The path to the electron
(Horst Wahl, QuarkNet lecture, June 2001)

- Early history of electricity -- beginnings, Franklin, Galvani, Volta
- Electricity: beginning of quantitative era – Coulomb, Ampère, Faraday
- Electric field
- Currents and magnetic field, induction
- Towards a field theory of electromagnetism
  - Faraday, Maxwell
  - Electromagnetic waves – prediction, properties
  - Electromagnetic waves – observation
- Discharge tubes, cathode rays
- Photoelectric effect (Hertz, Hallwachs)
- Studies of nature of cathode rays
- Measurements of e/m of cathode rays
  - Lorentz, Wiechert, Kaufmann, Thomson
- Further studies of photoelectric effect (Thomson, Lenard)
- Explanation of photoelectric effect, measurement of h (Einstein, Millikan)

Electricity -- history

- **Early history**
  - Greeks discovered about 600BC that amber, when rubbed with wool, attracts other objects
  - "Electric phenomena"
    - named after "electron", Greek word for amber;
    - studied by many through ages;
    - real progress in understanding only gained in 18th century;
    - Charles Dufay (1745): there are two types of electricity
  - Benjamin Franklin (1706-1790) (US politician, diplomat, scientist, writer,printer)
    - lightning as electrical phenomenon
    - lightning rod
    - coined name "positive" and "negative" for the two kinds of electric charge
  - Luigi Galvani (1737-1798) (Prof. of Anatomy at U. of Bologna)
    - "De viribus electricitatis in motu musculari commentarius" (1791)
    - electric phenomena in muscular motion (experiments with froglegs)
  - Alessandro Volta (1745-1827)
    - electrophorus (1775)
    - straw electroscope (1781)
    - condensator (1782)
    - relation between chemical reactions and electricity (1796)
    - "Voltaic cell" (battery) (1800)

History of electricity—beginning of the quantitative era

- Charles Augustin de Coulomb (1736-1806)
  - like charges repel, unlike charges attract each other;
  - discovered "Coulomb's Law", using torsion balance invented by him.
- André Marie Ampère (1775-1836) (Prof. Physics at École Polytechnique, Paris)
  - La théorie des phénomènes électrodynamiques'' (1826)
  - attraction and repulsion of electric currents,
  - direction of magnetic field of a current,
  - explanation of magnetism as due to "molecular currents".
- Michael Faraday (1791-1867) (bookbinder's apprentice, self-taught chemist and physicist, prof. of physics and chemistry)
- "Experimental researches in electricity" (1844-1845)
- "Experimental researches in chemistry and physics" (1859)
  - concept of "electric field", field lines (lines of force)
  - induction (1831)
  - basic laws of electrochemistry (1833-1834)
  - investigations of dielectrics
  - studies of gas discharges
  - diamagnetism
  - magnetic rotation of plane of polarization of light (1845)

ELECTRIC FIELD

- "field of force": exists in a region of space when an appropriate object (called the "test object" or "probe") placed at any point in the region experiences a force.
- force depends on a property of the test object (e.g. charge,..), the "test charge";
- "field strength" = (force experienced by test object) divided by (test charge), = *"force per unit test charge"*;
- for electrostatic force, this field strength is called "electrostatic field" or "electric field";
- field can be visualized by "lines of force" or "field lines", which give the direction of the field at every point, i.e. *the force experienced by a test-charge at any point in space is in the direction tangent to the line of force at that point*;
- the density (concentration) of field lines corresponds to the magnitude of thefield strength: *the denser the concentration of lines, the stronger the field; the farther apart the lines, the weaker the field*;
- electrostatic field lines begin on positive and end on negative charges;
- field lines do not cross;
- originally, field lines were invented (by Faraday) as means of visualization, but eventually were regarded as standing for an invisible physical reality - the electric field;
- *In modern view, all forces ("interactions") are due to fields, described by "gauge field theories".*

Currents and magnetic fields

- electric current
    - = ordered flow of electric charge;
    - unit of current = 1 Ampère = 1A = 1 Coulomb/second;
- all charges generate electric fields -- moving charges also generate magnetic fields
- *a straight current carrying wire generates a cylindrical magnetic field in the space surrounding it (magnetic field lines are circles around the wire)*
- *a current carrying wire loop generates a magnetic field similar to that of a bar magnet (magnetic dipole field)*
- **magnetic force on moving charge** -
      "Lorentz force":
$$F = q \, v \times B$$
      (B is the magnetic field strength,
      v the velocity of the charge q)
    - force is perpendicular to both magnetic field and velocity
    - no force when motion parallel to magnetic field
- electric fields act on all charges --
      magnetic fields act only on moving charges
- unit of magnetic field = 1 Tesla = 1 T
  1 Tesla = 1 Newton / (Ampère meter)

Electromagnetic induction

- flux of the field:
    - flux of the field through a surface = the total net number of field lines penetrating the surface.
    - for a uniform field B, the flux is just the product of the field strength and the "effective" area of the surface; the effective area is the area "offered" to or "penetrated" by the field lines (i.e. the equivalent area perpendicular to the field).
    - all other things equal, the flux is maximal if the surface is perpendicular to the field direction; it is = zero if the surface is parallel to the field direction.

- Faraday's law of induction
    - **When the magnetic flux through the surface enclosed by a wire loop changes, an "electromotoric force" (voltage) is "induced" in the wire loop** ($\Rightarrow$electric field)
    - the induced voltage is equal to the rate of change of the flux: $V = -\Delta\Phi/\Delta t$
    - Lenz' rule: the direction of the induced electric field is such as to counteract the effect that produced it (energy conservation!!)
    - ways to change the flux:
        - vary the field strength
        - move the wire loop in and out of the field area (or move the wire loop in a non-uniform field)
        - change the area enclosed by the wire loop (e.g. by deforming it)
        - change the angle between the wire loop and the field direction (e.g. by rotating the wire loop)
    - *induction is the basis of the "generators of electricity" that run in electric power plants.*

