
Electricity

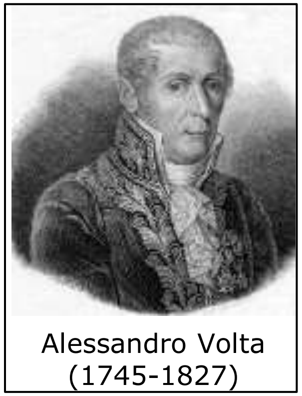
Agenda

Energy conservation, conversion, and transformation

- Potential energy, kinetic energy, work, and power
  - Variable force, chemical rearrangement energy (Enthalpy)
  - Examples
- Kinetic energy transfer,
  - Dissipation, randomization and spontaneous processes
  - Examples of thermal motion, Maxwell-Boltzmann distribution
- Electricity and Electromagnetic Power
  - Electric fields and currents, metallic and semiconductors
  - Magnetic induction
  - DC, AC circuits
- Thermodynamics principles and applications
  - First Law & Second Law of Thermodynamics, Entropy
  - Transfer of thermal energy (heat)
  - Conduction, convection, radiation (cooling)
  - Internal energy, equivalence of work and heat

Electricity: Transformative Historical Power

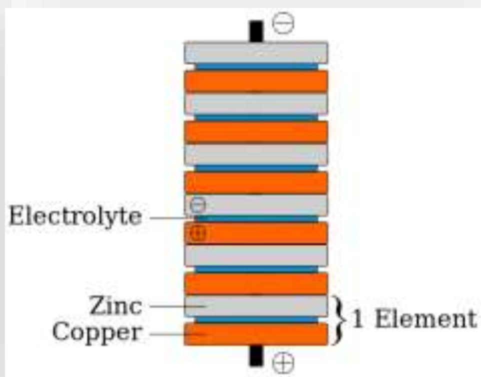
Luigi Galvani
(1737-1798)



Alessandro Volta
(1745-1827)

Static electricity know since ancient times (Thales, 600 BCE). Created by rubbing of amber with animal fur, Galvani's physiological frog leg experiments. Volta assisted Galvani, disagreed on nature of electricity.
Volta discovered battery ("Voltaic Pile"), announced March 20, 1800 to Royal Society, London.

Replica of Volta's first battery ("Voltaic Pile") Museum Tempio Voltiano.



