Introduction to the class

Modern physics for engineers

David Miller

Why modern physics for engineers

Why modern physics for engineers?

Classical physics, e.g., up to about 1870, explains much about the world of large-scale physical engineering

mechanics, engines, electric power, radio transmission, …

But understanding and engineering much of the modern world

needs more science

Modern physics and everyday science

Modern physics for everyday science

- processes of chemistry
- properties of materials
- why some materials conduct electricity and others insulate
- physical basis of color and how light interacts with materials
- how light bulbs and LEDs actually work
- why the sun gives off the amount of light it does
- why the sun is the color it is

Modern physics and technology

Modern physics and technology

Without modern physics

- we would have none of the devices of the information age
  - no transistors
  - no lasers
  - no photodetectors
  - no hard drives or any other digital memory
  - no computers

Modern physics and technology

no optical fiber communications

so no internet

no televisions

no digital cameras

no mobile phones

no display screens

no solar cells

no LED lighting

we would have little of what makes modern technology modern

The "good news" about modern physics for engineers

The good news

- A relatively small number of “modern physics” ideas
  - if we understand them well
    - let us understand how the world actually works

The good news

These ideas are well understood
- and they work well
  - Even if we add new physics later
    - this physics will still be useful
      - and will keep working through our lifetimes

A little modern physics goes a long way!

Teaching modern physics for engineers

Teaching modern physics for engineers

- In a typical sequence for physics students
  - these ideas take many courses to explain
    - in part because they provide background for many other branches of physics
- But our goal is to give key background for engineering
  - so we can skip much other material
    - This course tries to be as economical as possible
      - giving you a strong grounding
        - but just in the modern physics that is essential for engineering

Teaching modern physics for engineers

- Modern physics was discovered in the wrong order
  - Thermodynamics
  - Statistical mechanics
  - Quantum mechanics
    - and sometimes it is taught in the wrong order as a result
- We can save time by teaching it in the correct order
  - Quantum mechanics
  - Statistical mechanics
  - (Thermodynamics)

Teaching modern physics for engineers

This course will

- teach you what you really need to know
  - efficiently
- change the way you think about the world
  - and that will be useful
- remain useful for the rest of your lives
  - and you will no longer be 150 years out of date!

What we are going to learn

Main scientific topics of this class

Quantum mechanics

especially as it relates to

the atoms, electrons,

semiconductor materials and

photons of modern devices

Main scientific topics of this class

Statistical mechanics

- especially as it allows us to
  - understand the thermal distributions of electrons and photons
    - which is very important for all those devices
  - and see why entropy increase drives everything

A summary of the course

Course summary

Oscillations and waves

- Ideas of oscillations and waves
  - as a background to quantum mechanics and to light

The quantum view of the world

- Differences from the classical world view
- Schrödinger's wave equation and simple solutions
- Key ideas of quantum mechanics

Course summary

- Particles, atoms, and crystals
  - The quantum mechanical model of the hydrogen atom
  - Quantum mechanics of the crystalline materials
    - as in most modern electronic and optoelectronic devices
- Thermal distributions
  - The statistical idea of entropy
    - the second law of thermodynamics
  - Thermal distributions of electrons and photons

Course summary

Bands and electronic devices

- Understanding from quantum mechanics and statistical mechanics
  - how electronic devices work

Light and quantum mechanics

- The quantum mechanics of light absorption and emission

Course summary

Semiconductor optoelectronics

Principles and concepts of optoelectronic devices

in applications like

- communications
- lighting
- solar energy

The background to modern physics

Modern physics for engineers

David Miller

Matter

Matter

Thales of Miletus (c. 620 – c. 546 BCE)

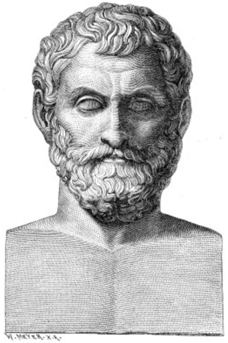
- matter is made of something

Empedocles (c. 490 – c. 430 BCE)

- matter is made of four elements
  - earth, air, fire, water

Today, we would recognize these as the different phases of matter

- solid (earth), liquid (water), gas (air), and fire (plasma)
  - rather than matter's constituents



