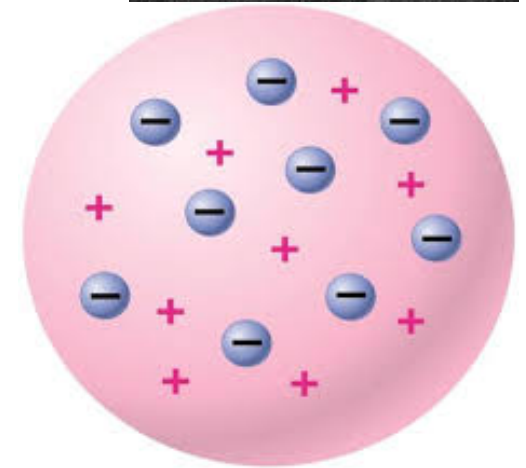
1896 Discovered that isolators under x-rays become conductive.

1897 Used Crookes tube to prove that cathode rays contain negatively charged particles much lighter than atoms— electrons — with sub-atomic size. He believed that they are fragments of atoms and exist in every material.

Emil Wiechert made the same discovery that years.

Fitz Gerald proposed that these are free electrons, the same particles that are inside the atom.

1898 Proposed the “Plum pudding model”
of the atom: electrons are dispersed in a positively charged “cake”.



1898 Showed that Neon gas has two kind of ions differing in charge or mass or both. Brought up the idea of isotopes: different mass for the same atomic number.

Thomson diverted the cathod ray beam in electric and magnetic fields, then in both fields perpendicular to each other, and measured the ratio of charge to mass, q/m . (mass spectrometer).

Ernest Rutherford 1871-1937 (New Zealand-England)

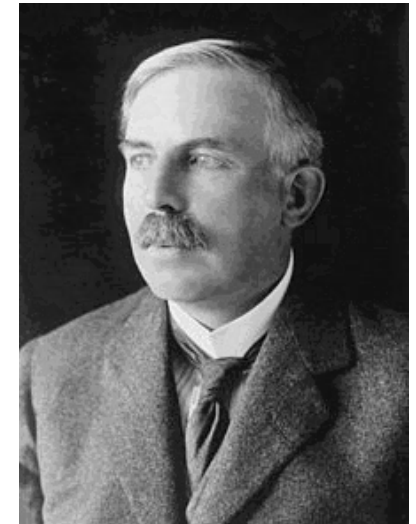
Nobel 1908

1899 Discovered that radiation from Radium contain a particle that is arrested by a few cm of air – “Alpha rays”.

The radiation from Uranium was much more permeable and trans-passed an aluminum foil: “Beta rays”.

Found that alpha rays ionizes gas much more strongly than beta rays.

1900 Understood that the source of these particles in the radioactive radiation is fragmentation of atoms into their parts.



Paul Ulrich Villard 1860-1934

1900 Discovered another type of radiation emitted from radioactive materials, called “Gamma” by **Rutherford**.

Frederick Soddy 1877-1956

1901 Showed with **Rutherford** that following Alpha and Beta emission the radioactive atom change to become a new element.

Kazimierz Fajans 1887-1975

1913 Showed independently of **Soddy** that beta emission convert an element to the element to its right in the periodic table of elements, while Alpha convert the emitting atom to the element two places left in the table.

Élie Joseph Cartan 1869-1951

1894 Presented a Lie groups called $U(1)$: unitary 1-dimensional, $SU(2)$: 2-dimensional matrix etc. Became useful for formulation of the spin.

Pieter Zeeman 1865-1943

Nobel 1902

1896 Discovered that spectral D line of Sodium emission splits when the flame is inside a magnetic field: Zeeman effect. Explained by **Lorentz** in his theory of the electron. The present explanation is the interaction energy of the electron spin with the magnetic field.



magnetic field
off



magnetic field
on

1892 Proposed a theory that charged particles contain excess of sub-particles charged positively or negatively, and electric current is a current of particles creating electromagnetic fields defined at every point in space by electric and magnetic vectors. Lorentz accepted “drift coefficient” of light derived from **Fresnel** interference.

The theory is incompatible with Michelson-Morley’s experiment.

1892 Explained Michelson-Morley’s result by contraction of length (like Fitz Gerald).

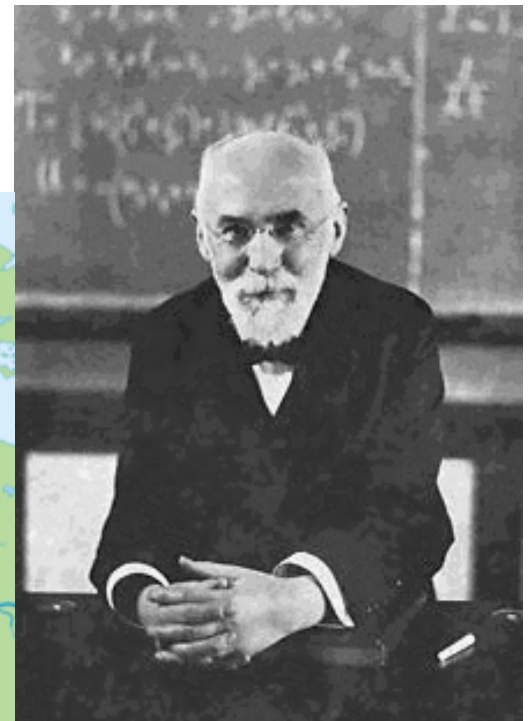
1895 Used the term “ions” for charged particles. Formulated an equation relating electric field to particles.

1895 Searching for electro-optical theory of moving bodies, presented Lorentz transformation first order in v/c . He called the transformed time “local time”.

1899 Treated mathematically his hypothesis of contraction of fast moving electrons.

1904 Space-time transformation that was used by Einstein in his special relativity. Theoretical explanation of **Zeeman’s effect** the magnetic “splitting” of emission lines from electron transitions in atoms.

1918-26 After WWI Lorentz participated in social committees, and solved numerically the tide effect on the dams along the Atlantic coast of Holland and Denmark.



Pierre Curie 1859 –1906 & Marie Sklodowska-Curie 1867-1934

Nobel 1903

1895 Pierre married his lab assistant, Marie, a Jewish emigrant from Poland.

Marie studied radiation from Uranium, and discovered that it turns air to be conductive.

1898 Pierre and Marie isolated Radium and Polonium from torbernite & pitchblende ores that emitted much stronger radiation than uranium. They named it “Radioactivity”, and claimed it is an atomic phenomenon.

1906 Pierre died in horse carriage accident.

1910 Marie has a love affair with Pierre's student, **Paul Langevin**.

1911 Marie received the second Nobel prize for isolating Radium and Polonium.

WWI Marie founded a radiological unit (X-rays) for treating wound soldiers.

1921 Touring the USA rose a wave of hysteric favor to Radium as a magic cure. Added to toothpaste, creams, etc.

1934 Marie died from Leukemia induced by excess radiation. She was the first woman to be buried in the Pantheon.

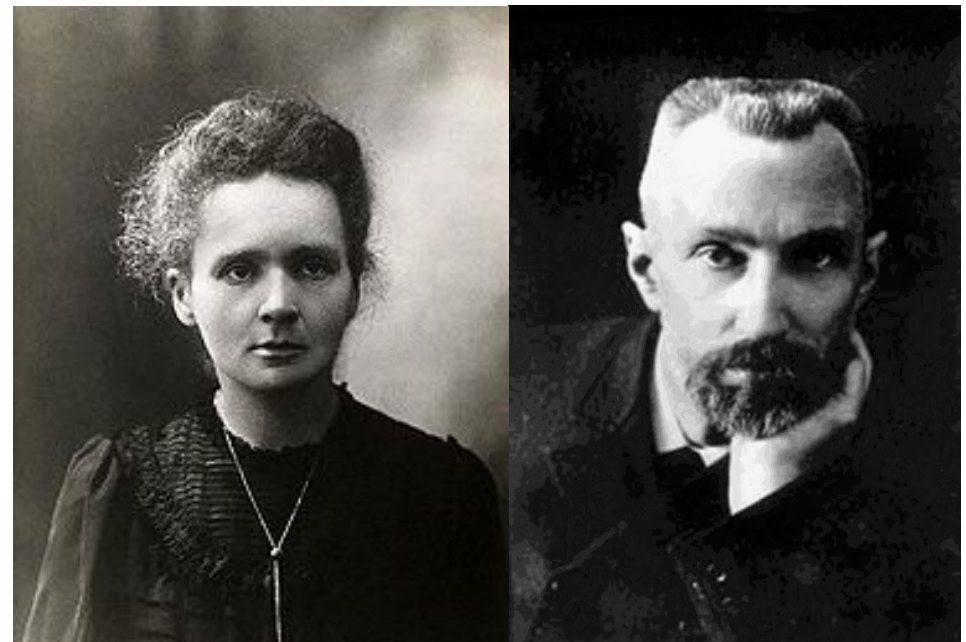
The unit of radioactive radiation
is named after them:

1 Curie=

3.7×10^{10} decays per second

8.9×10^{-16} Moles/sec

2.8×10^{-6} Moles/year



Philip Lenard 1862-1947

1894 Studied permeability of cathode rays in materials.

William Ramsay 1852-1916

1895 Discovered Helium in spectroscopic analysis of the gas created from Uranium disintegration. (Alpha rays are Helium atom).