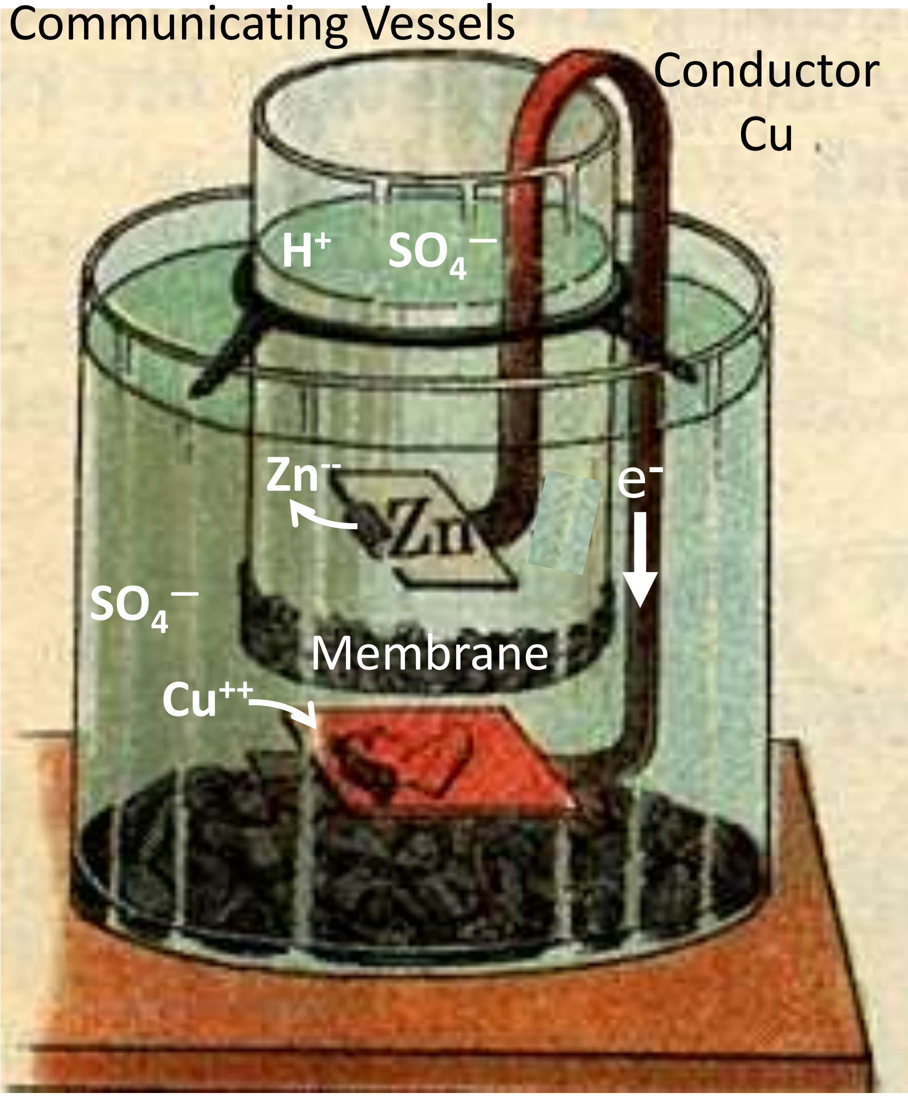
Schematics of Voltaic Pile

Stack of pairs of alternating copper (or silver) and zinc discs (electrodes) separated by cloth or cardboard soaked in brine (=electrolyte). Electro-motive force (emf, unit=Volt) builds up between metal electrodes (+electrolyte). Physiochemical reaction in the electrolyte destroys Zn electrode.

Top and bottom metal wires conduct electricity (e^-) produce spark when touching. → e^- electrical charges

Electric current increases with height of the stack (number of elements).

Electrolytic Solutions: Electroplating



Daniell Cell: Zn(s)| Zn^{2+}(aq)| Cu^{2+}(aq)|Cu(s)

Vessel solutions communicate via ion-permeable membrane. Electrodes immersed in *dissociated sulfate electrolyte* solutions. In solutions, electrons have small free path before capture → no e^- current in spite of electrostatic potential $\Delta\Phi$.

Metal band conducts e^- → enables current + chemical reactions:

→ Zn dissolves, Cu precipitates:

$$Zn(s)+Cu^{2+}(aq) \rightarrow Zn^{2+}(aq)+Cu(s)$$

2 "half redox reactions"

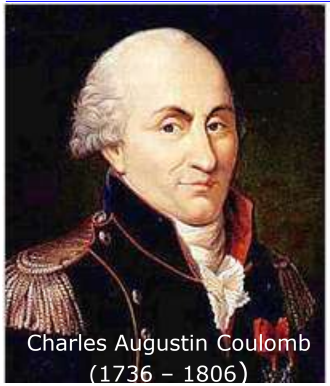
1) *Oxidation of Zn:* $Zn(s) \rightarrow Zn^{2+}(aq)+2e^-$

2) *Reduction of Cu:* $Cu^{2+}(aq)+2e^- \rightarrow Cu(s)$

Reaction energy $\Delta G^0_{rxn} = -213\, kJ/mol$

Electrons e^- are free charge carriers in metals, ions conduct in solutions.

Static Electric and Magnetic Fields



Coulomb Law: Electric potential (energy) of a point charge ***q***, at a distance ***r*** from the charge ***Q*** (relative to potential at infinity)

$$U(r) = q \cdot \frac{Q}{4\pi\,\varepsilon_0\, r}$$

Elementary charge
$e = 1.602 \cdot 10^{-19}$ Coulomb

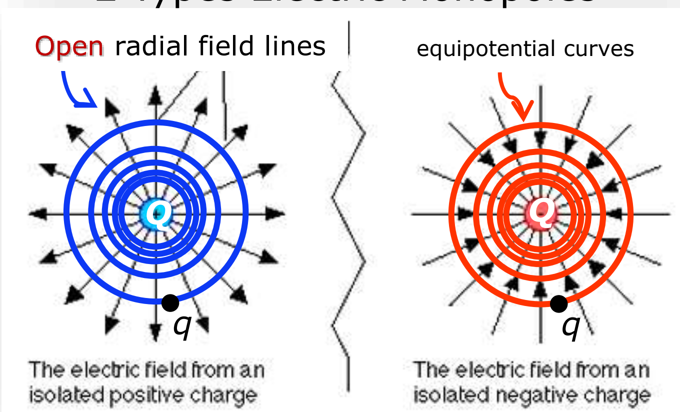
vacuum permittivity

$$\varepsilon_0 = 8.854 \cdot 10^{-12}\, \frac{F}{m}$$

$$(F = Farad \propto C^2 / N \cdot m)$$

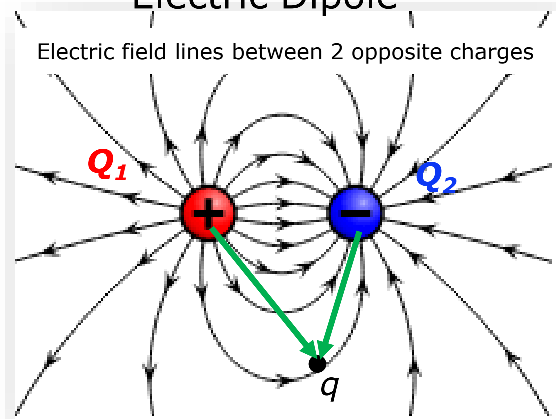
$$Coulomb\ \ force\,(\,field\,) \qquad \vec{F}(\vec{r}\,) = -\vec{\nabla} U(\vec{r}\,) := q \cdot \vec{E}$$

2 Types Electric Monopoles



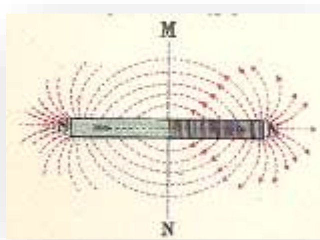
Electrostatic Interaction

Electric Dipole

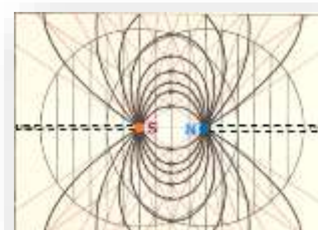


Some materials are permanently magnetic.