Thales of Miletus

From "Illustrerad verldshistoria utgifven av E. Wallis. volume I": *Thales*

Empedocles

From Thomas Stanley, (1655), The history of philosophy

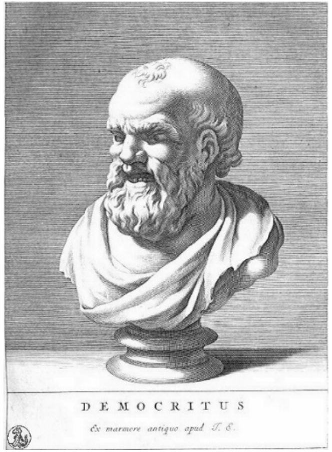
Matter

Democritus (c. 460 – c. 370 BCE) and/or his teacher Leucippus

- matter is composed of indivisible "atoms"
  - from the Greek, meaning "cannot be cut"

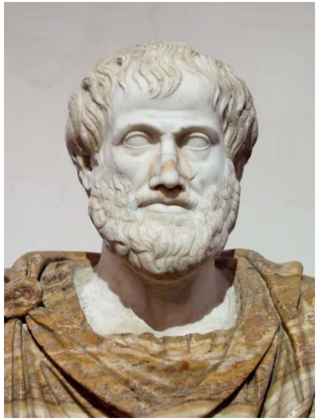
Aristotle (384 – 322 BCE)

- favors the "four elements" approach
  - which remains dominant for nearly 2000 years



Democritus

http://www.phil-fak.uni-duesseldorf.de/philo/galerie/antike/demokrit.html



Aristotle

Ludovisi collection, National Museum of Rome

Matter

This “four elements” approach

- formed the basis of alchemy, the precursor of modern chemistry
  - elements “sulphur” and “mercury” were added by Jabir (c. 721 – c. 815 CE)
- disputed by some, such as Avicenna (c. 980 – 1037)

Jābir ibn Hayyān

Codici Ashburnhamiani 1166, Biblioteca Medicea Laurenziana, Florence

Avicenna (Ibn-Sīnā)

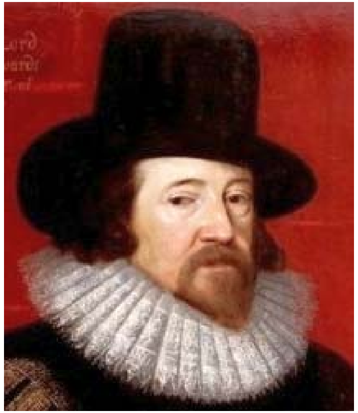
Tajikistani somoni

Matter

Scientific method

- From early deductive methods of Parmenides (c. 515 – c. 460 BCE), Leucippus and Democritus
  - and proceeding through scientific experiments such as those by Alhazen (Ibn al-Haytham) (c. 965 – c. 1040)
    - the modern scientific method is established, as discussed by Francis Bacon, René Descartes and Galileo, by the early 1600's

Alhazen

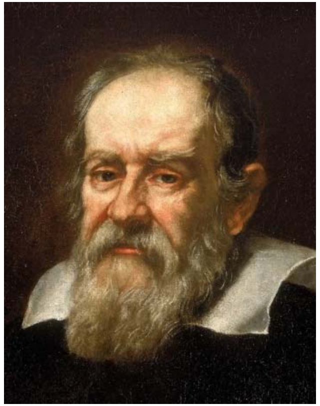


Francis Bacon

Palace on the Water, Warsaw

René Descartes

The Louvre, Paris



Galileo

National Maritime Museum, London

Matter

Robert Boyle (1627–1691) in "The Skeptical Chymist"

- argues towards modern ideas and a scientific approach to chemistry

In the 1700's, chemistry advances with

- identification of various elements
- some modern nomenclature
- quantitative understanding of reactions

conservation of mass in chemical reactions (in Antoine Lavoisier's classic "Traité Élémentaire de Chimie", 1789)

Robert Boyle

Chemical Heritage Foundation

Antoine Lavoisier

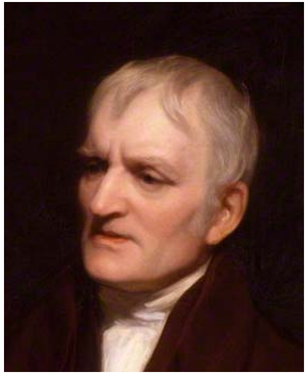
engraving by Delaistre, after Boilly

Matter

With the observation of definite proportions in compounds

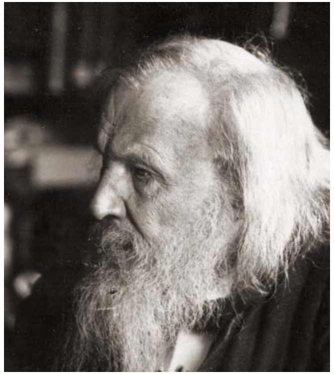
- by Joseph Proust in 1799
  - extended to show integer ratios by John Dalton
    - Dalton proposed a clear atomic theory in the first decade of the 1800's