William Ramsay & Morris Travers 1872-1961

1898 Discovered Neon, Krypton, Xenon and negatively charged particles – beta rays.

Wilhelm Wien 1864-1928

1897 Created tunnel rays with positive charge (named by **E. Goldstein**) and measured q/m ratio much lower than cathod rays: developed the basis for mass spectrometry.

1898 Discovered in gas, ions flowing: Protons: charged particle with hydrogen atomic mass.

MASS SPECTROMETER

Eugen Golstein 1850-1930

1886 Discovered negative particles (tunnel rays) moving from the cathode to the anode.

1899 Found that the particles are displaced in perpendicular electric and magnetic fields (both perpendicular to the rays direction), and that the displacement is proportional to the ration of charge to mass, q/m

Thomson improved the vacuum, and developed the mass spectrometer.

Explanation: Lorentz law:

The force executed on particles by the magnetic field is proportional to velocity, v and perpendicular to it: $\mathbf{F} = Q (\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Newton's law: $\mathbf{F} = m\mathbf{a}$

Therefore: $(m/Q)\mathbf{a} = \mathbf{E} + \mathbf{v} \times \mathbf{B}$

Force is perpendicular to the velocity, therefore it v is unchanged, and the acceleration is centripetal in circular orbit.

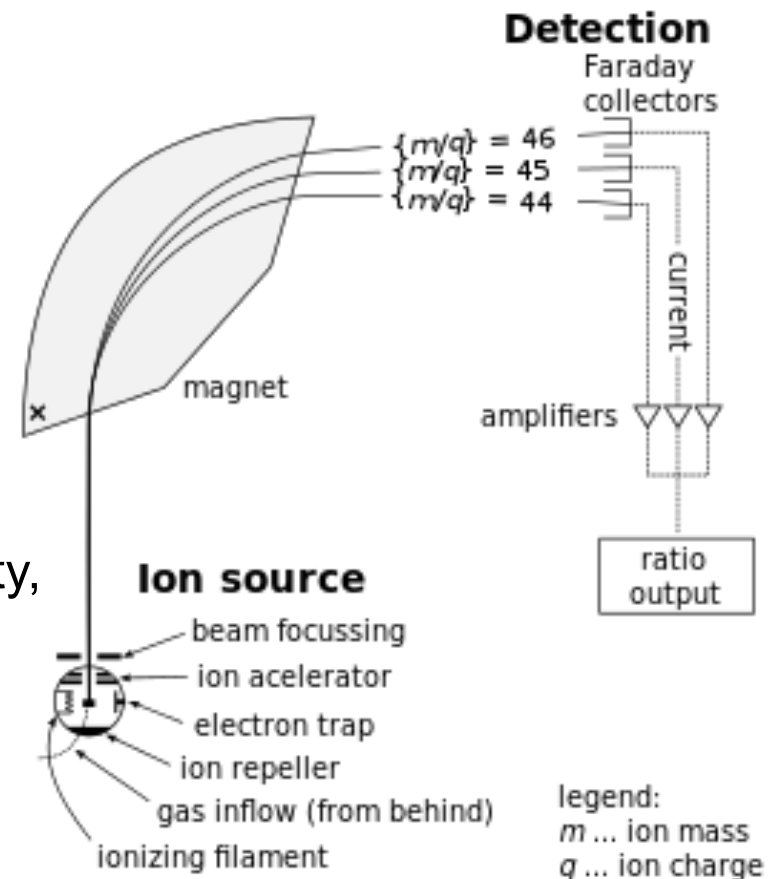
Hence the displacement, $\mathbf{D} = Q/m \cdot \mathbf{v} \cdot \text{const}$

Charged particles are injected with a given energy by Accelerating in a voltage V along a path L , with velocity, v :

$$E = V/L \quad F = EQ = ma \Rightarrow a = VQ/mL \quad V = \text{volts}$$

$$L = at^2/2 \Rightarrow t = \sqrt{2L/a} = \sqrt{2L^2m/VQ}$$

$$v = at = VQ/mL \cdot \sqrt{2L^2m/VQ} = \sqrt{2VQ/m}$$



Johann Jacob Balmer 1825-1898

1885 Fitted a mathematical equation to the wavelengths of the emission lines from Hydrogen:

$$\lambda = \frac{hm^2}{m^2 - n^2}$$

1854-1919 Johannes Rydberg

1888 Similar formula independently derived:
This formula inspired ideas about energy levels of electronic states in quantum mechanical atoms.

$$\frac{1}{\lambda_{\text{vac}}} = R \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

Walther Nernst 1864 – 1941

1918 Proposed chain reaction for chemistry, that was realized in nuclear physics.

ASTRONOMY

ASTRONOMY AND RELATIVITY

Johann Georg von Soldner 1776-1833

1801 Based on Newton's light particles theory, calculated the gravitational displacement of rays from a star by the sun to be 0.84 arc seconds. A decade later, relativity predicted twice displacement – Half from gravitation and half from the bending of space-time universe.

Bernhard Riemann 1826-1866

1859 Extended Gauss differential geometry to n-Dimensions: the mathematical foundations of Relativity.

Albert A. Michelson 1852 –1931

1890 Described the advantages of interferometry in determination of the angle of view and brightness of star sources that are below the telescope resolution.

Jules Henri Poincaré 1854 –1912

1892 Published the first of three volumes about stellar mechanics: many body problem. Showed that the differential equation is not integrable, and is therefore chaotic, due to resonances between degrees of freedom (as harmonic oscillator). Showed that Maxwell's equations are invariant to Lorentz space-time transformation. This is an important statement for the mathematical foundations of Relativity.

1898 Assumed that light is the limiting speed of particles, and is a constant: a relativistic idea.

Poincaré was one of the pioneers of topology. Poincaré's conjecture (see Mathematics) was only proved at **2006** by Gregory Fearlman.



Ludwig Boltzmann 1844 –1906

1897 Responding to **Ernst Zermelo's** time reversibility, he described the universe in thermal equilibrium (that is: dead) apart from a few small regions (like our galaxy) that at certain times go out of equilibrium and allow life to happen.

Jacobus Cornelius Kapteyn 1851-1922

1897 During measurements of star motion he found "star streaming" towards and away from the center of the galaxy.

VARIA

Johann Wolfgang von Goethe 1749-1832

A famous romantic poet, who was proud in his scientific books – although had no influence on temporary scientists.

Made experiments in colors (with wrong conclusions...), and devised a morphological classification method for plants and animals different than Linnaeus.

Alexander von Humboldt 1769 –1859

A geographer, geologist and biologist. Traveled 1799-1804 in the Amazonas forests and the Orinoco, with the French **Aimé Bonpland**. Later he also traveled to Russia. He believed in experiments and collection of facts, and not on theoretical philosophy. Was first to propose that the two sides of the Atlantic were separated from one ancient continent.

The Humboldt University in Berlin was founded by his brother, Wilhelm, who inherited the family fortune and continued to run their business.

Humboldt admired Gauss, and invited him to Berlin – the only case that Gauss left his home in Göttingen.

Jules Verne 1828-1905

The father of science fiction. Predicted many technologies decades before they materialized, but also invented many facts that are wrong.

1865 Published “A voyage to the moon” with a racket sent from Florida...

1864 “Journey to the Center of the Earth”, starting and ending at a volcano, inspired by Lyell.

1870 “Twenty Thousand Leagues Under the Sea” in the submarine Nautilus and Captain Nemo.

1873 “Around the World in Eighty Days” Felias Fogg and Paspарту his helper, who won the bid since they gained a day going against earth rotation.