Towards a field theory of electromagnetism

- 1831: Michael Faraday (1791 – 1867):
  - electromagnetic induction
  - "Lines of force"
  - concept of electric and magnetic "fields"
- 1856: James Clerk Maxwell (1831-1879): paper "On Faraday's lines of force"
  - Express Faraday's ideas in mathematical form
  - Show that field concept gives valid alternative to Ampère's treatment based on central forces
- 1856-1857: Wilhelm Weber (1804-1891) and Rudolph Kohlrausch (1809-1858):
  - Measurements of electric charges using electrostatic and magnetic forces
  - Comparison indicates that electric currents travel with speed of light

- 1861-1862: Maxwell's papers "On physical lines of force":
    - provide mathematical formulation of Faraday's force lines, study properties of ether;
    - Conclude that electromagnetic fields advance with speed $v = (\mu_0 \varepsilon_0)^{-\frac{1}{2}}$
    - Measurements of μ_0 and $\varepsilon_0 \Rightarrow v \approx c$, the speed of light
    - Conclusion: "light consists in the transverse undulations of the same medium which is the cause of electric and magnetic oscillations"
- 1864: Maxwell's paper: "A dynamical theory of the electromagnetic field"
    - Ignores the model previously proposed for the ether, but keeps the mathematical treatment;
    - Asserts that equations valid without any assumptions about nature of medium equations
    - "Maxwell's equations" describe interplay between electric and magnetic fields and their relation to charges and currents
    - M.e. lead to "wave equation" for "electromagnetic waves" propagating with speed $c = (\mu_0 \varepsilon_0)^{-\frac{1}{2}}$

    - Biographical Note:
        - James Clerk Maxwell (1831-1879), (Prof.Physics in Aberdeen, London, Cambridge)
            - theory of heat,
            - kinetic gas theory (Maxwell-Boltzmann velocity distribution),
            - theory of electricity and magnetism
        - Heinrich Hertz (1857-1894) (Prof. Physics Karlsruhe, Bonn)
            - wrote influential book on Maxwell's theory
            - experimental observation of electromagnetic radiation (1887) (radio waves)
            - influence of UV light on electric discharges

Electromagnetic waves -- prediction

- **MAXWELL'S EQUATIONS:**
  - are four differential equations summarizing nature of electricity and magnetism: (formulated by James Clerk Maxwell around 1860):

$$\vec{\nabla} \cdot \vec{D} = \rho \qquad \vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$(\vec{D} = \epsilon \cdot \vec{E}, \quad \vec{B} = \mu \cdot \vec{H})$$

  - *(1) Electric charges generate electric fields.*
  - *(2) Magnetic field lines are closed loops; there are no magnetic monopoles.*
  - *(3) Currents and changing electric fields produce magnetic fields.*
  - *(4) Changing magnetic fields produce electric fields.*
  - Together with the equation for the Lorentz force, these equations describe all electromagnetic phenomena (i.e. all electromagnetic phenomena can be derived from them.)
  - from Maxwell's equations one can derive another equation which has the form of a "*wave equation*".
  - This differential equation was known from mechanics to have solutions which describe wave phenomena in mechanics.

Electromagnetic wave equation

- From the analogy between wave equation for mechanical waves and the wave equation in terms of electric and magnetic fields, Maxwell concluded that there should be also solutions to the wave equation derived from his equations -- "**electromagnetic waves**", corresponding to the propagation of oscillations of the electric and magnetic fields.

- **speed of electromagnetic waves** is also derived from this wave equation, expressed in terms of constants which appear in the relation between charge and electric field ($k = 1/(4\pi\varepsilon)$ in Coulomb's law) and between current and magnetic field (μ in Ampère's law).

- This speed turns out to be = the speed of light!

- Conclusion and prediction:
  - *light is just a form of electromagnetic radiation*
  - *there should be other forms of electromagnetic radiation (different frequencies) which can be produced by making charges "wiggle";*
  - *This was experimentally verified by Heinrich Hertz: (built devices to generate and to receive e.m. waves - first human-made radio waves)*

Electromagnetic waves:

- **electromagnetic radiation**
  - = *coupled, oscillating electric and magnetic fields moving through space at the speed of light;*
  - magnetic and electric fields "feed on each other", obeying Maxwell's 3rd and 4th laws
  - e.m. waves do not need material carrier - move through vacuum (- no "ether");
  - *e.m. waves are transverse waves* - electric field perpendicular to magnetic field, both perpendicular to direction of propagation;
  - **speed of light** ≈ 300 000 km/sec = 186 000 miles/second
    (*this is the speed of light in vacuum*)
    (speed of light in air is very similar)
  - electromagnetic waves generated by accelerating charges
  - Electromagnetic spectrum:

name	wavelength λ in m	frequency f or ν in Hz
γ	$< 10^{-10}$	$> 3 \cdot 10^{18}$
X-rays	$< 10^{-8}$	$> 3 \cdot 10^{16}$
UV	$10^{-8} - 4 \cdot 10^{-7}$	$3 \cdot 10^{16} - 7.5 \cdot 10^{14}$
visible	$4 \cdot 10^{-7} - 7 \cdot 10^{-7}$	$7.5 \cdot 10^{14} - 4.3 \cdot 10^{14}$
infrared	$\approx 3 \cdot 10^{-5}$	$\approx 10^{13}$
microwaves	$\approx 3 \cdot 10^{-2}$	$\approx 10^{10}$
UHF	$\approx 3 \cdot 10^{-1}$	$\approx 10^{9}$
VHF 7 - 13	$\approx 10^{-1}$	$\approx 3 \cdot 10^{8}$
FM	≈ 3	$\approx 10^{8}$
VHF 2 - 6	≈ 30	$\approx 10^{7}$
AM	≈ 300	$\approx 10^{6}$

Discharge tubes

- 1855- 1857: Heinrich Geissler (1815-1879) (Bonn)
  - Mercury pump (can reach 10^{-3} torr)
  - Build discharge tube (glass tube with two electrodes, filled with gas at very low pressure) at lower pressure than ever before ("Geissler tube")
  - (big improvement over tubes built previously by Humphrey Davy)
- 1858: Geissler and Julius Plücker (1801-1868):
  - Detailed study of discharges, pressure dependence
  - See influence of magnet on discharges
- 1869: Johann Hittorf (1824-1914) (Münster)
  - determined that discharge in a vacuum tube was accomplished by the emission of rays (named "glow rays" by him, later termed "cathode rays") capable of casting a shadow of an opaque body on the wall of the tube.
  - rays seemed to travel in straight lines and produce a fluorescent glow where they passed through the glass.
  - Rays deflected by magnetic field
- 1870's: William Crookes (1832-1919) (London):
  - detailed investigation of discharges;
  - Confirms Hittorf's findings about deflection in magnetic field
 - Concludes that rays consist of particles carrying negative charge