In 1869 Dmitri Mendeleev published his periodic table



John Dalton

National Portrait Gallery, London



Dmitri Mendeleev

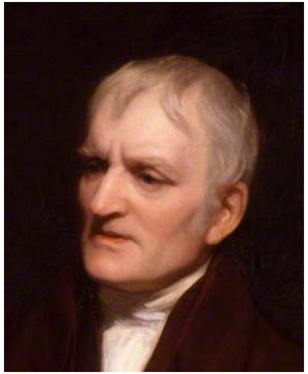
Reihen	Gruppe I. — R^2O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev's periodic table of 1871

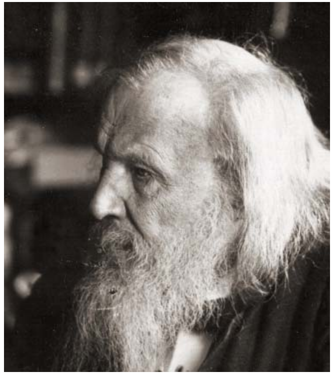
Matter

But we had no idea of
- what atoms were
- what made them different
- and why they had their specific chemical properties

To understand this
- we needed quantum theory
  - which would take about another 50 years



John Dalton
National Portrait Gallery, London



Dmitri Mendeleev

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Mendeleev's periodic table of 1871

Laws of motion

Laws of motion

Early ideas from Aristotle's time held that

- if you did not keep pushing something, it would stop moving

The continuous movement of the "heavens" was explained by saying they lay on perfect celestial spheres centered round the earth

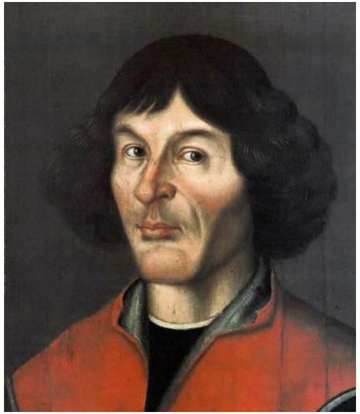
- Ptolemy (c. 90 – c. 168 CE) put together such an astronomical model
  - constructing tables used for astrology
    - though planetary orbits are hard to explain this way

Nicolaus Copernicus (1473 – 1543)

- proposed a "heliocentric" view as a simpler model that agreed with measurements

Ptolemy

by Andre Thevet, 1584



Nicolaus Copernicus

portrait from Town Hall in Thorn/Toruń - 1580

Laws of motion

- Using accurate measurements by Tycho Brahe (1546 – 1601)
  - Johannes Kepler (1571 –1630) deduced rules
    - Kepler's Laws of Planetary Motion (1609 and 1619) for the elliptical orbits of planets round the sun
- Galileo
  - observed a pendulum swung with the same period regardless of amplitude
  - argued that velocity of falling bodies was not proportional to their weight
  - advocated a law of inertia - bodies keep on moving even if they are not pushed

Tycho Brahe

By Gemperlin (Lund Observatory)

Johannes Kepler

Unknown artist (1610) (in Kremsmünster)

Laws of motion

Isaac Newton (1642–1726/7) proposed his three Laws of Motion and his gravitational theory in 1687

- which explained Kepler's Laws
  - and are used to this day

He created calculus to construct his theory

More mathematically sophisticated versions were developed by

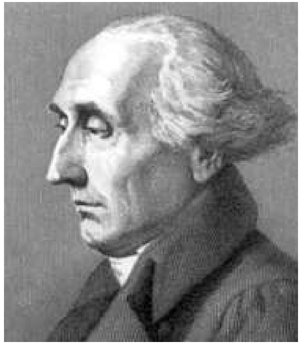
- Joseph-Louis Lagrange (1736–1813) in 1788
  - extended by William Hamilton (1805–1865) in 1833

Albert Einstein's theories of relativity

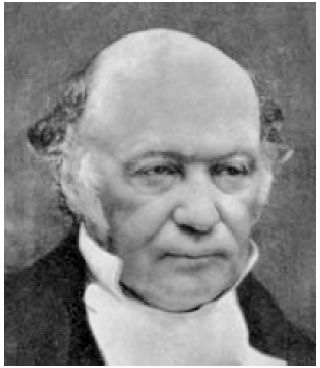
- special (1905) and general (1916)
  - formally superseded Newton's models

