Agenda

Energy conservation, conversion, and transformation

- Potential energy, kinetic energy, work, and power
  - Variable force, chemical rearrangement energy (Enthalpy)
  - Examples

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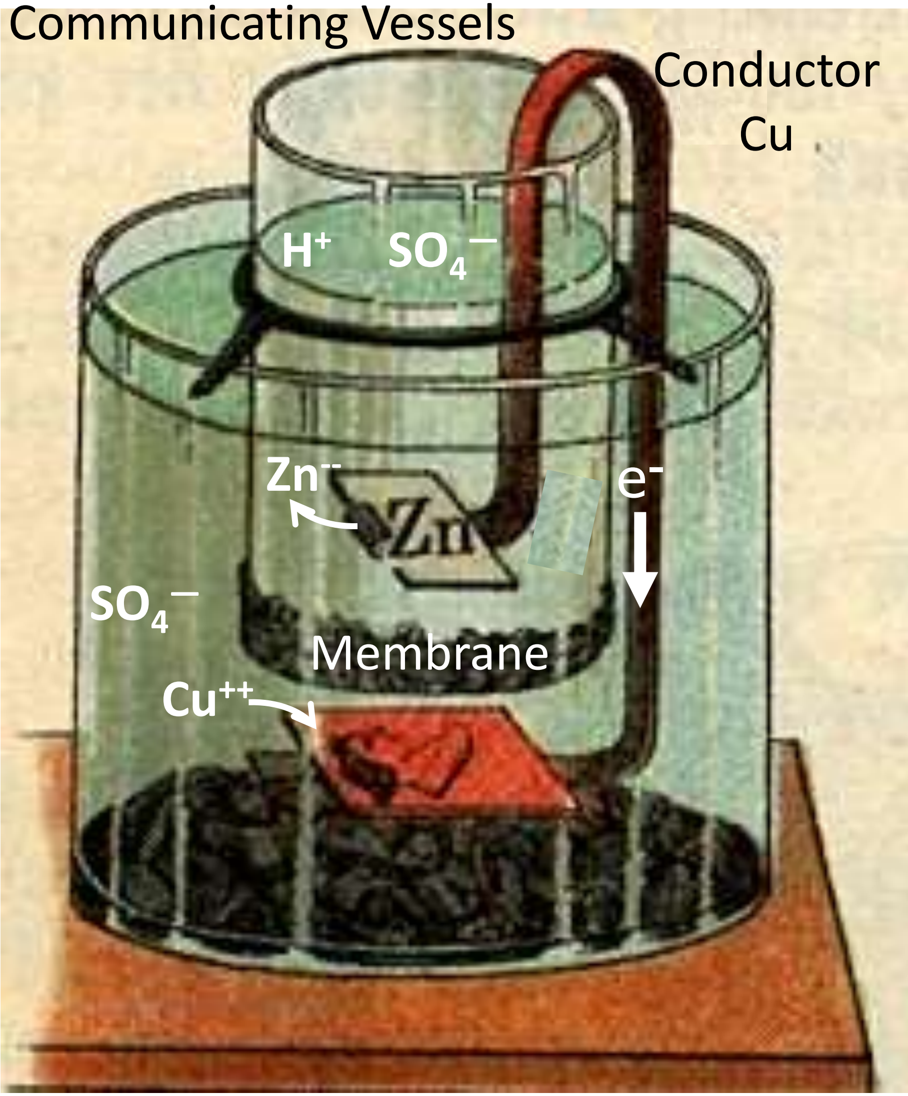
- Kinetic energy transfer,
  - Dissipation, randomization and spontaneous processes
  - Examples of thermal motion, Maxwell-Boltzmann distribution

- Electricity and Electromagnetic Power
  - Electric fields and currents, metallic and semiconductors
  - Magnetic induction
  - 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

W. Udo Schröder, 2024

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"

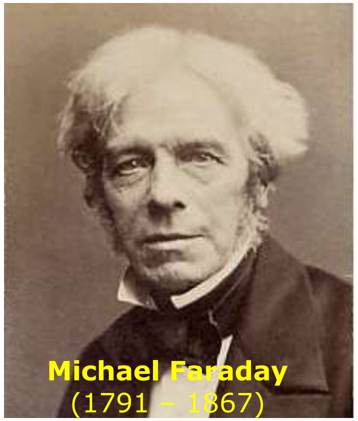
1) *Oxidation of Zn:* $Zn(s) \rightarrow Zn^{2+}(aq)+2e^-$