Electromagnetic waves--Observation

- 1886 - 1887: Heinrich Hertz (1857-1894) (Karlsruhe)
  - Built apparatus to generate and detect electromagnetic waves predicted by Maxwell's theory
    - High voltage induction coil to cause spark discharge between two pieces of brass; once spark forms conducting path between two brass conductors $\Rightarrow$ charge oscillated back and forth, emitting e.m. radiation
    - Circular copper wire with spark gap used as receiver; presence of oscillating charge in receiver signaled by spark across the spark gap
  - Experiment successful –
    - detected radiation up to 50 ft away
    - Established that radiation had properties reminiscent of light: was reflected and refracted as expected, could be polarized, speed = speed of light

Photoelectric effect

- 1887: Heinrich Hertz:
    - In experiments on e.m. waves, unexpected new observation: when receiver spark gap is shielded from light of transmitter spark, the maximum spark-length became smaller
    - Further investigation showed:
        - Glass effectively shielded the spark
        - Quartz did not
        - Use of quartz prism to break up light into wavelength components $\Rightarrow$ find that wavelenght which makes little spark more powerful was in the UV
        - Hertz' conclusion: "I confine myself at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomena are brought about"
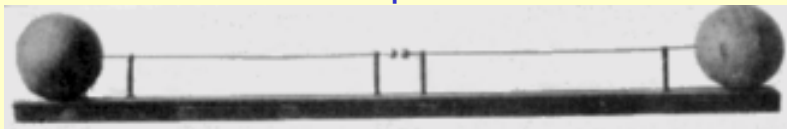
Photoelectric effect– further studies

- 1888: Wilhelm Hallwachs (1859-1922) (Dresden)
    - Performs experiment to elucidate effect observed by Hertz:
        - ◆ Clean circular plate of Zn mounted on insulating stand; plate connected by wire to gold leaf electroscope
        - ◆ Electroscope charged with negative charge – stays charged for a while; but if Zn plate illuminated with UV light, electroscope loses charge quickly
        - ◆ Electroscope charged with positive charge:
        - ◆ UV light has no influence on speed of charge leakage.
    - But still no explanation
    - Calls effect "lichtelektrische Entladung" (light-electric discharge)

Grundversuch der lichtelektrischen Entladung.

Grundversuch der lichtelektrischen Erregung.

Fig. 2.
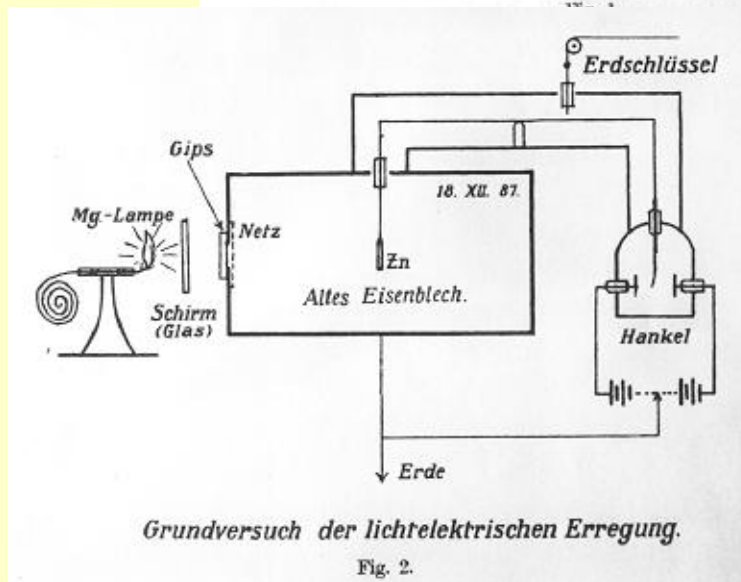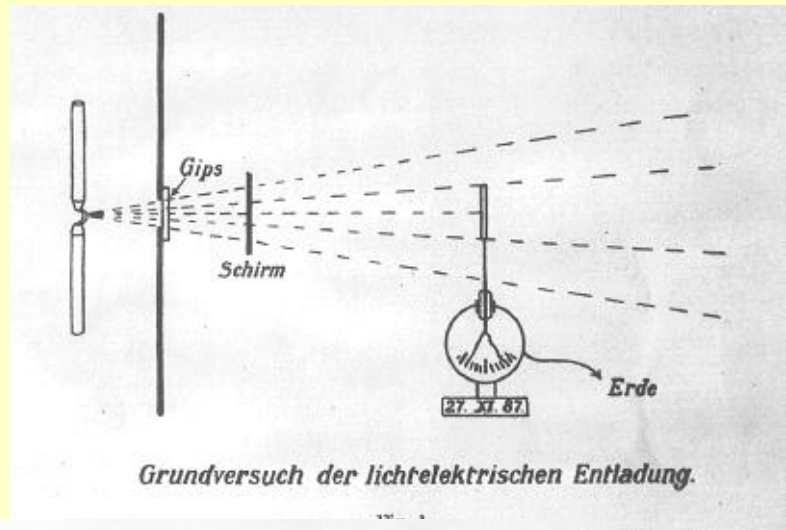
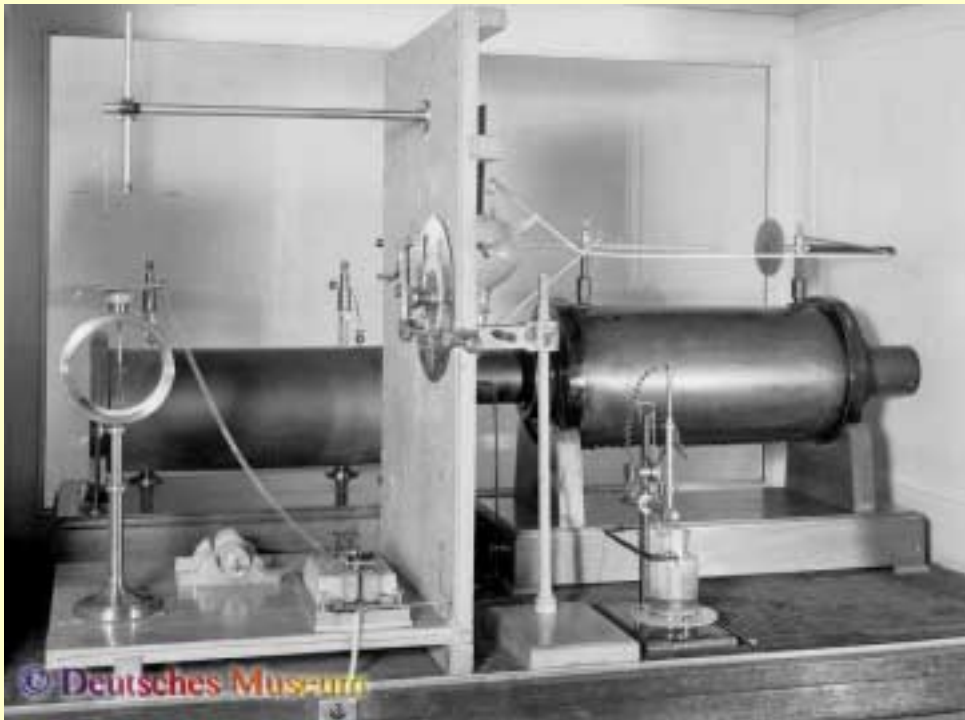# Cathode rays