Isaac Newton

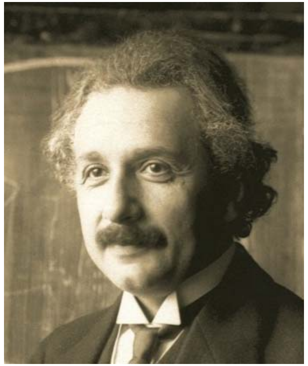
by Sir Godfrey Kneller, 1689



Lagrange



William Hamilton



Albert Einstein

Light, electromagnetism and Maxwell's equations

Light

Empedocles' theory argued that light rays emanated from the eyes towards objects

~ 300 BCE, Euclid constructed a geometrical theory

with light rays traveling in straight lines

which allowed a theory of perspective

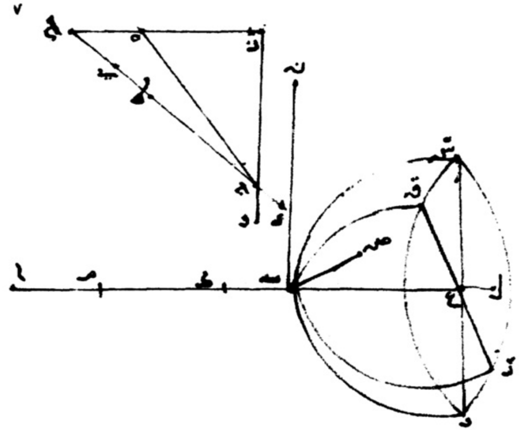
Later, Alhazen analyzed the Greek optical theories

but proposed that light travels in rays to the eye from different points on an object

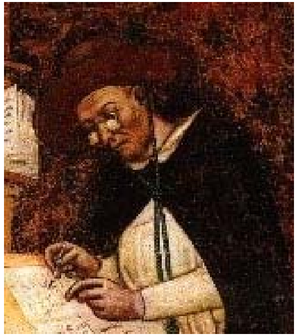
Models by Ibn Sahl (c. 940-1000)

successfully analyzed both reflection and refraction

Wearable eyeglasses were in use by the 1300's



Ibn Sahl's analysis of refraction



portrait of Hugh de Provence, 1352, showing eyeglasses

Light

The modern law of refraction, Snell's law,

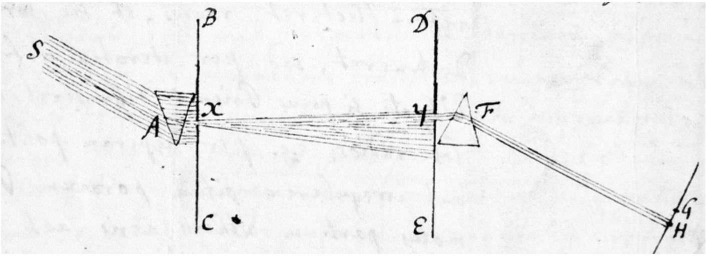
- was found by Willebrord Snellius (1580–1626) in 1621

Clear observations of diffraction of light were made in the 1600's by Francesco Grimaldi (1618 –1663)

Newton's experiments with prisms around 1670 – 72

- splitting up white light and putting it back together
  - showed white light is made up out of the different "spectral" colors

Willebrord Snellius



Newton's drawing of his prism experiment

From a letter to the Royal Society, 1672

Light

Newton advocated a “corpuscular” theory of light

- with particles traveling in straight lines

Christiaan Huygens (1629-1695) in 1690 proposed that light is a wave phenomenon

- describing “Huygens’ Principle”

Thomas Young (1803) proved the wave nature of light with the “two slit” experiment

Augustin-Jean Fresnel extended the theory (1821)

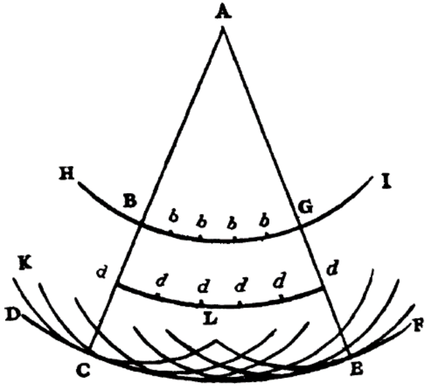
- and with François Arago he determined that light was a “transverse” wave, with polarizations

Hippolyte Fizeau made the first time-of-flight measurements of the velocity of light in 1849