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

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

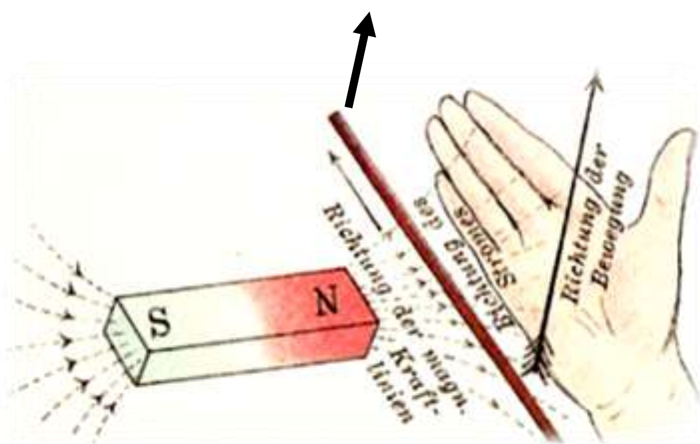
Electrons e^- are free charge carriers in metals, ions conduct in solutions.

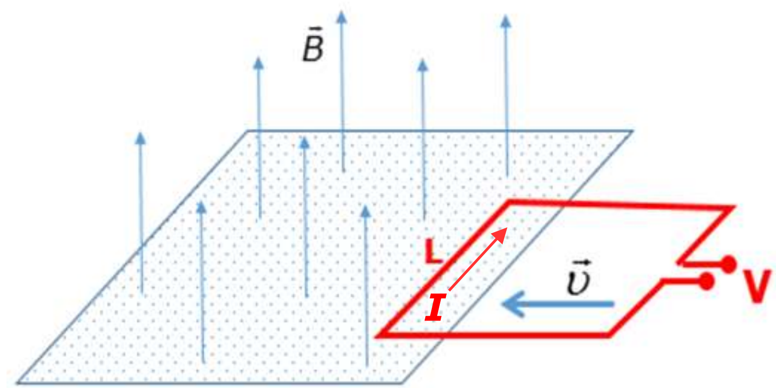
Electromagnetic Induction



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).

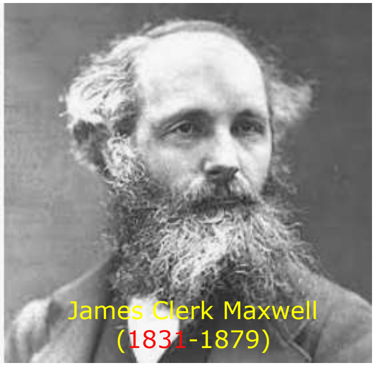
Right-hand rule (Lenz's Law):
Moving wire in direction of thumb through B forces electron current in direction of fingers.





Moving electric charges = current $I = dq/dt \triangleq q \cdot \upsilon$
←→ magnetic field *B*,
Changing magnetic field Δ*B*(*t*)←→electron current Δ*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	$\oiint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma}\mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{B}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma}\mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\left(\iint_{\Sigma}\mathbf{J}\cdot\mathrm{d}\mathbf{S} + \varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{E}\cdot\mathrm{d}\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

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

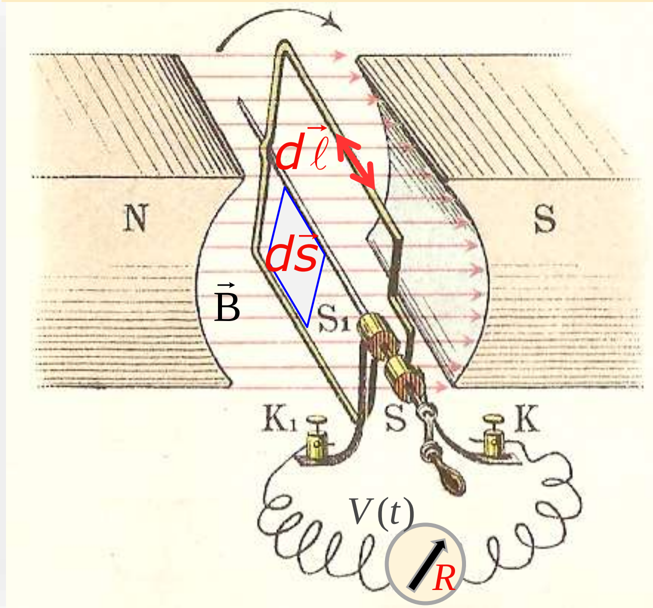
the permittivity of free space, ε_0, and
the permeability of free space, μ_0, and
the speed of light, $c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$