Permanent Dipole Magnets:
N and S
(no monopoles !)

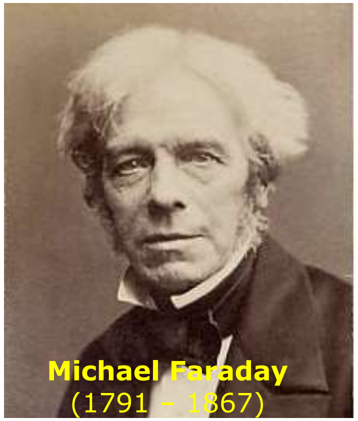


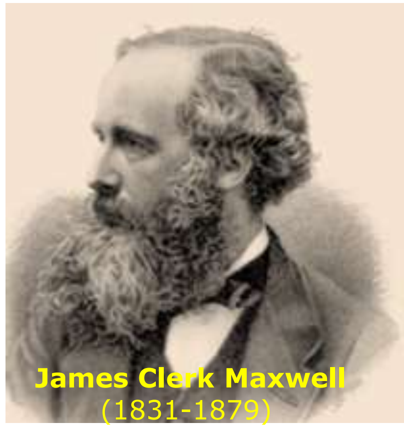
Magnetostatic Interaction



Closed magnetic field lines between N and S poles

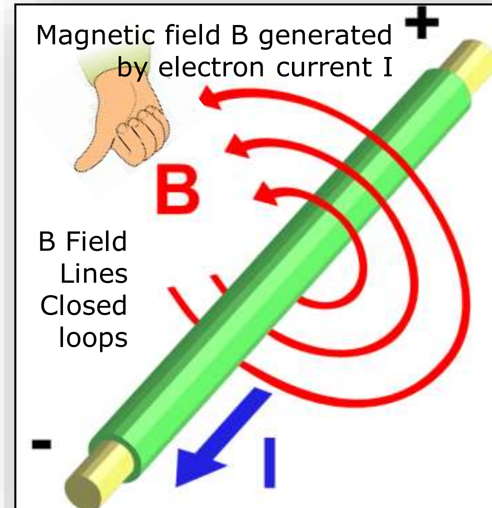
Static Magnetic Field from Electric Currents



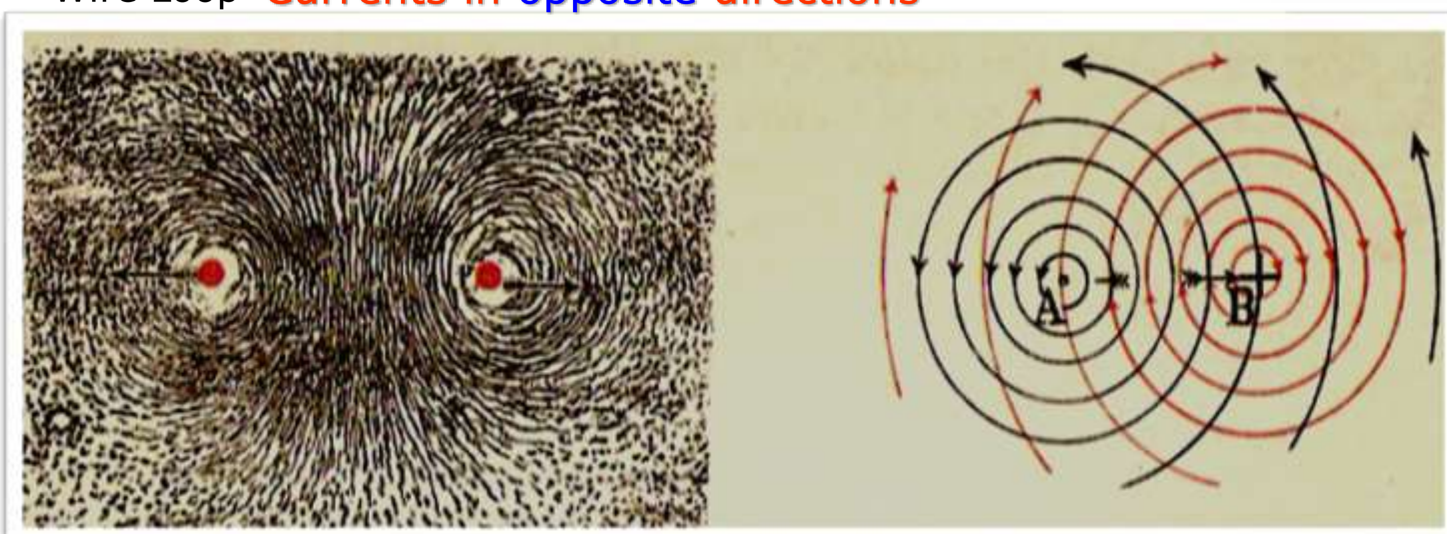


Faraday: English experimenter → magnetic fields around electrical wires.