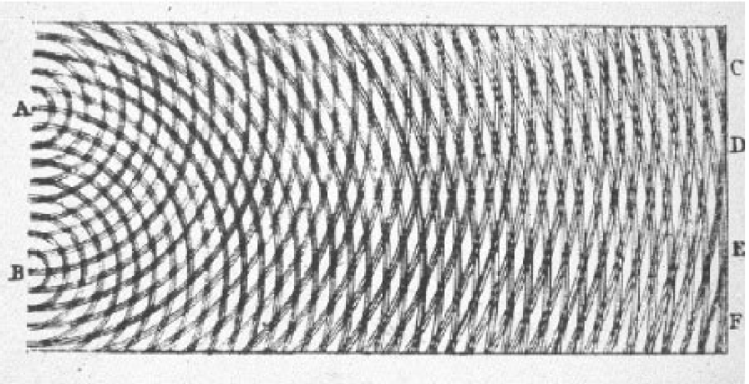
- obtaining an answer within 5% of the modern value

At this point in the mid 1800’s, there was still

- no clear connection between light and electromagnetism



from Huygens’ “Treatise on Light”



Young’s drawing of the two-slit experiment

T. Young, “Course of Lectures on Natural Philosophy and the Mechanical Arts,” 1807

Electromagnetism

The ancient Greeks knew that rubbing amber with fur could lead to attraction

- what we know as electrostatic attraction

Lodestone (naturally occurring magnetite) was also known to attract iron objects

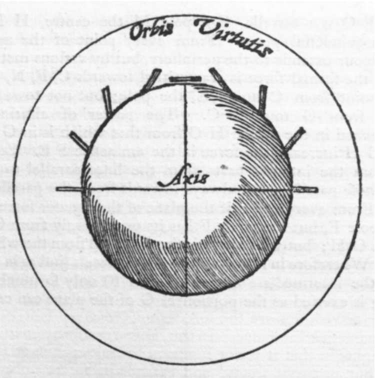
- e.g., in 4th century BCE writings of Wang Xu

Shen Kuo (1031 – 1095) later wrote about the magnetic needle compass

- Writings ~ 1111 – 1117 by Zhu Yu document its use for navigation

In 1600, William Gilbert concluded that the Earth was magnetic

- hence the action of magnetic compasses



from Gilbert's De Magnete (1600)

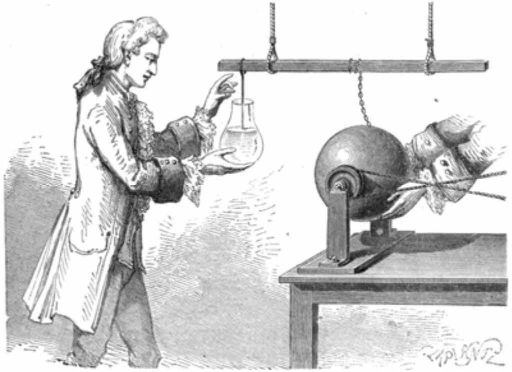
Electromagnetism

The invention of the Leyden jar capacitor

- apparently independently by both Pieter van Musschenbroek of Leyden and by Ewald von Kleist in 1745
  - allowed electrical charge to be accumulated and stored

Benjamin Franklin may have flown a kite into a thunderstorm in 1752

- capturing the resulting charge from the lightning in a Leyden jar



van Musschenbroek’s experiment

A. P. Deschanel (1876) Elementary Treatise on Natural Philosophy

by Benjamin West (1816), Philadelphia Museum of Art

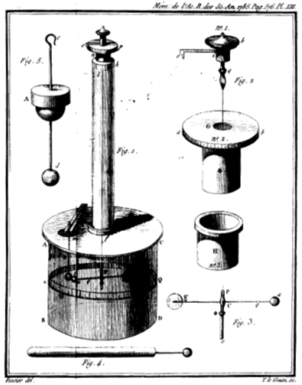
Electromagnetism

Charles Coulomb introduced

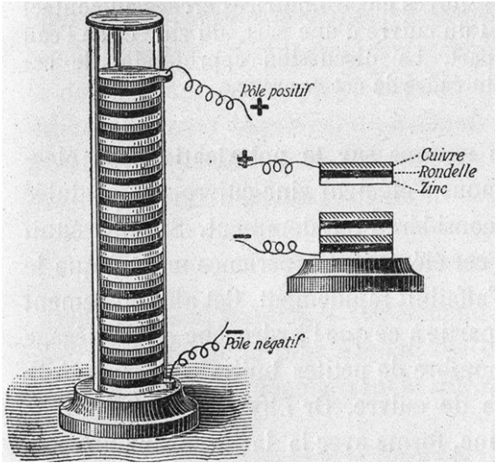
- the inverse square law of electrostatics in 1785