- 1894: Hertz and Philipp Lenard (1862-1947):
    - Further investigations of cathode rays using discharge tubes:
        - Cathode rays penetrate through thin Al window ate end of tube,
        - Cause fluorescence over distance of few centimeters in air
        - Deflected by magnetic field
        - No deflection by electric fields

            (later explained due to insufficiently good vacuum)
- 1895: Wilhelm Röntgen (1845-1923) (Würzburg)
    - Uses discharge tubes designed by Hittorf and Lenard (but improved pump) to verify Hertz' and Lenard's experiments
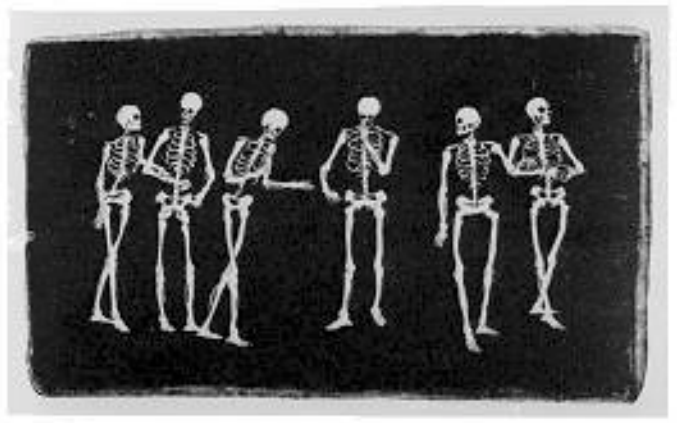   - Discovers X-rays -- forget about cathode rays!

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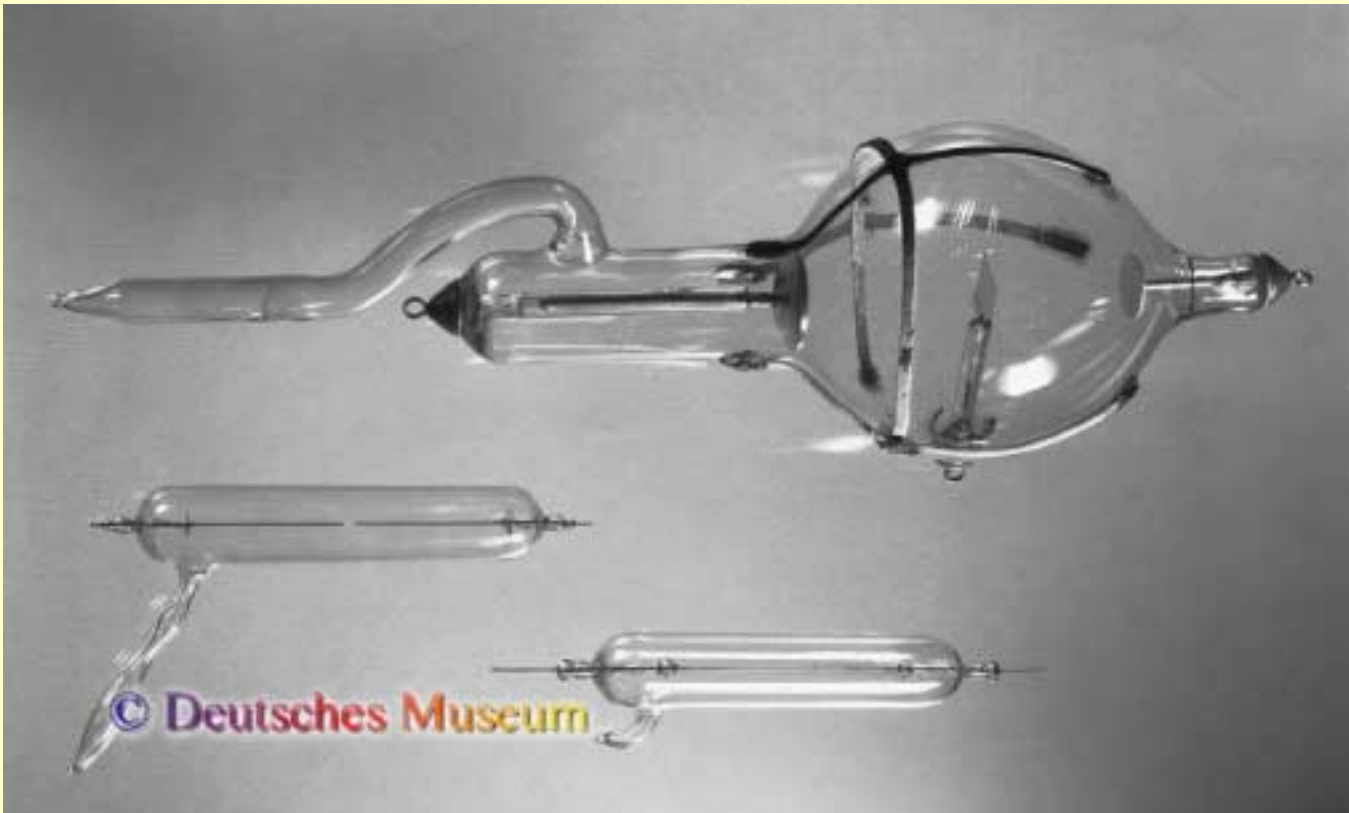
- Röntgen and X-rays:

Hand of Anna Röntgen
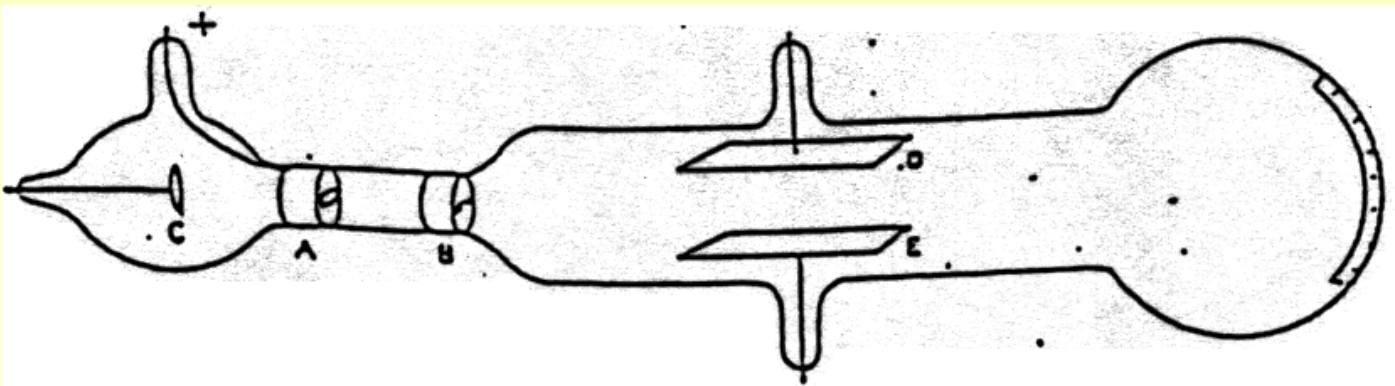
From Life magazine,6 April 1896
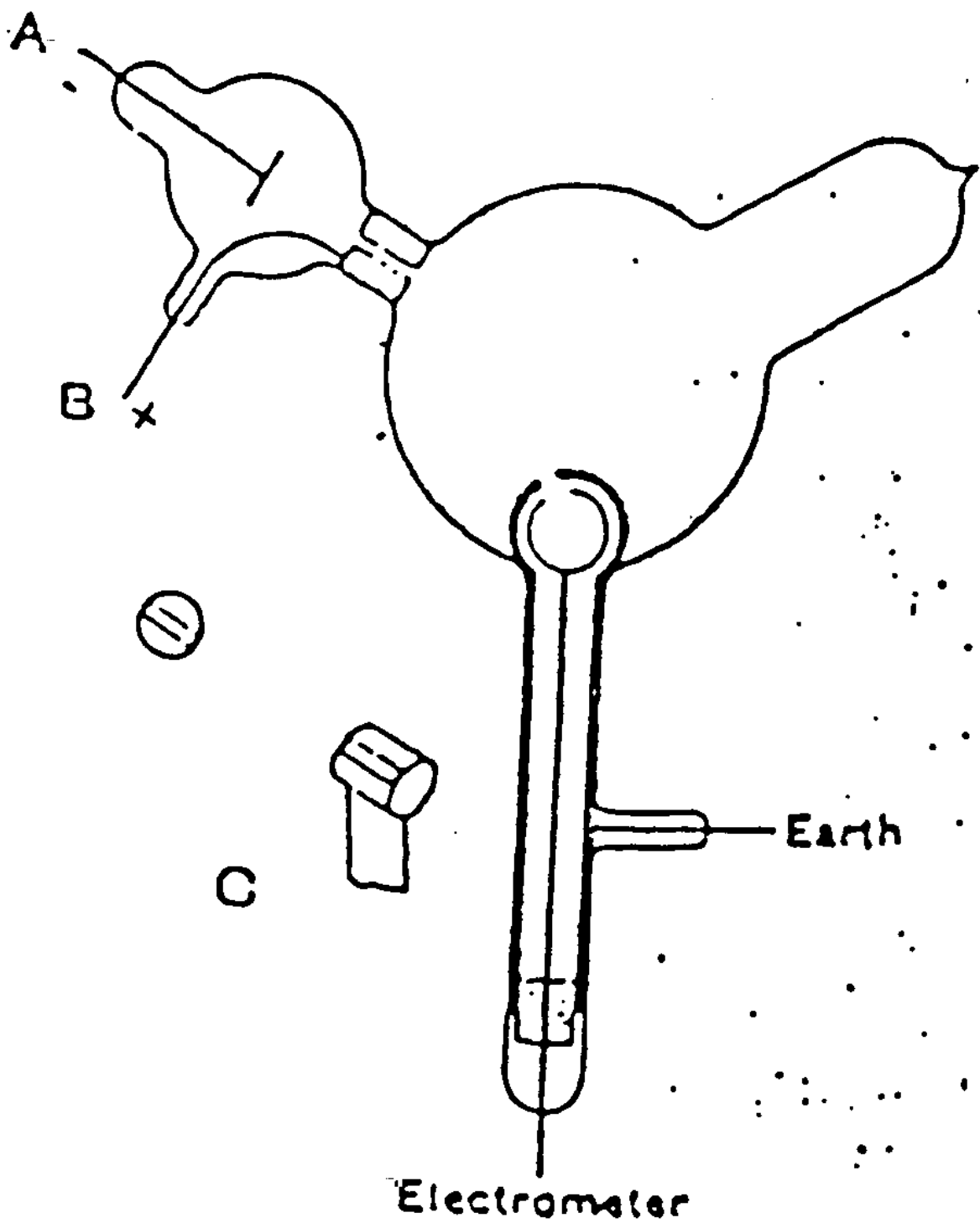
Studies of the nature of cathode rays