Unified theory of electromagnetism by J.C. Maxwell



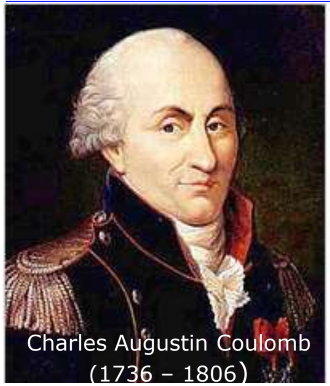
Wire Loop Currents in opposite directions



In the inside region magnetic fields are parallel and add.

Magnetic field lines = always closed loops: visible with iron filings, middle B strong+aligned

Work in Electrostatic Fields

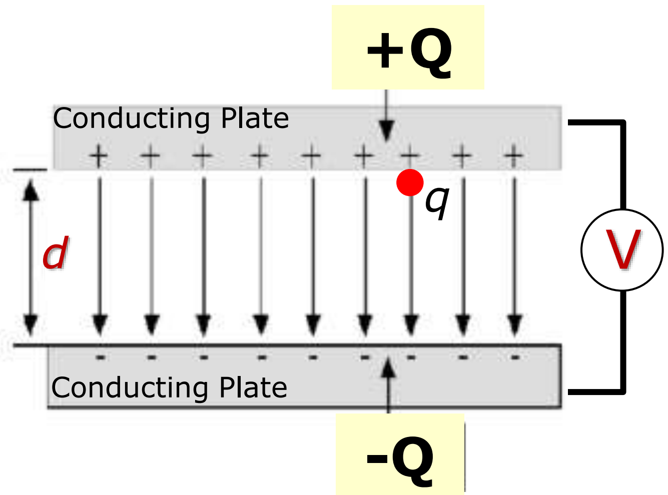


Coulomb Law: Electric potential (energy) of a point charge q at distance r from the charge Q (relative to r=∞) is defined as

$$\text{Potential energy of } q \text{ in 1-dim potential}: U(r) = q \cdot \left(\frac{Q}{4\pi\varepsilon_0 r} \right)$$

$$\text{Coulomb force on } q: \boxed{\vec{F}(\vec{r}) = -\vec{\nabla} U(\vec{r}) := q \cdot \vec{E}} \rightarrow \boxed{\text{electric field } \vec{E}(\vec{r})}$$

Uniform, homogeneous electric field $\vec{E}$ between two parallel conducting plates, space filled with vacuum or *dielectric medium* of permittivity ε.



$$\boxed{\left|\vec{E}\right| = \frac{V}{d} \quad unit\left[E\right] = \frac{Volts}{m}}$$

Particle of charge q, unit $[q]$= 1e = $1.602 \cdot 10^{-19}$C.

Force on particle: $\boxed{\vec{F} = q \cdot \vec{E}}$ $\quad unit\left[F\right] = N$

Energy gained between plates $\boxed{W = F \cdot d = q \cdot V}$

Power gained $P = \dfrac{\Delta W}{\Delta t} = \dfrac{q}{\Delta t} \cdot E \cdot d \rightarrow \boxed{P = I \cdot V}$

Electric current I, $\left[I\right] = A\ (Ampere) = C/s$

Particle of charge q=e falling through 1V differential gains energy E=1eV. 1eV=$1.602 \cdot 10^{-19}$J.

Electrodynamics of Moving Charges

James Clerk Maxwell
(1831-1879)

Developed a unified understanding of electric and magnetic phenomena → Maxwell's equations = set of partial differential equations that, together with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits, much of today's technology.

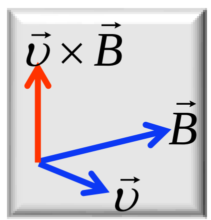
$Particle\ el.\ charge\ q,\ velocity\ \vec{\upsilon}$