Alessandro Volta created the voltaic cell and the battery in 1799

- using copper or silver discs separated from zinc discs in brine
  - This allowed much more convenient experiments using electrical currents and voltages



Coulomb's torsional balance



Voltaic pile

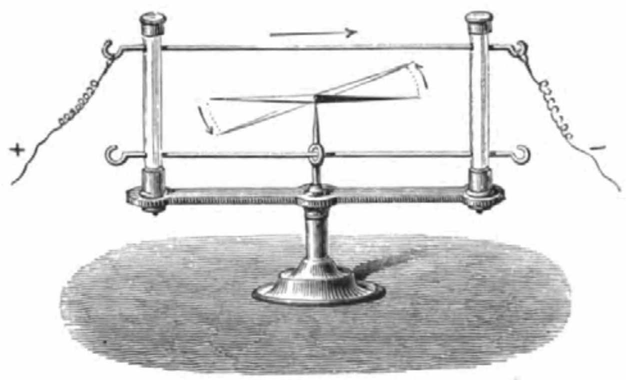
Electromagnetism

Hans Christian Ørsted in 1820 noticed that

- a compass needle could be deflected by passing a current through a wire

In the same year, André-Marie Ampère showed that

- passing a current through a coil of wire caused it to behave like a magnet



Apparatus for Ørsted's experiment

A. P. Deschanel 1876 Elementary Treatise on Natural Philosophy

Electromagnetism

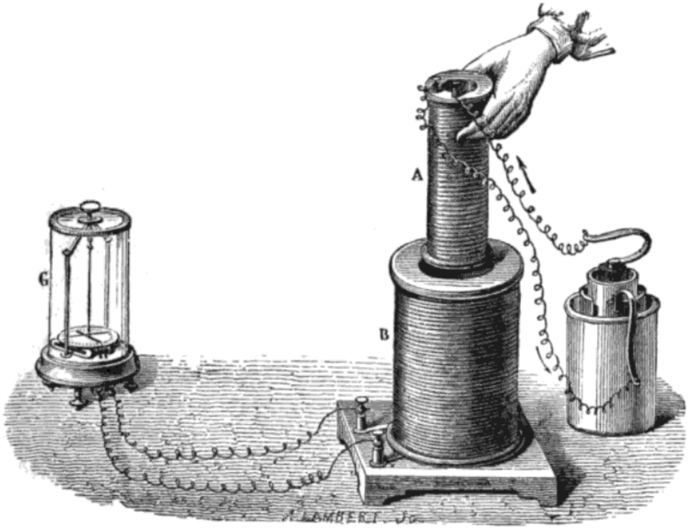
Michael Faraday observed electromagnetic induction in 1831

- Turning on and off a current in one coil of wire
  - can induce a current in another coil

and moving a magnet through a coil of wire

- can also similarly induce a current

So changing magnetic fields can create electric fields



Apparatus for an induction experiment

A. W. Poyser (1892) Magnetism and electricity

Maxwell's equations

In 1865, James Clerk Maxwell (1831–1879) proposed

- just as changing magnetic fields could produce electric fields
  - so changing electric fields would produce magnetic ones
    - He therefore synthesized all of electromagnetism in his equations

James Clerk Maxwell

Maxwell's equations

With changing magnetic fields giving electric fields

and changing electric fields giving magnetic ones

these equations predict wave motion

with a wave velocity that agreed with the measured velocity of light

leading to the proposal that light was electromagnetic radiation

James Clerk Maxwell

Thermodynamics

Thermodynamics

- Fire has been used since prehistoric times for
  - cooking, heating, and possibly also for clearing land for agriculture
- Hero of Alexandria (c. 10 – c. 70 CE) described a simple steam engine, the aeolipile
  - based on jets of steam from water inside a heated sphere
- He and others may have understood the expansion of air when it is heated
  - By the early 1600's several scientists were using a tube closed at one end and with its other end in water as a thermometer