- 1895: Jean Perrin (1870-1942) (Paris):
  - Modifies cathode ray tube – adds "Faraday cup" which is connected to electrometer
  - Shows that cathode rays carry negative charge
- 1896: Hendrik A Lorentz (1853-1928) (Leiden)
  - Formulates atomistic interpretation of Maxwell's equations in terms of electrically charged particles (called "ions" by him)
  - "Lorentz force" = force exerted by magnetic field on moving charged particles
- 1896: Pieter A. Zeeman (1865-1943) (Amsterdam)
  - Observes broadening of Na D line in magnetic field
  - measures broadening vs field strength
- 1896: Explanation of this effect by Lorentz:
  - ◆ based on light emitted by "ions" orbiting within Na atom
  - ◆ Calculates expected broadening $\Delta f \propto (e/m)B$
  - ◆ By comparing with measured line broadening, obtains estimate of e/m of "ions" in Na atom:
    $e/m \approx 10^7$ emu/g $\approx 10^{11}$ C/kg
    (cf modern value of 1.76×10 C^{11}/kg)
- 1897: three experiments measuring e/m, all with improved vacuum:
  - Emil Wiechert (1861-1928) (Königsberg)
    - ◆ Measures e/m – value similar to that obtained by Lorentz
    - ◆ Assuming value for charge = that of H ion, concludes that "charge carrying entity is about 2000 times smaller than H atom"
    - ◆ Cathode rays part of atom?
    - ◆ Study was his PhD thesis, published in obscure journal – largely ignored
  - Walther Kaufmann (1871-1947) (Berlin)
    - ◆ Obtains similar value for e/m, points out discrepancy, but n explanation
  - J. J. Thomson

1897: Joseph John Thomson (1856-1940) (Cambridge)

- Improves on tube built by Perrin with Faraday cup to verify Perrin's result of negative charge
- Conclude that cathode rays are negatively charged "corpuscles"
- Then designs other tube with electric deflection plates inside tube, for e/m measurement
- Result for e/m in agreement with that obtained by Lorentz, Wiechert, Kaufmann,
- Bold conclusion: "we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter... is of one and the same kind; this matter being the substance from which all the chemical elements are built up."
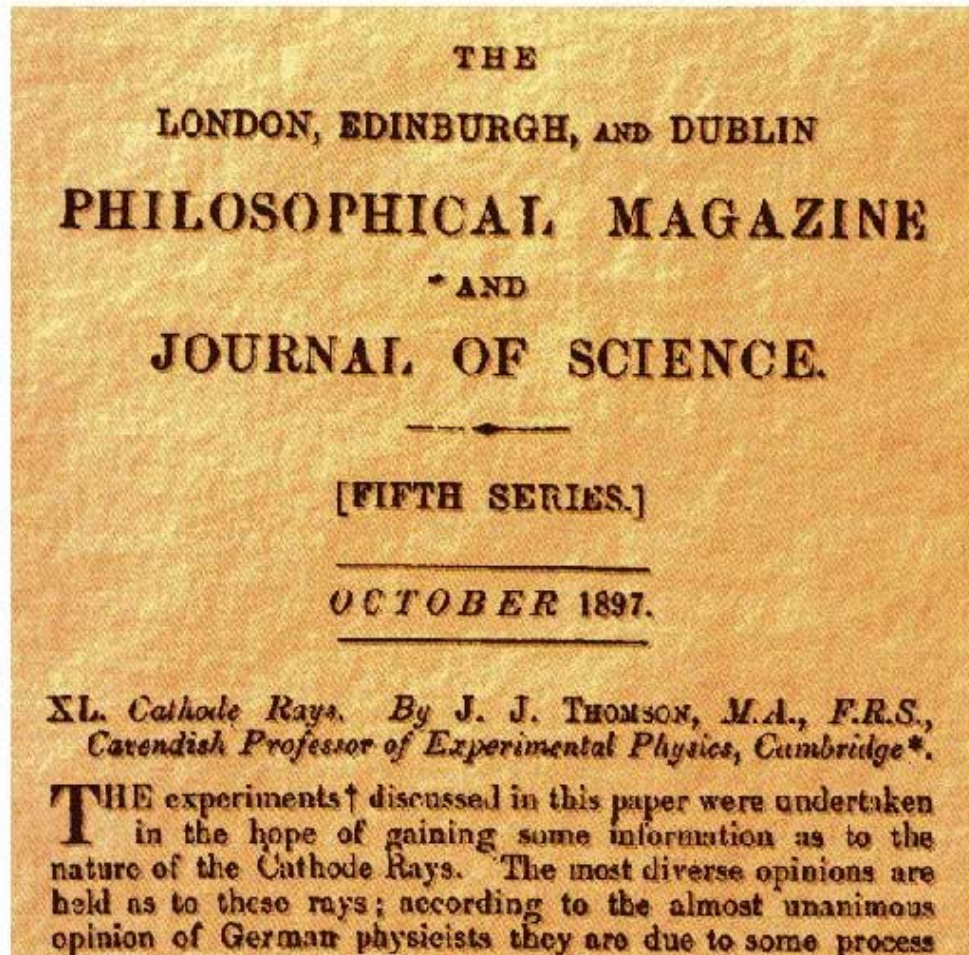
A

B ×

C

Earth

Electrometer

Thomson's paper on cathode rays

Joseph J.
Thomson
(1856 - 1940)
Nobelpreis 1906

Thomsons Publikation von 1897

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

OCTOBER 1897.