$Electric\ (\vec{E}),\ magnetic\ (\vec{B})\ fields$

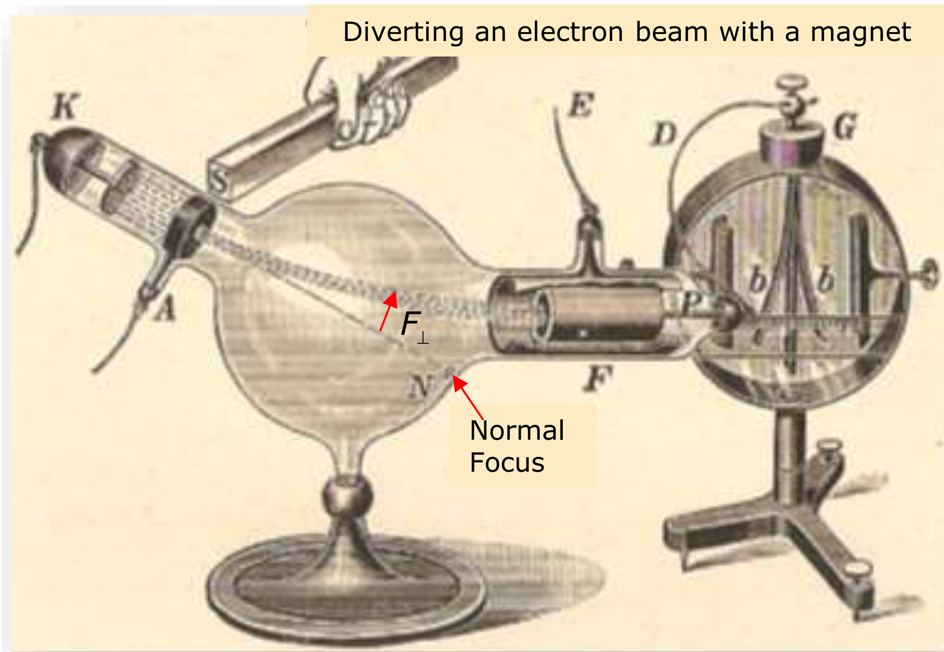
$\rightarrow Lorentz\ \ Force:$

$$\boxed{\begin{array}{l}\vec{F}=q\cdot\left(\vec{E}+\vec{\upsilon}\times\vec{B}\right)\\ E=0\rightarrow F_{\perp}=q\upsilon B=i\cdot B\end{array}}$$

$Electric\ current\ \ i=q\cdot\upsilon$

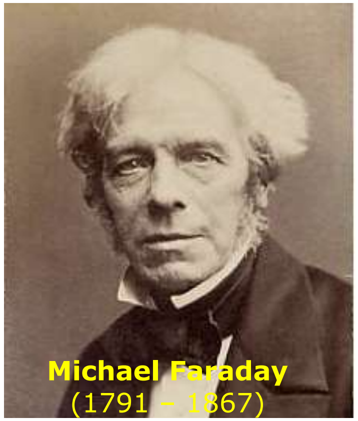


Vector cross product



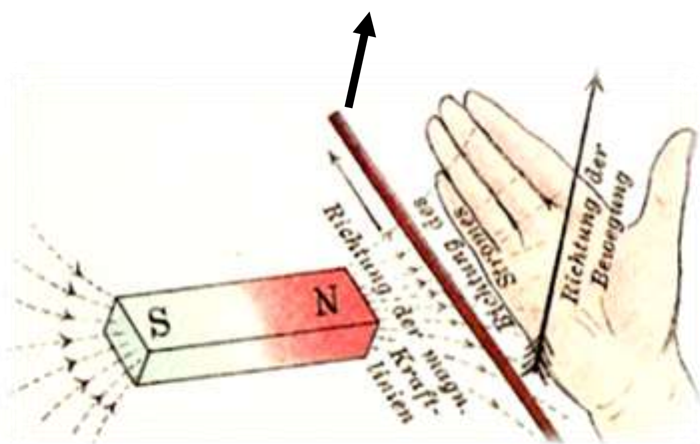
Moving electric charges *q* across magnetic field direction ($\vec{\upsilon}\perp\vec{B}$) produces a force $F_{\perp}$ on the charges, perpendicular to velocity direction → accelerates electric charges → produces charge movement = **electrical current *I*(*t*) perpendicular to *B*(*t*) field.**

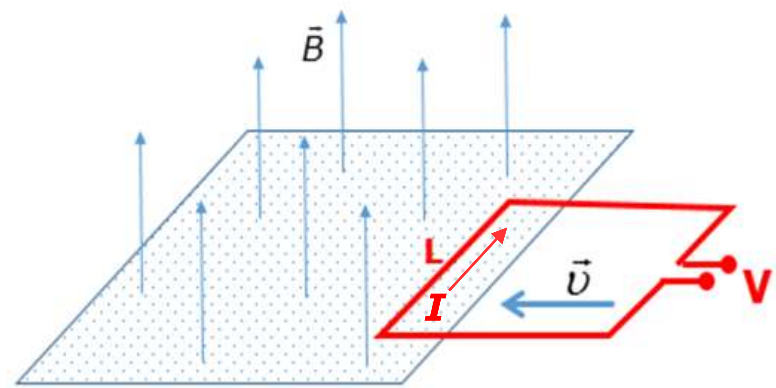
Electromagnetic Induction


Michael Faraday
(1791 – 1867)

Induction:
Moving electric conductor (Cu wire) across static magnetic field *B* interacts *like* $B(t)$ with electrons in wire → induces current (electron flow) in the wire (attempts to cancel effect of external *B* field → generates charge ΔQ and potential difference ΔU ("voltage") between wire ends).