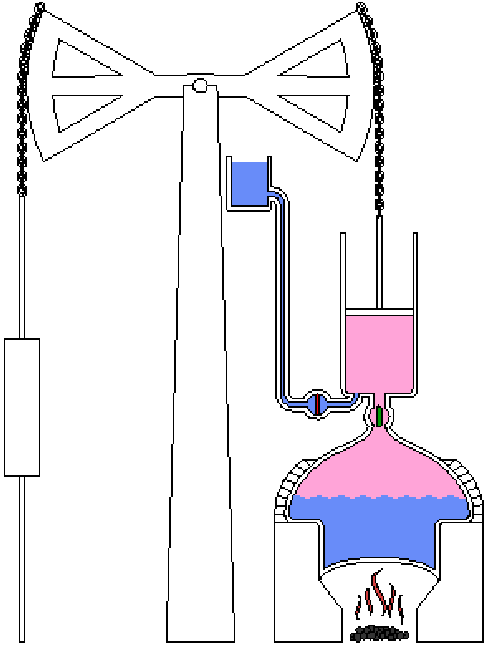
Hero's Aeolipile

Knight's American Mechanical Dictionary, 1876

Thermoscope of Santorio Santorii (1612)

Thermodynamics

- The growth of mining required a method to drain the mines of water
  - Thomas Savery invented the first commercially used steam engine in 1798
- Thomas Newcomen's engine of 1712 employed a piston in a cylinder
- James Watt in 1774 invented the separate condenser steam engine
  - which greatly improved the efficiency



Newcomen's atmospheric engine

Thermodynamics

Daniel Fahrenheit developed a reliable thermometer based on the expansion of mercury in 1724

Joseph Black introduced the idea of latent heat in 1762

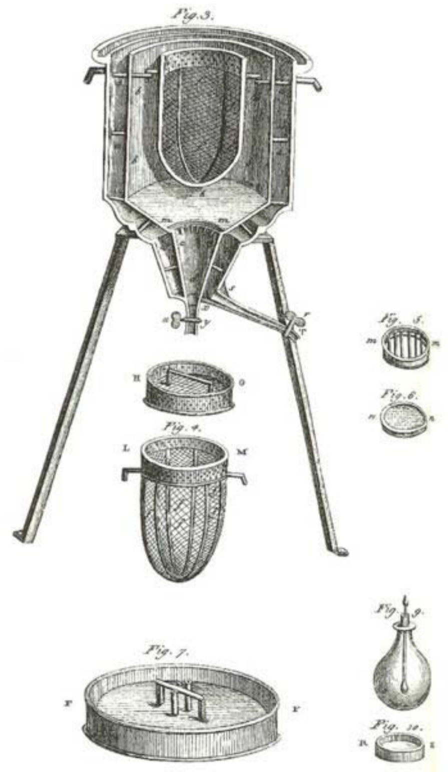
Lavoisier used an ice-calorimeter in 1782-83

based on latent heat

to measure heat generated from various chemical reactions

With meaningful thermometers and calorimeters

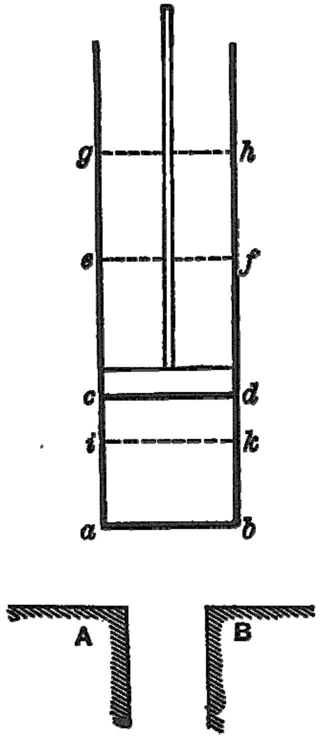
thermodynamics could start to become a quantitative science



Lavoisier's ice calorimeter

Thermodynamics

- Sadi Carnot in 1824 considered the question of the efficiency of heat engines like steam engines
  - proposing that only the difference in the temperature of the "hot" and "cold" reservoirs mattered in an ideal engine
- At that time, the nature of heat was still not clear, being viewed in terms of "caloric"
  - a supposed fluid not yet identified with energy

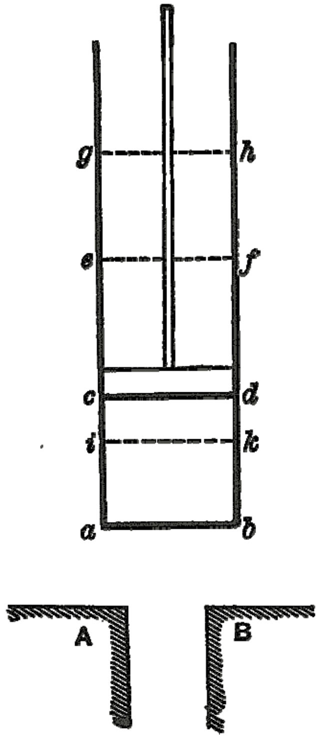


Carnot's ideal engine (A and B are different temperature reservoirs)