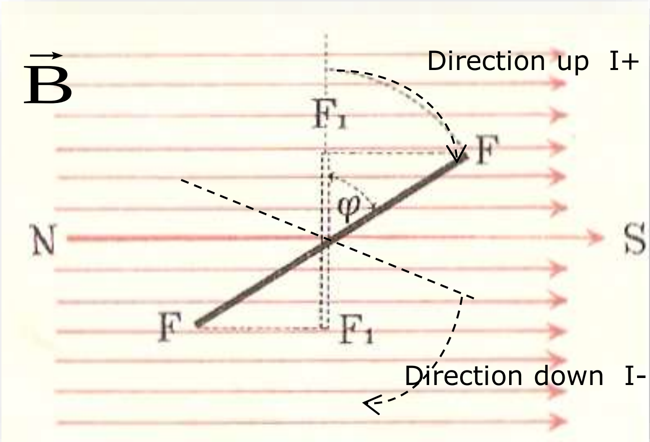
Magnetic flux through plane surface $\vec{S}$

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

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)

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

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

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

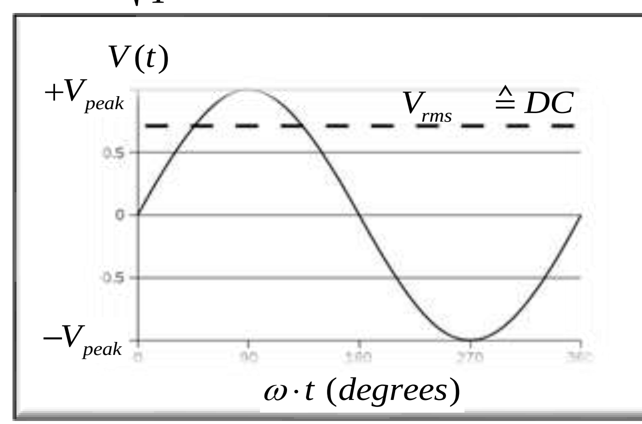
$$V(t) = V_{peak}\cdot\sin(\omega\cdot t) \qquad I(t) = (V_{peak}/R)\cdot\sin(\omega\cdot t)$$

Amplitude   Phase

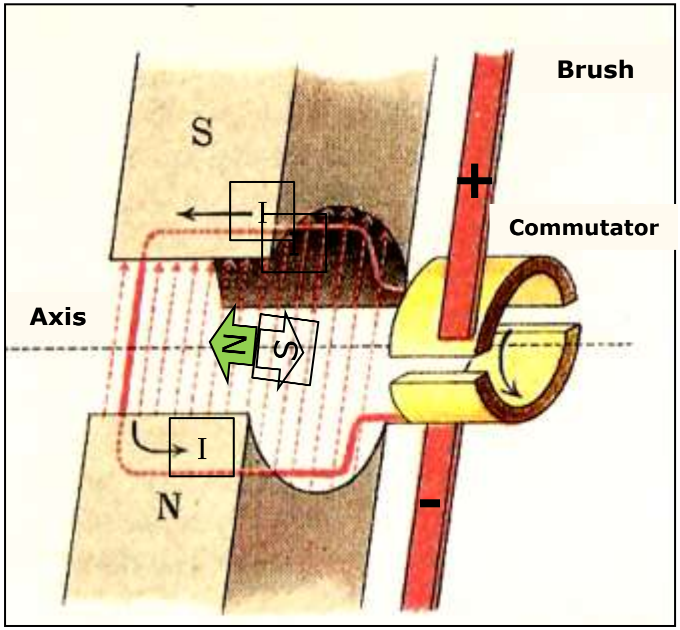
$$\text{Amplitude } V_{peak},\ V_{peak-to-peak} = 2V_{peak}$$