SCIENTIFIC PRINCIPLES

Hans Christian Ørsted 1777-1851

1812 Defined the concept of “thinking experiment”:– *Gedanken Experiment*.

Charles Sanders Pierce 1839-1919 & Joseph Jastrow 1863-1944

1885 Defined “blind experiment”.

Joseph Fourier 1768-1830

1822 Presented the use of physical dimensions, and their balancing in formulae.

William Whewell 1795-1866

1840 Used “scientist” replacing “natural philosopher”.

Augustus de Morgan 1806-1871

1847 Published the first scientific bibliography..

CHEMISTRY

SPECTROSCOPY AND DISCOVERY OF NEW ELEMENTS



William Herschel 1738-1822 & Caroline Herschel 1750-1848

1800 Herschel dispersed sunlight by a prism to form the rainbow spectral colors from violet to red, and discovered infrared by a heated thermometer beyond the red light.

Johann Wilhelm Ritter 1776-1809 Germany

After Herschel discovered the heating radiation (infrared) Ritter searched a cooling radiation beyond the violet of the spectrum.

1801 Discovered the ultraviolet radiation, that did not cool, but disintegrated AgCl forming free silver. From this result he developed photographic plates.

William Hyde Wollaston 1766-1828

1802 Discovered dark spectral lines in sunlight spectrum. This is an important finding not only to identify gases in the sun, but as a tool to study atomic structure.

Sir William Crookes 1832-1919

1861 Discovered Thallium by spectroscopy

William Huggins 1824-1910

1863 Collected spectra from stars, and demonstrated gases similar to the sun..

Osmond Fisher 1817-1914

1895 Isolated Helium, named after the god of the sun, Helios, since its absorption dark lines were found in the sun spectrum.

Humphry Davy 1778-1829

1798 Studied breathing of gases, and became addicted to NO - laughing gas. Many years passed before it was used for dentists anesthesia.

1808 Isolated a series of new elements by electrolysis: Potassium K, Sodium Na, Magnesium Mg, Calcium Ca, Strontium St, Barium Ba, and Aluminum Al.

1810 Isolated chlorine, 36 years after **Scheele**, and proved it is an element.

1815 Invented the safe lamp for coal mines, preventing flame from exiting the iron net.

Davy became a public figure since he popularized chemistry.

He understood that chemical properties depend on the compounds and the atomic structure: (diamond and graphite are the same element in different structure). He realized that not all acids contain hydrogen, but not necessarily oxygen (not as Lavoisier thought). Heat is generated when oxygen binds other compounds. And he discovered that oars are metal oxides.

He defined the chemical bond as attraction between electric charges.



Joseph Louis Proust 1754-1826

1799 The law of constant ratios of atoms in compounds, stoichiometry, that motivated Dalton's atomic theory.

John Dalton 1766-1844

1801-2 The law of partial pressure in gas mixtures.

$$p_{\text{total}} = \sum_{i=1}^n p_i$$

1808 Law of integer ratios in reactions between gases.

The atomic theory: 1. Elements are composed of atoms.

2. All atoms of the same element are identical in size and mass.

3. Atoms are unbreakable, cannot be created or destroyed.

4. Atoms of different elements react together to form molecules at integer ratios that is always the same for each compound.



Dalton and his brother were color blind, therefore he concluded it is a inherited feature.

Lorenzo Romano Amadeo Carlo Avogadro 1776-1856

1811 Equal volumes of gas at the same temperature and pressure contain the same number of molecules.

Hence gas weight is proportional to the atomic weight, and hence the definition of "Mole": 1 Mole contain Avogadro's number of molecules = $6.02214179 \times 10^{23}$ (the number was actually evaluated later and named after Avogadro)



**Johann Wilhelm Ritter 1776-1810, William Nicholson 1753-1815
& Anthony Carlisle 1768-1840**

1800 Produced oxygen and hydrogen from water by electrolysis with Volta cell.

William Hyde Wollaston 1766-1828

1803 Discovered Paladium.

Jöns Jacob Berzelius 1779-1848

1806 Noted, in a book on chemistry of life, that muscles contain milk acid (isolated from milk by Scheel).

Pierre Louis Dulong 1785-1838

1811 Discovered Nitrogen trichloride – NCl_3 an explosive oil.

Gottlieb Konstantin Sigizmundovich Kirchhoff 1764-1833

1815 Reported that Gluten from wheat is converted into dextrin and sugar.

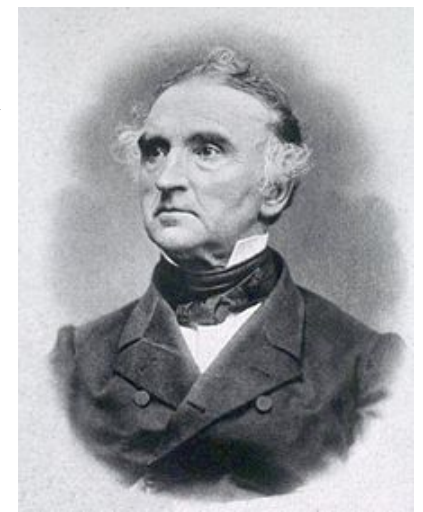
Eilhard Mitscherlich 1794-1863

1822 Discovered “isomorphism” similar crystals to different materials. Concluded that crystal structure depends on the number and arrangement (coordination number) of the atoms, but not their identity.

Justus von Liebig 1803-1873

Among the fathers of organic chemistry. Worked with **Friedrich Wöhler** (the synthesizer of Urea) and was a pioneer in educating organic chemistry and designing modern laboratory tools.

1840 Found that rate of plants growth is not determined by the major compounds (water air) but by minute necessary ones, such as minerals (mainly Nitrates) “law of limiting factors”. This drove to artificial fertilization.



John Bennett Lawes 1814-1900

1837-8 Started plant growing experiments in pots, and moved to agricultural farm, where he implemented fertilization with superphosphates (phosphates treated by sulfuric acid)



Osmond Fisher 1817-1914

1895 Isolated Helium. Named after the god of the sun, Helios, since its spectral lines were found as dark (absorption) lines in sun light.



Claude-Louis Berthollet 1748-1822

With **Laviosier** and others – determined the signs for the chemical Elements (one or two letters).

1785 Discovered that the rate of a chemical reaction is proportional to the density of the reactants and the strength of the affinity between them.

He understood that the inverse reaction existed, and hence there are equilibrium concentrations in chemical reactions between reactants and products.



Jöns Jakob Berzelius 1779-1848 Swedish



1808 Proposed name system for the elements, two letters abbreviation and the method of annotating chemical reactions, including the type and number of the reactants and products and their balancing. The number of atoms is a lower index. (Later atomic weight of the isotope in upper index).

Berzelius did not believe in ordering properties of chemicals, i.e. by molecular weight.

1817 Isolated Selenium and in the lab of **J. A. Arfwedsen** discovered Lithium.

1828 Discovered Thorium.

1830 Isolation of Vanadium in the lab of **N. G. Sefström**

1840 Proposed the name “Allotropy” for several forms of the same compound.

William Robert Grove 1811-1896 Scotland

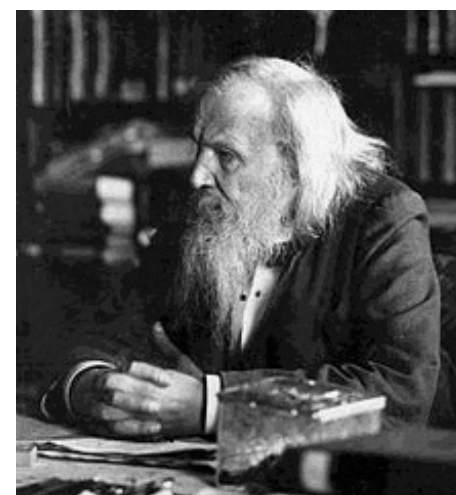
1842 Showed heat decomposition of molecules into their components. Steam is decomposed into oxygen and Hydrogen, and they recombine to form water when cooled. Anticipated conservation of energy. Developed the first fuel cell: combining hydrogen and oxygen generates electricity.



Dmitri Ivanovich Mendeleev 1834–1907

1869 Published the periodic table of 66 known elements, Rows are according to atomic weight, and columns are by Similarity of properties. He left vacancies where he predicted yet undiscovered elements and cited their properties.