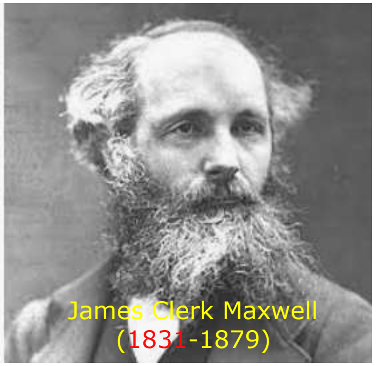
Right-hand rule (Lenz's Law):
Moving wire in direction of thumb through B forces electron current in direction of fingers.





Moving electric charges = current $I = dq/dt \triangleq q \cdot \upsilon$
←→ magnetic field *B*,
Changing magnetic field $\Delta B(t)$←→electron current $\Delta I(t)$.

Electromagnetic Field Theory: Maxwell Equations



Combination of individual laws of electric and magnetic interactions into one theoretical framework:
MEq describe an electric vector field $\vec{E}(\vec{r},t)$ and a magnetic (pseudo) vector field, $\vec{B}(\vec{r},t)$, as well as their interactions.
The sources are the total electric charge density (total charge per unit volume), $\boldsymbol{\rho}$, and the total electric current density (total current per unit area), $\boldsymbol{J}$.

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho\, dV$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\boxed{\oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_{\Sigma}\mathbf{B}\cdot d\mathbf{S}}$	$\boxed{\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0\left(\iint_{\Sigma}\mathbf{J}\cdot d\mathbf{S} + \varepsilon_0\frac{d}{dt}\iint_{\Sigma}\mathbf{E}\cdot d\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

$Here: \vec{B} := magnetic\ \ flux\ \vec{\Phi}$

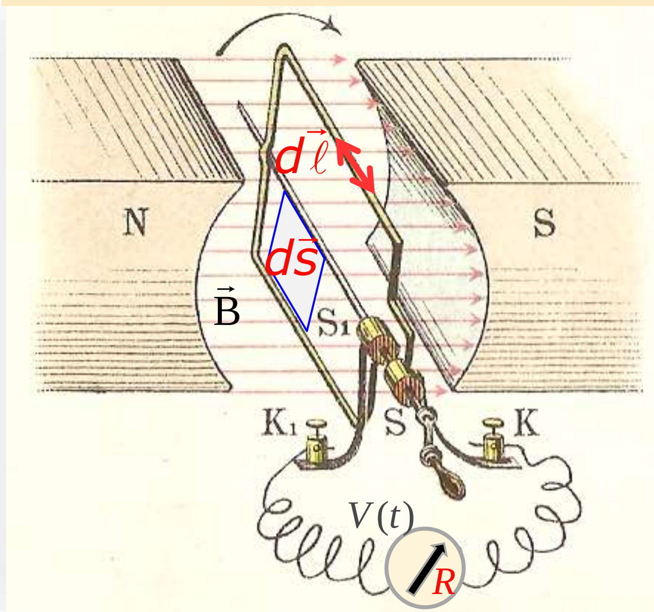
the permittivity of free space, ε_0, and
the permeability of free space, μ_0, and
the speed of light, $c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$

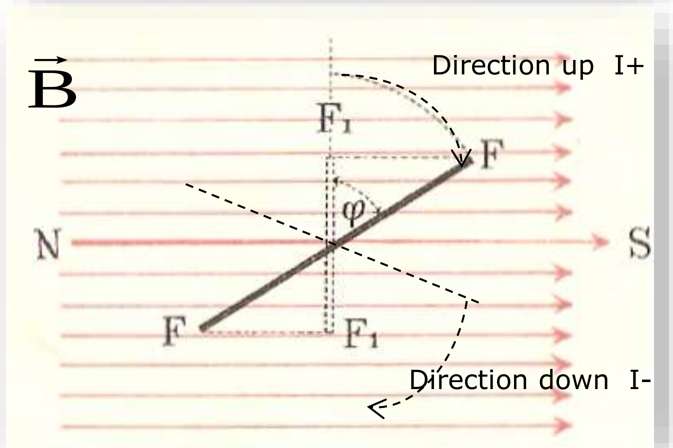
Magnetic flux through plane surface $\vec{S}$

$$\vec{\Phi} := \vec{B}\cdot\vec{S} := B_{\perp}\cdot S\cdot\vec{n}_S \quad Unit\ [\Phi] = Wb\ (Weber) = volt - s$$

Principle of Generator (Dynamo)

Voltage induced on wire loop turning in B field





Direction of flow of electricity (electrons e$^-$) in a wire-conductor loop → induced electro-motive force *emf* (Faraday's Law)

$$t-\text{variable } B: \boxed{\partial B(t)/\partial t = -\vec{\nabla}\times\vec{E}(t)} \quad \text{circulating electric field}$$

$$\text{Integral form}: \frac{\partial}{\partial t}\int_{Loop\ Area}\vec{B}(t)\cdot d\vec{s} = -\oint_{Loop\ Rim}\vec{E}\cdot d\vec{\ell} \propto \text{work (on } q)$$