Thermodynamics

Benjamin Thompson (Count Rumford) in 1798 showed heat could be generated by friction

- He immersed a cannon barrel in water and then bored it out with a blunt tool
  - boiling the water
    - So, mechanical energy could be converted to heat



Carnot's ideal engine (A and B are different temperature reservoirs)

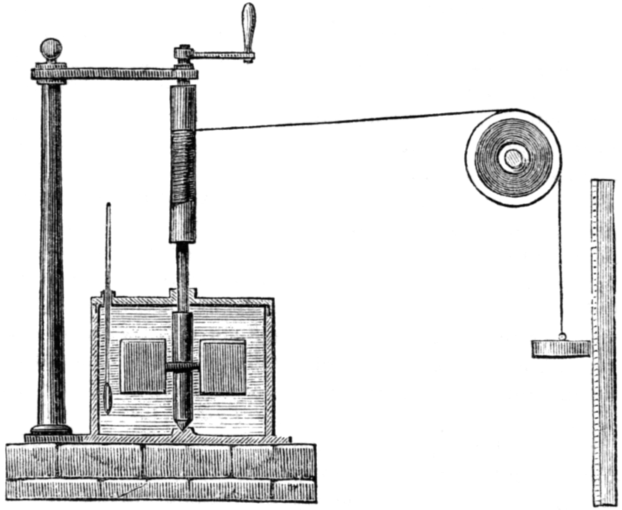
Thermodynamics

Using a falling weight to drive a paddle immersed in water

- in 1845 James Joule deduced a consistent specific heat for water

This led to the proposal that in fact

- heat was energy
  - and that the energy was conserved overall in thermal phenomena
    - which becomes the First Law of Thermodynamics



Joule's apparatus

Harper's New Monthly Magazine, No. 231, August, 1869

Thermodynamics

Two key ideas that emerge from these advances in thermodynamics are

- entropy - usually credited to Rudolf Clausius from his work in the 1850's and 1860's
- and the Second Law of Thermodynamics

Both Clausius (in 1854) and William Thomson (Lord Kelvin) (in 1851) give statements of the Second Law

The entropy change ΔS resulting from a flow of heat (energy) ΔQ into a system at temperature T

- can be defined through $\Delta S = \dfrac{\Delta Q}{T}$

Entropy and the Second Law of Thermodynamics

- Here T is expressed relative to absolute zero temperature
  - a notion introduced by Kelvin in 1848
- Informally, the Second Law of Thermodynamics can be stated
  - "in some isolated total system entropy cannot decrease"
    - This principle puts a limit on the efficiency of heat engines

Entropy and the Second Law of Thermodynamics

To understand what entropy really is

- we need to change to thinking about kinetic theory
  - the idea that heat is really the energy stored in the random motions of atoms or other entities

This is statistical mechanics

- started by James Clerk Maxwell in 1871
- and a particularly important paper by Ludwig Boltzmann (1844 – 1906) in 1875
- with major contributions by Josiah Gibbs (1839 – 1903)

Transitioning to modern physics

Modern physics for engineers

David Miller

Exploiting classical physics

Exploiting "classical" physics

- Topics up to ~ 1870, could all be called "classical physics"
- Engineering based on it continued to develop
  - e.g., in electromagnetism alone
    - electrical power and light
    - telegraph cables
    - the telephone
    - radio transmission

Exploiting "classical" physics

The thermodynamics of heat and entropy

- laid the basis for modern chemical thermodynamics
- underpinned the continued growth in efficiencies and types of heat engines
  - such as internal combustion engines

State of our knowledge as of ~ 1870

State of our knowledge as of ~ 1870

The ideas of chemical elements were working, but we had

- no underlying theory of them
- no theory of material properties

We understood

- electromagnetism
- waves
  - and resulting models of light

But we had no model of how light interacted with anything

State of our knowledge as of ~ 1870

We had working concepts for thermodynamics

- energy
- entropy
- heat engines

but not their physical basis

The start of modern physics

The start of modern physics

This point in time, at approximately 1870

- is the (somewhat arbitrary) start of "modern physics"

It ultimately answered questions

- of the basis of chemistry
- of how light was generated and interacted with matter
- of what lay behind the ideas of thermodymanics

The start of modern physics

It enabled much of the modern technology of the 20th and 21st centuries

- and it completely changed how we thought
  - introducing new and very powerful concepts