1871 A thorough inspection into the periodic table lead to predict the elements Galium, Scandium and Germanium.



William Ramsay 1852-1916 Nobel 1904

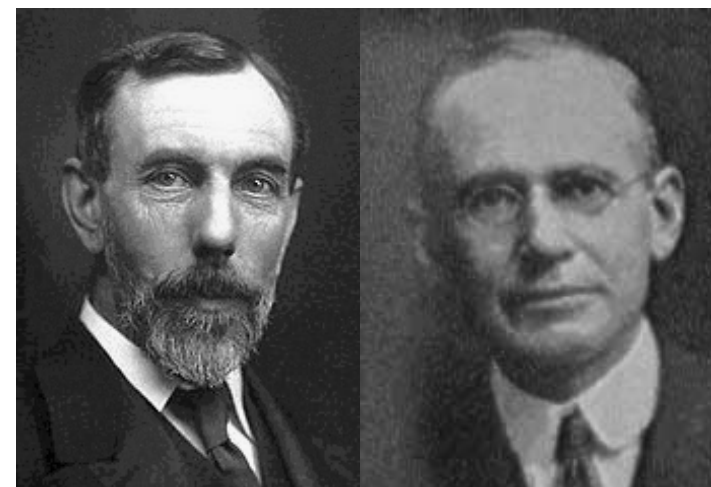
& Morris William Travers 1872-1906

Liquefied air, determined the phase transition temperature, and applied to purify noble gases from air

1898 Isolated the noble gases Neon, Xenon and Krypton.

Argon was discovered by **Lord Raleigh**.

They also positioned the gases in the periodic table.



THE PERIODIC TABLE OF THE ELEMENTS

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb				
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No				

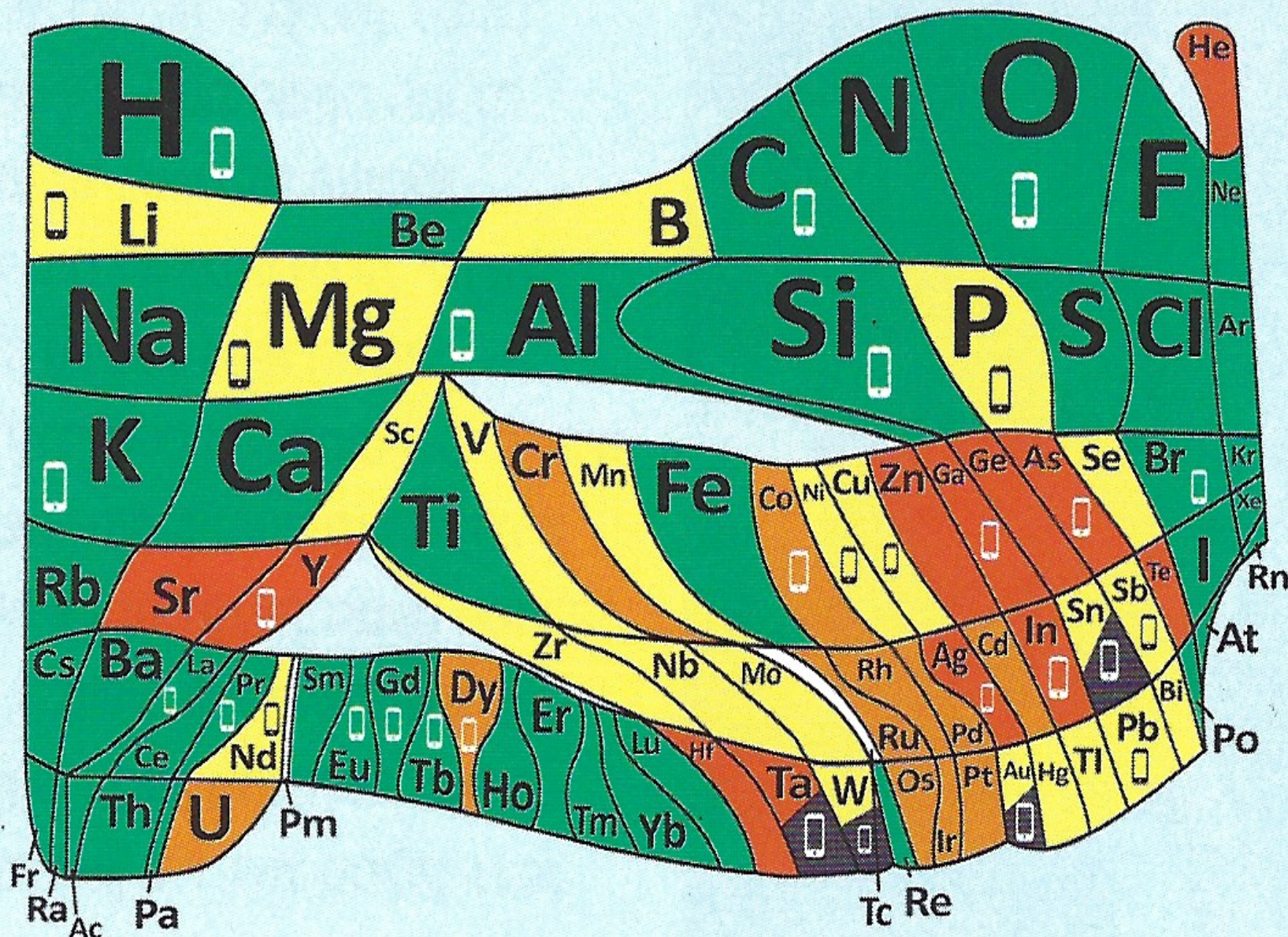


United Nations
Educational, Scientific and
Cultural Organization



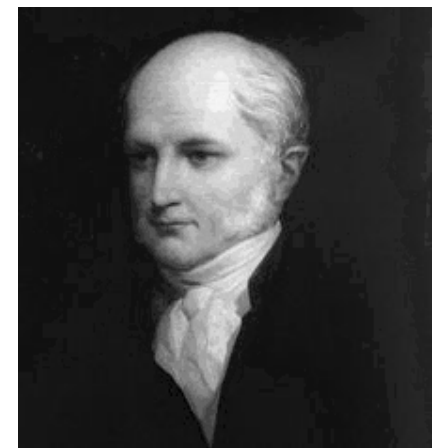
International Year
of the Periodic Table
of Chemical Elements

An interesting presentation of 90 elements of the periodic table:
each element is in a box sized according to their abundancy
on earth



William Prout 1785-1850

1815 Atomic weight is an integer multiple of the weight of hydrogen – wrongly assumed that all atoms are clusters of hydrogen atoms.

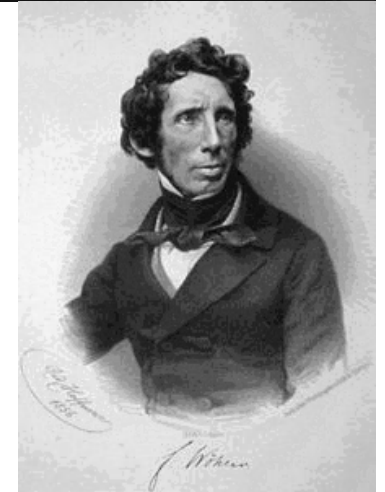


Friedrich Wöhler 1800-1882

1825 Discovered isomeres with **Justus von Liebig** (the name is after Berzelius) - Different arrangement of the same atoms in a molecule.

1828 Synthesized Urea – the first organic molecule synthesized from inorganic compound - ammonium cyanate. End of “Vitalism”.

1832 Characterized radicals in reactions.



Johann Wolfgang Döbereiner 1780-1849

1823 Discovered that a stream of hydrogen aimed at black platinum plating turns it red then white from heat, then ignite a flame burning the hydrogen.

Built a gas ignitor without flame. This brought Berzelius to the idea of catalysis (understood that also fermentation of sugar is a catalytic process).

1829 Attempting to classify the elements, he found triplets of elements where the properties of one is the average of the other two.

Michael Faraday 1791-1867

1825 Isolated Benzene – the first aromatic molecule.

Friedrich August Kekulé von Stradonitz 1829-1896

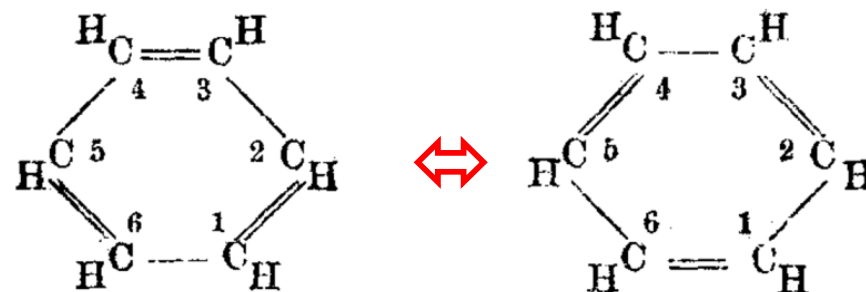
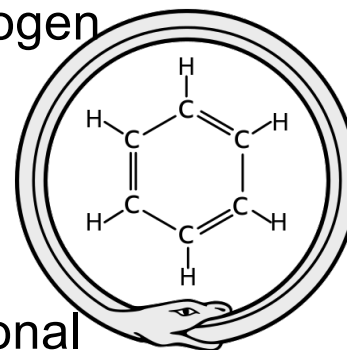
1865 Understood that Benzene contain carbon and hydrogen atoms in Hexagonal structure (the story tells he dreamed about a snake biting his tail): ring molecules.