Time dependent A/C Voltage $V(t)$ and Current $I(t)$

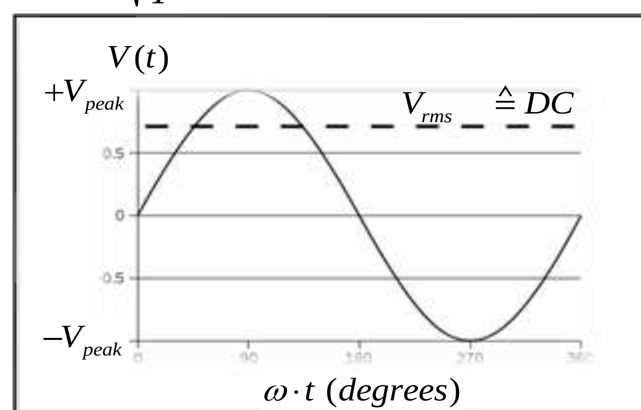
$$V(t) = V_{peak}\cdot\sin(\omega\cdot t) \qquad I(t) = \left(V_{peak}/R\right)\cdot\sin(\omega\cdot t)$$

Amplitude Phase

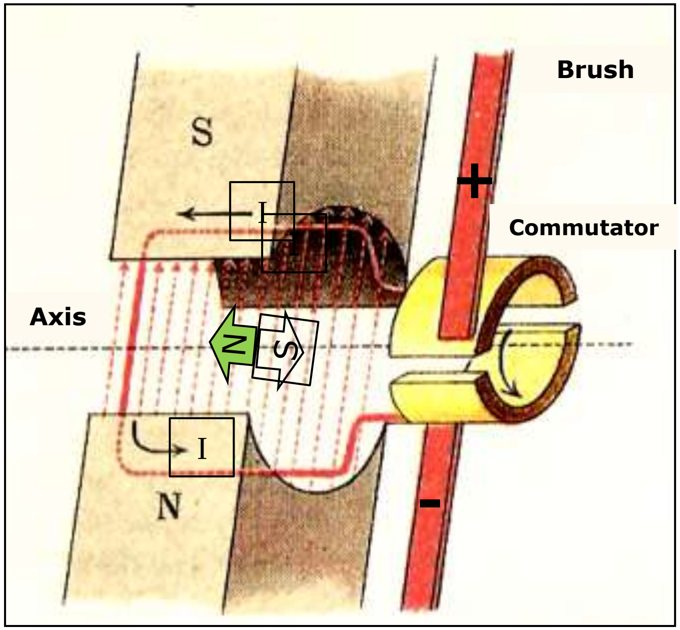
$$\text{Amplitude } V_{peak},\ V_{peak-to-peak} = 2V_{peak}$$

$$\text{Angular frequency } \omega = \partial\varphi/\partial t = 2\cdot\pi\cdot f = 2\pi/T$$

$$\text{Effective voltage}: \langle V(t)\rangle = V_{rms} = \sqrt{\frac{1}{T}\int_0^T V^2(t)dt} = V_{peak}/\sqrt{2}$$