XL. *Cathode Rays.* By J. J. THOMSON, *M.A.*, *F.R.S.*, *Cavendish Professor of Experimental Physics, Cambridge*.

THE experiments† discussed in this paper were undertaken in the hope of gaining some information as to the nature of the Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process
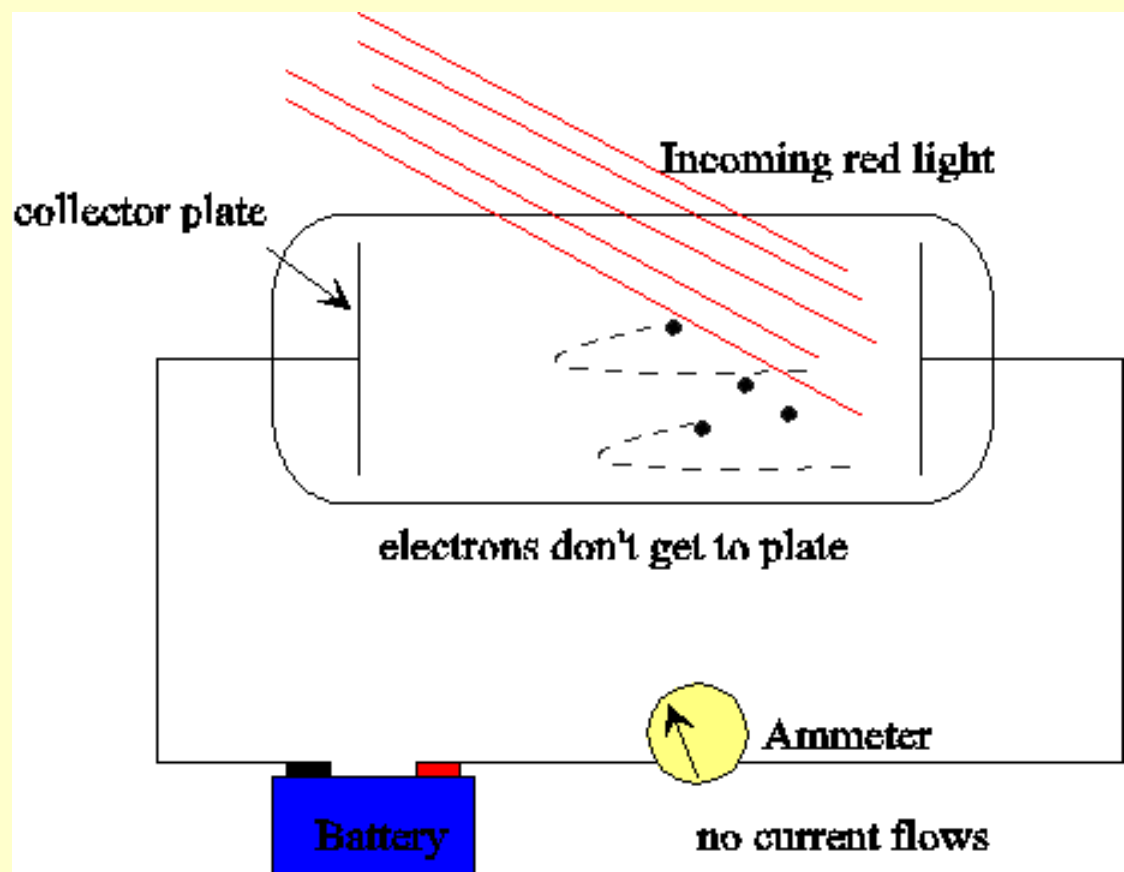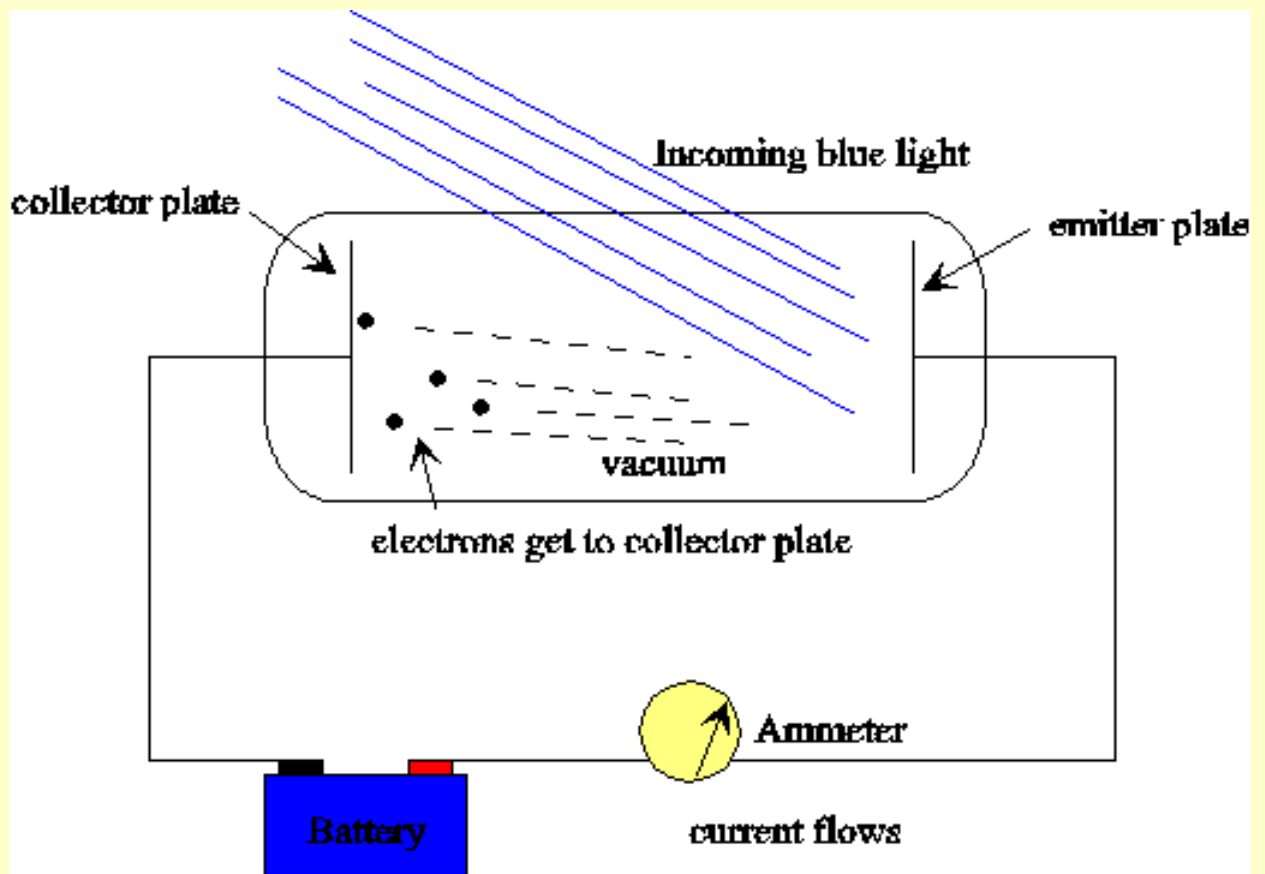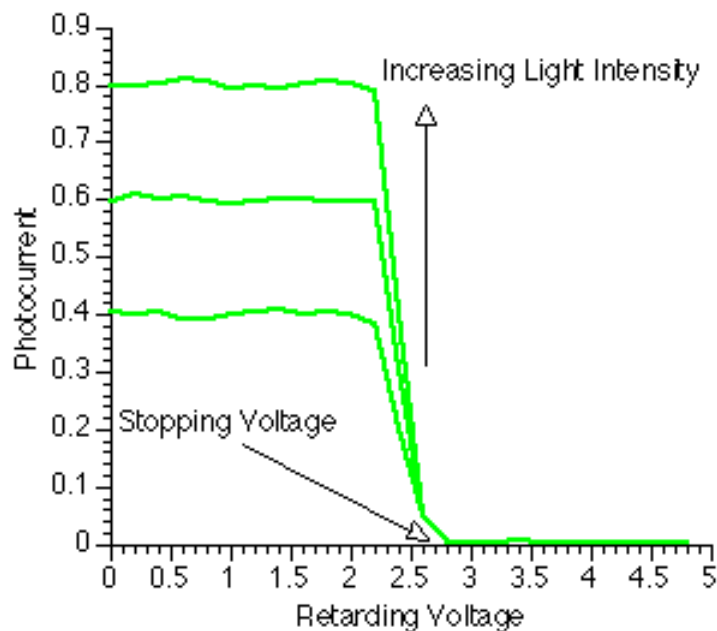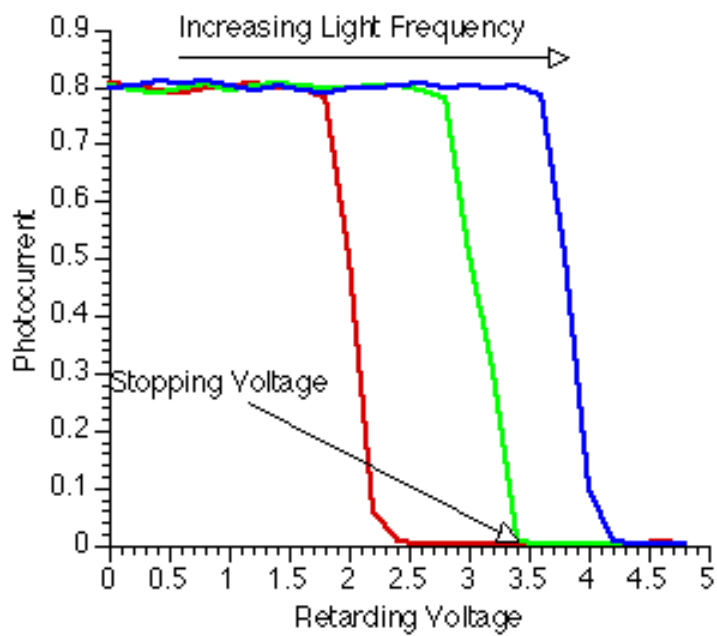
James Joseph Thomson (1856- 1940):
- 3rd Cavendish professor at Cambridge (after Maxwell and Rayleigh) (1884- 1919)
- Master of Trinity College (1918-1940)