1857-8 One of the founders of structural chemistry.

He proposed that carbons make chain molecules.

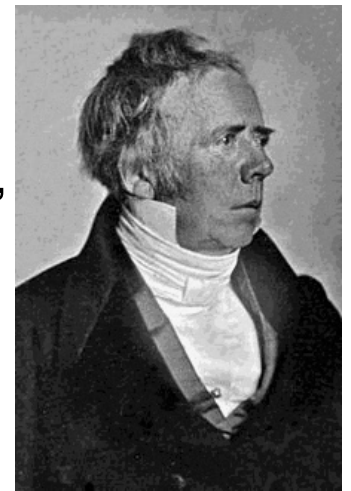
Archibald Scott Couper independently drew the hexagonal Structure, where lines denote “affinity unit”, chemical bond between atoms. From knowledge of the affinity (Carbon affinity is 4). Organic Chemistry developed very fast. The ring structure was deduced from the number of isomers. When the hydrogens are replaced by two atoms: C_6H_5X & $C_6H_4(NH_2)(CH_3)$ 1 and 3 isomers were found.

The double bond was still a puzzle – solved by **Kekulé** in a model of switching double / single bonds.



Hans Christian Ørsted 1777-1851

1825 Following **Davy's** he claim that "Alum" is a salt from unknown metal, Ørsted isolated Aluminum by heating the salt with Potassium amalgam.

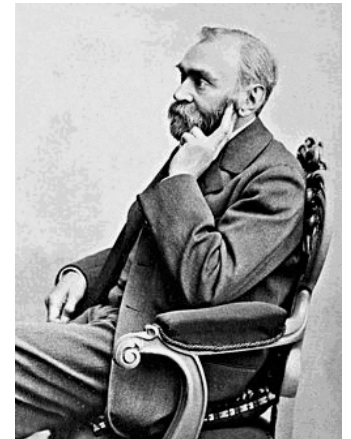


Thomas Graham 1805-1869

1833 Studied the capability of forming several types of salts: multi-base phosphate compounds: bi- and tri-phosphates.

Anselme Payen 1795-1871

1833 Isolated the first enzyme: diastase.



William Morton 1819-1868

1846 A dentist who started use of anesthesia (NO).

Ascani Sobrero 1812-1888

1846 Discovered nitroglycerin.



Alfred Nobel 1833-1896

1866 Registered a patent on Dynamite.

Germain Hess 1802-1850

1840 Hess law – an early version of energy conservation law: Energy change in a chemical reaction depends only on the initial and final states, not the intermediates.

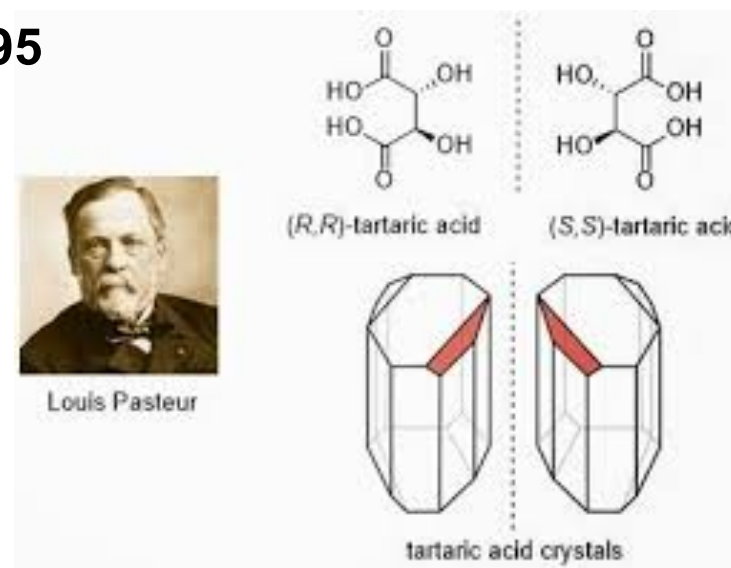
Christian Friedrich Schönbein 1799-1868

1840 Isolated Ozone (the name comes from the smell).

Also: Fuel cell, Nitrocellulose

Louis Pasteur 1822-1895

1848 Discovered that synthesized tartaric acid contain a mixture of „Levo“ and „Dextro“ conformations – (racemic mixture) – while crystals contain only one conformation: The birth of stereochemistry.



Benjamin Silliman, Jr. 1816-1885

1855 Developed a pioneering method for fractional distillation of rock oil (petroleum) and industrial production of Kerosene – birth of petrochemical industry.

Friedlieb Ferdinand Runge 1794-1867

1931-4 Isolated carbolic acid, leucol, pyrol, and cyanol from distillation of coal tar. He synthesized Black-Aniline from cyanol, and patented it at 1934

1850 Developed paper chromatography – high resolving power separation of compounds.

William Henry Perkin 1838-1907

1855 Synthesized the first purple paint – mauveine, in an attempt to isolate quinine from coal tar.

1857 Birth of the paint industry.

Johann Friedrich Wilhelm Adolf von Baeyer 1835-1917

Nobel 1905

1865 Started his work on hydro-aromatic Indigo paints- a milestone in organic chemistry and paint industry.

Merck Company

1859 Isolated Cocaine and patented it.

Adolf Wilhelm Hermann Kolbe 1818-1884

1845 Synthesized Acetic acid

1859 Synthesized salicylic acid

Gustav Robert Kirchhoff 1824-1887 & Robert Bunsen 1811-1899

1859-90 Established the foundations of spectroscopy for chemical analysis.
Discovered and isolated Cesium, Rubidium, Indium, Helium and other new elements.

1860 Interpreted **Fraunhofer's** black lines in sunlight by Helium absorption at the periphery of the sun. A proof that stars have the same elements as earth.

Bunsen explained the action of Geysers.

Invented the Bunsen burner and other chemical lab equipment.

Sir William Crookes 1832-1919

1861 discovered Thallium by spectroscopy,

Anders Jonas Ångström 1814-1874

1861 Confirmed the Helium atmosphere around the sun by spectroscopy.

Stanislao Cannizzaro 1826-1910

1860 Using Avogadro's principle, he edited elements table by atomic weight as multiples of hydrogen weight (atomic number). He understood that hydrogen gas molecules are two hydrogen atoms. This led to Mendeleev periodic table.

Coined the name "Hydroxyl" to OH radical.

Johann Josef Loschmidt 1821-1895

1865 Determined the number of molecules in 1 Mole and named it Avogadro number.
Used the kinetic theory of gases, giving the mean free path between collisions, l , as a function of molecules diameter and number, n_0 , which he got by estimating l .

Alexander Parkes 1813-1890

1862 Presented Parkesine in an exhibition in London, a synthetic polymer. The birth of plastic industry.

**Alexandre-Emile Béguyer de Chancourtois John Newlands 1820-1886
& William Odling 1829-1921**

1862 Early models of the periodic table. 57 elements, including unknown vacancies.
:The telluric helix – “rule of octaves”: every 8th elements has similar properties.

John Alexander Reina Newlands 1820-1886

1864 The first two dimensional periodic table by weight and octave rule.

Julius Lothar Meyer 1830-1895

1864 Organized the elements by valency. The compounds dependence on atomic weight has properties periodicity.

Dmitri Ivanovich Mendeléeiev 1834-1907 & Julius Lothar Meyer 1830-1895

1869 Independently built the periodic table of the chemical elements. **Meyer** showed that **Newlands** octave rule is true in the first two cycles only. Meyer also plotted the atomic volume vs. the atomic weight.