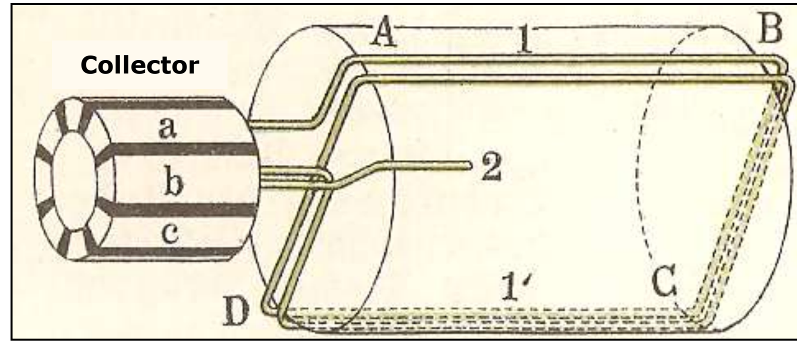


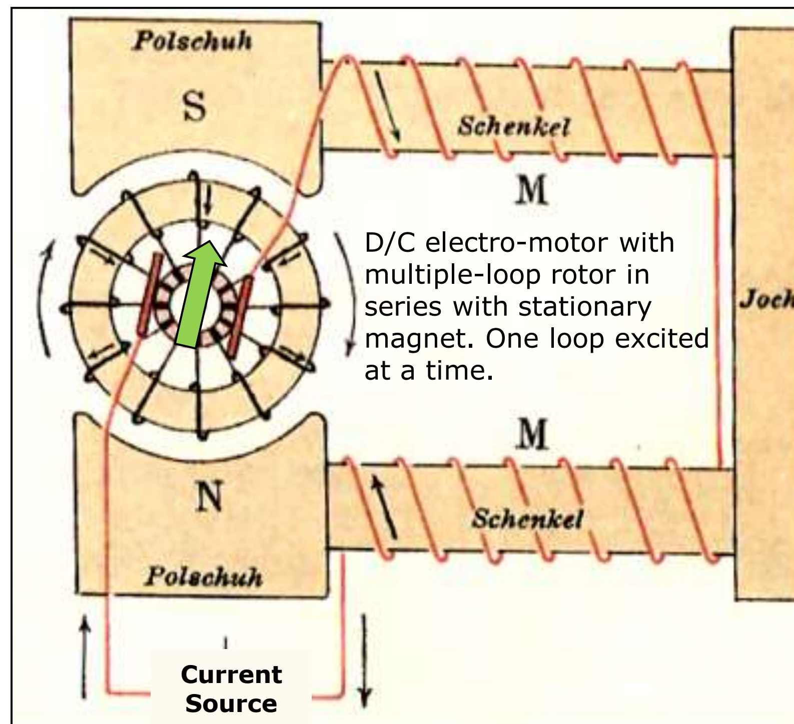
Principle of D/C Electro-Motor



Current (I) loop creates alternating *N-S* electro-magnet, which "feels" a torque and tends to align parallel to the field of permanent magnets and turns loop. Polarity reverses magnet polarity at max. alignment.

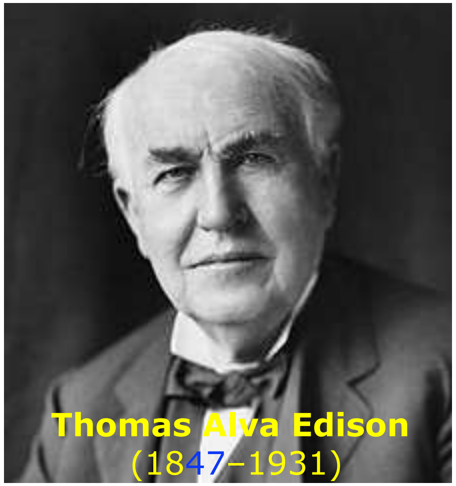
Mechanical rotation of wire loop in field of permanent magnets generates voltage at commutator/collector → **Dynamo/Alternator**
Direction of current depends on orientation of loop in magnetic field → AC or DC currents

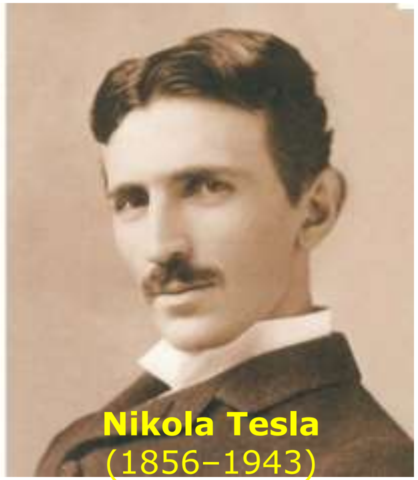




D/C electro-motor with multiple-loop rotor in series with stationary magnet. One loop excited at a time.

Advent of Hydroelectric Power

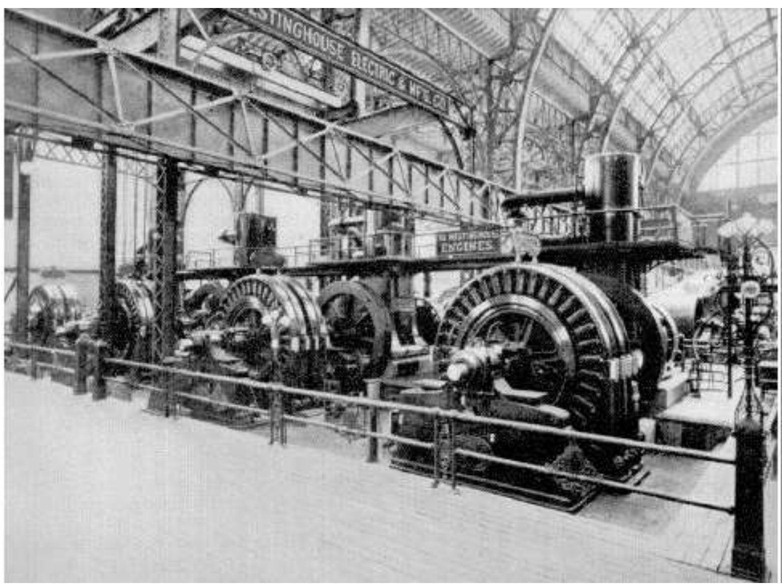


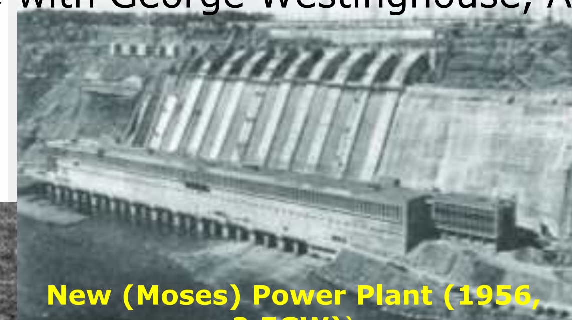


Influential inventors of DC (Edison) and AC (Tesla) electrical power transmission over large distances.

Electrical lighting, wireless radio,….
Power wars (→ J.P. Morgan).

1895: Built 1. hydro electric power station (Niagara, with George Westinghouse, AC)





Start of new chapter in hydropower
→ many hydro-electric power plants