Further studies of photoelectric effect

- 1899: J.J. Thomson: studies of photoelectric effect:
    - Modifies cathode ray tube: make metal surface to be exposed to light the cathode in a cathode ray tube
    - Finds that particles emitted due to light are the same as cathode rays (same e/m)

- 1902: Philipp Lenard
    - Studies of photoelectric effect
        - Measured variation of energy of emitted photoelectrons with light intensity
        - Use retarding potential to measure energy of ejected electrons: photo-current stops when retarding potential reaches V_{stop}
        - Surprises:
            - V_{stop} *does not* depend on light intensity
            - energy of electrons *does* depend on color (frequency) of light

Incoming blue light

collector plate

emitter plate

electrons get to collector plate

vacuum

Ammeter

Battery

current flows

Incoming red light

collector plate

electrons don't get to plate

Ammeter

Battery

no current flows

Increasing Light Frequency

Stopping Voltage

Photocurrent vs. Retarding Voltage

Increasing Light Intensity

Stopping Voltage

- 1905: Albert Einstein (1879-1955) (Bern)
  - Gives explanation of observation relating to photoelectric effect:
    - Assume that incoming radiation consists of "light quanta" of energy hf
      (h = Planck's constant, f=frequency)
    - $\Rightarrow$ electrons will leave surface of metal with energy
      $$E = hf - W$$
      W = "work function" = energy necessary to get electron out of the metal
    - When cranking up retarding voltage until current stops, the highest energy electrons must have had energy eV_{stop} on leaving the cathode
    - Therefore
      $$eV_{stop} = hf - W$$

    - $\Rightarrow$ Minimum light frequency for a given metal, that for which quantum of energy is equal to work function
- 1906 – 1916 Robert Millikan (1868-1963) (Chicago)
  - Did not accept Einstein's explanation
  - Tried to disprove it by precise measurements
  - Result: confirmation of Einstein's theory, measurement of h with 0.5% precision
- 1923: Arthur Compton (1892-1962)(St.Louis):
  - Observes scattering of X-rays on electrons