Jacobus Henricus van 't Hoff 1852-1911

Nobel 1901

1873 Chemical Reactions kinetics.

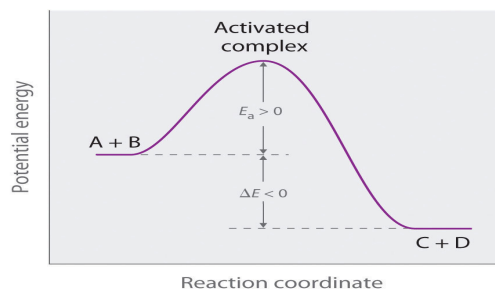
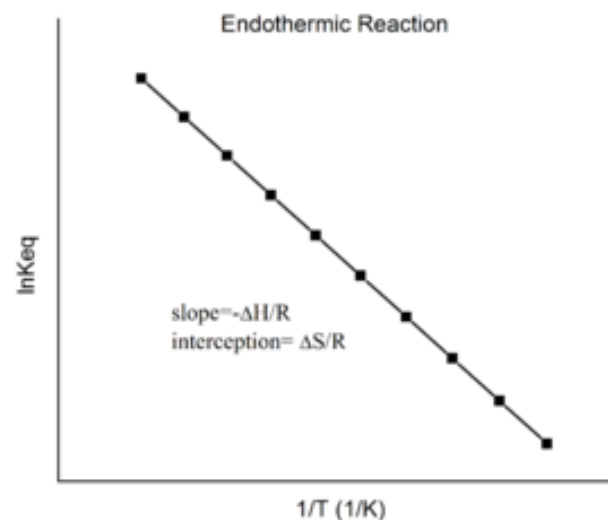
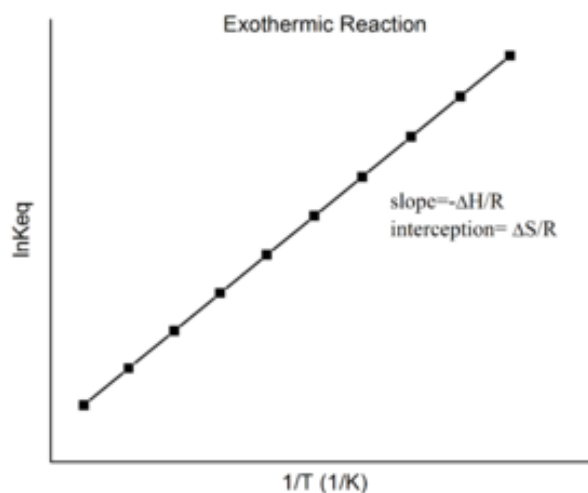
Jacobus Henricus van 't Hoff & Joseph Achille Le Bel 1847-1930

1873 Worked independently on a three-dimensional model for chemical bonds, that explains Pasteur's optical activity. Van't Hoff's Equation relates the reaction constants to the activation energy ΔH and the temperature T .

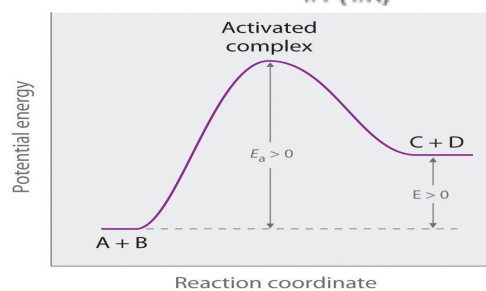
$$\ln \left(\frac{K_2}{K_1} \right) = \frac{-\Delta H^\ominus}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right).$$

The slope is determined by sign of ΔH : the reaction is Endothermic or Exothermic.

1873 Chemical and osmotic equilibrium in conducting solutions.



(a)



(b)

Exothermic and Endothermic reactions

Alfred Werner 1866-1919

1893 Discovered the octahedral structure of Cobalt compounds – three-dimensional structure.

Henri Moissan 1852-1907

Nobel 1906

1886 Isolated Fluorine by electrophoresis and studied it.
Invented an electric arc furnace that carries his name.

Eduard Buchner 1860-1917

Nobel 1907

1897 Cell-free fermentation (pressed yeast extract).

J. de Rey-Pailhade 1850-1934

1888 Discovered Philothion (Glutathion) – a small molecule from living source with so many reducing functions that it was connected to the “essence of life”. For example, it turns Sulfur into Hydrogen Sulfate (hence the name – Thio-Sulfur Affinity-philos)

James Dewar 1842-1923

1898 Liquidated Hydrogen

Gottlieb Daimler 1834-1900

1883 Registered a patent for internal combustion engine.

John William Strutt, 3rd Baron Rayleigh 1842-1919 England **Nobel 1904**

1894 Together with **William Ramsay** they discovered the noble gas Argon, first by spectroscopy and later by the different weight of what was left after clearing oxygen and nitrogen from air and from ammonia.

John Wesley Hyatt 1837-1920

1869 Produced Celluloid – the first synthetic plastic to find wide use.

Hilaire de Chardonnet 1839-1924

1884 Invented the first artificial cloth made of cellulose – Rayon: artificial silk.

Hermann Emil Fischer 1852-1919 Nobel 1902

1898 Proposed the structure of purines, and synthesized them.
Studies the chemistry of sugars.

Thomas Chrowder Chamberlain 1843-1928

1899 Interested in the behavior of materials under extreme conditions, such as the sun, assuming they can accept much higher energies than normal, and explain how earth (from fosile findings) is older than the sun (based on estimation of its decaying energy). Later, relativity explained the source of energy in the sun from fusion.

ELECTROLYTES

ELECTROLYTES

Nobel 1920

Walther Nernst 1864 – 1941

1888 A theory for the electric potential in ionic solutions and batteries. Applied in ionic flow via biological membranes: membrane potential.

$$E = \frac{RT}{zF} \ln \frac{[\text{ion outside cell}]}{[\text{ion inside cell}]} = 2.3026 \frac{RT}{zF} \log_{10} \frac{[\text{ion outside cell}]}{[\text{ion inside cell}]}.$$

R is the universal gas constant: $R = 8.314\,472(15) \text{ J K}^{-1} \text{ mol}^{-1}$

F is the Faraday constant, the number of coulombs per mole of electrons:

$F = 9.648\,533\,99(24) \times 10^4 \text{ C mol}^{-1}$

z is the number of moles of electrons transferred in the cell reaction or half-reaction

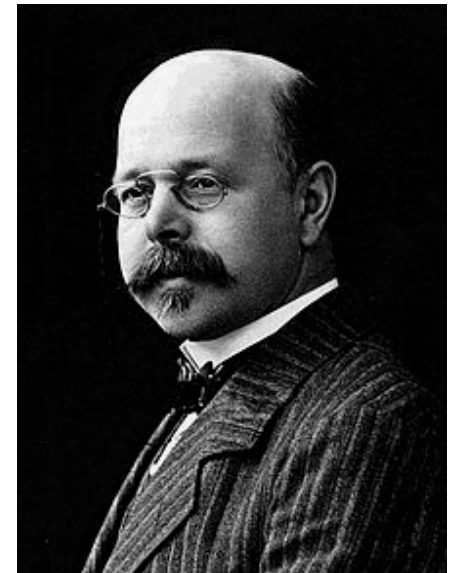
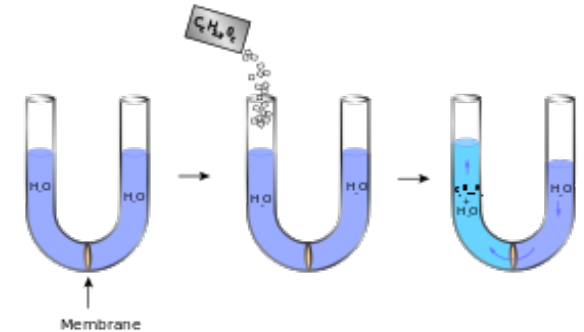
Osmotic pressure in membrane impermeable to ions, but letting water pass.

1897 Invented incandescent lamp with ceramic filament.

1903 Filament from rare Metal oxides: Nernst IR glower.

1905 The 3rd law of thermodynamics – approach to absolute zero, entropy diminished. Measured free energy and chemical equilibrium.

1918 Chain reactions – the idea was about chemistry but was realized for nuclear reactions.



Svante August Arrhenius 1859 –1927

Nobel 1903

1883 Attributed conductivity in salt solutions to electrolyte currents.

1887 Concluded that in dilute solutions of electrolytes acids, bases and salts are decomposed into positive and negative ions, according to van't Hoff's equilibrium.

1889 Presented the idea of chemical reaction activation energy, connecting it to the reaction kinetic rate constants:

Defined a pH as the negative log of the activity of H⁺ ions (activity is proportional to molar concentration)

$$k = Ae^{-E_a/(RT)}$$

$$\text{pH} = -\log_{10}(a_{\text{H}^+}) = \log_{10} \left(\frac{1}{a_{\text{H}^+}} \right)$$



DAVY MEDAL in CHEMISTRY

**Awarded by
The British Royal Academy,
London**

1877 **Robert Wilhelm Bunsen and Gustav Robert Kirchhoff** "For their researches & discoveries in spectrum analysis"

1878 **Louis Paul Cailletet and Raoul Pictet** "For their researches, conducted independently, but contemporaneously, on the condensation of the so-called permanent gases"

1879 **Paul Emile Lecoq de Boisbaudran** "For his discovery of gallium"

1880 **Charles Friedel** "For his researches on the organic compounds of silicon, and other investigations"

1881 **Adolf von Baeyer** "For his synthesis of indigo"

1882 **Dmitri Mendeleev and Lothar Meyer** "For their discovery of the periodic relations of the atomic weights"

1883 **Marcellin Berthelot and Julius Thomsen** "For their researches in thermo-chemistry"

1884 **Adolph Wilhelm Hermann Kolbe** "For his researches in the isomerism of alcohols"

1885 **Jean Servais Stas** "For his researches on the atomic weights"

1886 **Jean Charles Galissard de Marignac** "For his researches on atomic weights"

1887 **John Alexander Reina Newlands** "For his discovery of the periodic law of the chemical elements"

1888 **Sir William Crookes** "For his investigations on the behaviour of substances under the influences of the electric discharge in a high vacuum"

1889 **Sir William Henry Perkin** "For his researches on magnetic rotation in relation to chemical constitution"

1890 **Emil Fischer** "For his discoveries in organic chemistry and especially for his researches on the carbo-hydrates"

1891 **Victor Meyer** "For his researches on the determination of vapour densities at high temperatures"

1892 **Francois Marie Raoult** "For his researches on the freezing points of solutions, and on the vapour pressures of solutions"

1892 **Jacobus Henricus van 't Hoff and Joseph Le Bel** "In recognition of their introduction of the theory of asymmetric carbon, and its use in explaining the constitution of optically active carbon compounds"

1894 **Per Theodor Cleve** "For his researches on the chemistry of the rare earths"

1895 **Sir William Ramsay** "For his share in the discovery of argon, and for his discoveries regarding gaseous constituents of terrestrial minerals"

1896 **Henri Moissan** "For the isolation of fluorine, and the use of the electric furnace in the preparation of refractory metals and their compounds"

1897 **John Hall Gladstone** "For his numerous contributions to chemical science, and especially for his important work in the application of optical methods to chemistry"

1898 **Johannes Wislicenus** "For his contributions to organic chemistry especially in the domain of stereochemical isomerism"

1899 **Edward Schunck** "For his researches on madder, indigo, and chlorophyll"

APPENDIX:

Laureates of the Copley Medal 19th Century

**Awarded by
the British Royal Academy of Sciences**

- 1800 **Edward Charles Howard** "For his Paper on a New Fulminating Mercury"
- 1801 **Astley Cooper** "For his Papers – on the effects which take place from the destruction of the Membrana Tympani of the Ear; with an account of an operation for the removal of a particular species of Deafness"
- 1802 **William Hyde Wollaston** "For his various Papers printed in the Philosophical Transactions"
- 1803 **Richard Chenevix** "For his various Chemical Papers printed in the Philosophical Transactions"
- 1804 **Smithson Tennant** "For his various Chemical Discoveries communicated to the Society, and printed in several volumes of the Philosophical Transactions"
- 1805 **Humphry Davy** "For his various Communications published in the Philosophical Transactions"
- 1806 **Thomas Andrew Knight** "For his various Papers on Vegetation, printed in the Philosophical Transactions"
- 1807 **Everard Home** "For his various Papers on Anatomy and Physiology, printed in the Philosophical Transactions" —
- 1808 **William Henry** "For his various papers communicated to the society, and printed in the Philosophical Transactions" —
- 1809 **Edward Troughton** "For the Account of his Method of dividing Astronomical Instruments, printed in the last volume of the Philosophical Transactions"

- 1811 **Benjamin Collins Brodie** "For his Papers printed in the Philosophical Transactions. On the influence of the Brain on the action of the Heart, and the generation of Animal Heat; and on the different modes in which death is brought on by certain Vegetable Poisons"
- 1813 **William Thomas Brande** "For his Communications concerning the Alcohol contained in Fermented Liquors and other Papers, printed in the Philosophical Transactions"
- 1814 **James Ivory** "For his various Mathematical Contributions printed in the Philosophical Transactions"
- 1815 **David Brewster** "For his Paper on the Polarization of Light by Reflection from Transparent Bodies"
- 1817 **Henry Kater** "For his Experiments on the Pendulum"
- 1818 **Robert Seppings** "For his Papers on the construction of Ships of War, printed in the Philosophical Transactions"
- 1820 **Hans Christian Ørsted** "For his Electro-magnetic Discoveries"
- 1821 **Edward Sabine** "For his various Communications to the Royal Society relating to his researches made in the late Expedition to the Arctic Regions."
- John Herschel** "For his Papers printed in the Philosophical Transactions."
- 1822 **William Buckland** "For his Paper on the Fossil Teeth and Bones discovered in a Cave at Kirkdale"

- 1823 **John Pond** "For his various Communications to the Royal Society"
- 1824 **John Brinkley** "For his various Communications to the Royal Society"
- 1825 **François Arago** "For the Discovery of the Magnetic Properties of substances not containing Iron. "For the Discovery of the power of various bodies, principally metallic, to receive magnetic impressions, in the same, though in a more evanescent manner than malleable Iron, and in an infinitely less intense degree."
- Peter Barlow** "For his various Communications on the subject of Magnetism."
- 1826 **James South** "For his observations of Double Stars, and his Paper on the Discordances between the Suns observed and computed Right Ascensions, published in the Transactions of the Society. For his Paper of Observations of the Apparent Distances and Positions of Four Hundred and Fifty-eight Double and Triple Stars, published in the present volume (1826, Part 1.) of the Transactions"
- 1827 **William Prout** "For his Paper entitled, On the ultimate Composition of simple alimentary substances, with some preliminary remarks on the analysis of organized bodies in general."
- Henry Foster** "For his magnetic and other observations made during the Arctic expedition to Port Bowen."

- 1831 **George Biddell Airy** "For his Papers, On the principle of the construction of the Achromatic Eye-pieces of Telescopes, – On the Spherical Aberration of the Eye-pieces of Telescopes, and for other Papers on Optical Subjects in the Transactions of the Cambridge Philosophical Society"
- 1832 **Michael Faraday** "For his discovery of Magneto-Electricity as detailed in his Experimental Researches in Electricity, published in the Philosophical Transactions for the present year."
- Siméon Denis Poisson** "For his work entitled, Nouvelle Theorie de l'Action Capillaire."
- 1834 **Giovanni Antonio Amedeo Plana** "For his work entitled, Theorie du Mouvement de la Lune"
- 1835 **William Snow Harris** "For his experimental investigations of the force of electricity of high intensity contained in the Philosophical Transactions of 1834"
- 1836 **Jacob Berzelius** "For his systematic application of the doctrine of definite proportions to the analysis of mineral bodies, as contained in his Nouveau Systeme de Mineralogie, and in other of his works."
- Francis Kiernan** "For his discoveries relating to the structure of the liver, as detailed in his paper communicated to the Royal Society, and published in the Philosophical Transactions for 1833."

1837 **Antoine César Becquerel** "For his various memoirs on the subject of electricity, published in the Memoires de l'Académie Royale des Sciences de l'Institut de France, and particularly for those on the production of crystals of metallic sulphurets and of sulphur, by the long-continued action of electricity of very low tension, and published in the tenth volume of those Memoires."

John Frederic Daniell "For his two papers on voltaic combinations published in the Philosophical Transactions for 1836."

1838 **Carl Friedrich Gauss** "For his inventions and mathematical researches in magnetism."

Michael Faraday "For his researches in specific electrical induction."

1839 **Robert Brown** "For his discoveries during a series of years, on the subject of vegetable impregnation"

1840 **Justus von Liebig** "For his discoveries in organic chemistry, and particularly for his development of the composition and theory of organic radicals."

Jacques Charles François Sturm "For his "Memoire sur la Resolution des Equations Numeriques," published in the Memoires des Savans Etrangers for 1835."

1841 **Georg Ohm** "For his researches into the laws of electric currents contained in various memoirs published in Schweiggers Journal, Poggendorffs Annalen and in a separate work entitled Die galvanische Kette mathematisch bearbeitet" [74]

1842 **James MacCullagh** "For his researches connected with the wave theory of light, contained in the Transactions of the Royal Irish Academy"

- 1843 **Jean-Baptiste Dumas** "For his late valuable researches in organic chemistry, particularly those contained in a series of memoirs on chemical types and the doctrine of substitution, and also for his elaborate investigations of the atomic weights of carbon, oxygen, hydrogen, nitrogen and other elements"
- 1844 **Carlo Matteucci** "For his various researches in animal electricity" [76]
- 1845 **Theodor Schwann** "For his physiological researches on the development of animal & vegetable textures, published in his work entitled Mikroskopische Untersuchungen uber die Uebereinstimmung in der Struktur u. dem Wachsthun der Thiese u. Bflanzen"
- 1846 **Urbain Le Verrier** "For his investigations relative to the disturbances of Uranus by which he proved the existence and predicted the place of the new Planet; the Council considering such prediction confirmed as it was by the immediate discovery of the Planet to be one of the proudest triumphs of modern analysis applied to the Newtonian Theory of Gravitation"
- 1847 **John Herschel** "For his work entitled Results of Astronomical Observations made during the years 1834, 1835, 1836, 1837 and 1838, at the Cape of Good Hope; being a completion of a telescopic survey of the whole surface of the visible heavens, commenced in 1825"

- 1848 **John Couch Adams** "For his investigations relative to the disturbances of Uranus, and for his application of the inverse problem of perturbations thereto"
- 1849 **Roderick Murchison** "For the eminent services he has rendered to geological science during many years of active observation in several parts of Europe; and especially for the establishment of that classification of the older Palaeozoic deposits designated the Silurian System, as set forth in the two works entitled The Silurian System founded on Geological Researches in England, and The Geology of Russia in Europe and the Ural Mountains"
- 1850 **Peter Andreas Hansen** "For his researches in physical astronomy"
- 1851 **Richard Owen** "On account of his important discoveries in comparative anatomy & palaeontology, contained in the Philosophical Transactions and numerous other works"
- 1852 **Alexander von Humboldt** "For his eminent services in terrestrial physics, during a series of years"
- 1853 **Heinrich Wilhelm Dove** "For his work on the distribution of heat over the surface of the Earth"
- 1854 **Johannes Peter Müller** "For his important contributions to different branches of physiology and comparative anatomy, and particularly for his researches on the embryology of the Echinodermata, contained in a series of memoirs published in the Transactions of the Royal Academy of Sciences of Berlin"

- 1855 **Léon Foucault** "For his various researches in experimental physics" [52]
- 1856 **Henri Milne-Edwards** "For his researches in comparative anatomy and zoology"
- 1857 **Michel Eugène Chevreul** "For his researches in organic chemistry, particularly on the composition of the fats, and for his researches on the contrast of colours"
- 1858 **Charles Lyell** "For his various researches and writings by which he has contributed to the advance of geology"
- 1859 **Wilhelm Eduard Weber** "For the investigations contained in his Maasbestimmungen and other researches in electricity, magnetism, acoustics"
- 1860 **Robert Bunsen** "For his researches on cacodyls, gaseous analysis, the Voltaire phenomena of Iceland; and other researches"
- 1861 **Louis Agassiz** "For his eminent researches in palaeontology and other branches of science, and particularly for his great works the Poissons Fossiles, and his Poissons du Vieux Gres Rouge dEcosse"
- 1862 **Thomas Graham** "For three memoirs of the diffusion of liquids, published in the Philosophical Transactions for 1850 and 1851; for a memoir on osmotic force in the Philosophical Transactions for 1854; and particularly for a paper on liquid diffusion applied to analysis, including a distinction of compounds into colloids & crystalloids published in the Philosophical Transactions for 1861"

- 1863 **Adam Sedgwick** "For his original observations and discoveries in the geology of the Palaeozoic Series of rocks, and more especially for his determination of the characters of the Devonian System, by observations of the order of superposition of the Killas rocks & their fossils in Devonshire"
- 1864 **Charles Darwin** "For his important researches in geology, zoology, and botanical physiology"
- 1865 **Michel Chasles** "For his historical and original researches in pure geometry"
- 1866 **Julius Plücker** "For his researches in analytical geometry, magnetism, & spectral analysis"
- 1867 **Karl Ernst von Baer** "For his discoveries in embryology and comparative anatomy, and for his contributions to the philosophy of zoology"
- 1868 **Charles Wheatstone** "For his researches in acoustics, optics, electricity and magnetism"
- 1869 **Henri Victor Regnault** "For the second volume of his Relation des Experiences pour determiner les lois et les donnees physiques necessaries au calcul des machines a feu, including his elaborate investigations on the specific heat of gases and vapours, and various papers on the elastic force of vapours"
- 1870 **James Prescott Joule** "For his experimental researches on the dynamical theory of heat"

- 1871 **Julius von Mayer** "For his researches on the mechanics of heat; including essays on: – 1. The force of inorganic nature. 2. Organic motion in connection with nutrition. 3. Fever. 4. Celestial dynamics. 5. The mechanical equivalent of heat"
- 1872 **Friedrich Wöhler** "For his numerous contributions to the science of chemistry, and more especially for his researches on the products of the decomposition of cyanogens by ammonia; on the derivatives of uric acid; on the benzoyl series; on boron, silicon, & their compounds; and on meteoric stones"
- 1873 **Hermann von Helmholtz** "For his researches in physics and physiology"
- 1874 Louis Pasteur "For his researches on fermentation and on pelerine"
- 1875 **August Wilhelm von Hofmann** "For his numerous contributions to the science of chemistry, and especially for his researches on the derivatives of ammonia"
- 1876 **Claude Bernard** "For his numerous contributions to the science of physiology"
- 1877 **James Dwight Dana** "For his biological, geological, and mineralogical investigations, carried on through half a century, and for the valuable works in which his conclusions and discoveries have been published"
- 1878 **Jean-Baptiste Boussingault** "For his long-continued and important researches and discoveries in agricultural chemistry"
- 1879 **Rudolf Clausius** "For his well-known researches upon heat"

- 1880 **James Joseph Sylvester** "For his long continued investigations & discoveries in mathematics"
- 1881 **Charles-Adolphe Wurtz** "For his discovery of the organic ammonias, the glycols, and other investigations which have exercised considerable influence on the progress of chemistry"
- 1882 **Arthur Cayley** "For his numerous profound and comprehensive researches in pure mathematics"
- 1883 **William Thomson (Lord Kelvin)** "For (1) his discovery of the law of the universal dissipation of energy; (2) his researches and eminent services in physics, both experimental & mathematical, especially in the theory of electricity and thermodynamics"
- 1884 **Carl Ludwig** "For his investigations in physiology, and the great services which he has rendered to physiological science"
- 1885 **August Kekulé** "For his researches in organic chemistry"
- 1886 **Franz Ernst Neumann** "For his researches in theoretical optics and electrodynamics"
- 1887 **Joseph Dalton Hooker** "For his services to botanical science as an investigator, author, and traveller"
- 1888 **Thomas Henry Huxley** "For his investigations on the morphology and histology of vertebrate and invertebrate animals, and for his services to biological science in general during many past years"

- 1889 **George Salmon** "For his various papers on subjects of pure mathematics, and for the valuable mathematical treatises of which he is the author"
- 1890 **Simon Newcomb** "For his contributions to the progress of gravitational astronomy"
- 1891 **Stanislao Cannizzaro** "For his contributions to chemical philosophy especially for his application of Avogadro's theory"
- 1892 **Rudolf Virchow** "For his investigations in pathology, pathological anatomy, and prehistoric archaeology"
- 1893 **George Stokes** "For his researches and discoveries in physical science"
- 1894 **Edward Frankland** "For his eminent services to theoretical & applied chemistry"
- 1895 **Karl Weierstrass** "For his investigations in pure mathematics"
- 1896 **Karl Gegenbaur** "For his life-long researches in comparative anatomy in all branches of the animal kingdom. etc., etc"
- 1897 **Albert von Kölliker** "In recognition of his important work in embryology, comparative anatomy, and physiology, and especially for his eminence as a histologist"
- 1898 **William Huggins** "For his researches in spectrum analysis applied to the heavenly bodies"
- 1899 **John William Strutt (Lord Rayleigh)** "In recognition of his contributions to physical science"