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

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

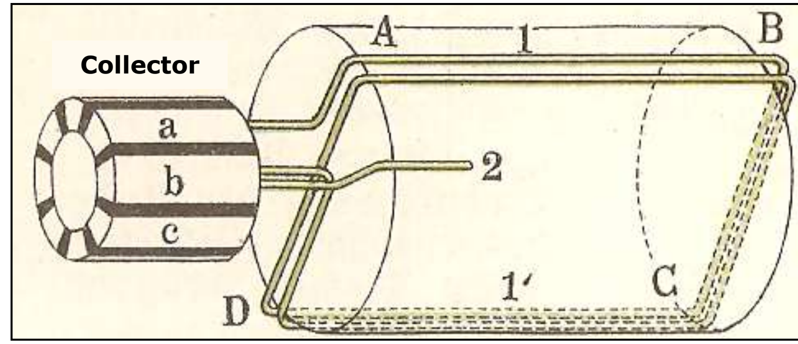


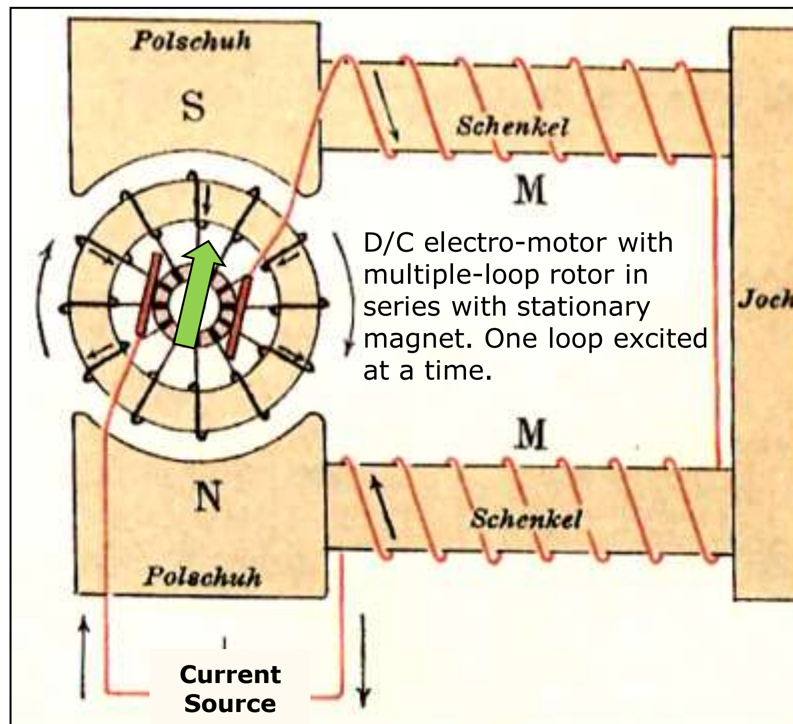
Principle of D/C Electro-Motor



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.

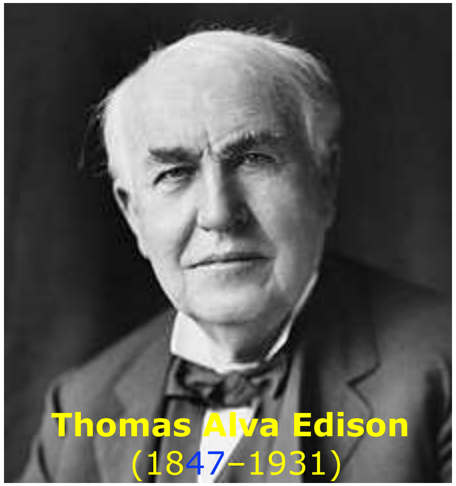
Mechanical rotation of wire loop in field of permanent magnets generates voltage at commutator/collector → **Dynamo/Alternator**
Direction of current depends on orientation of loop in magnetic field → AC or DC currents

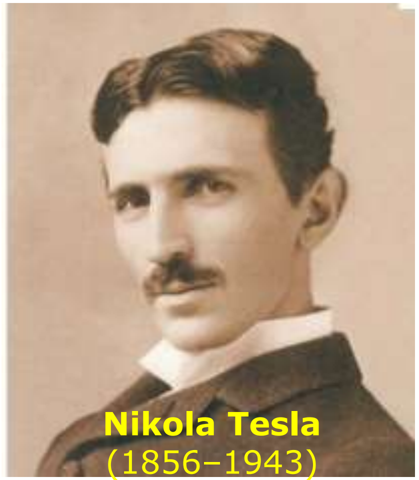




D/C electro-motor with multiple-loop rotor in series with stationary magnet. One loop excited at a time.

Advent of Hydroelectric Power

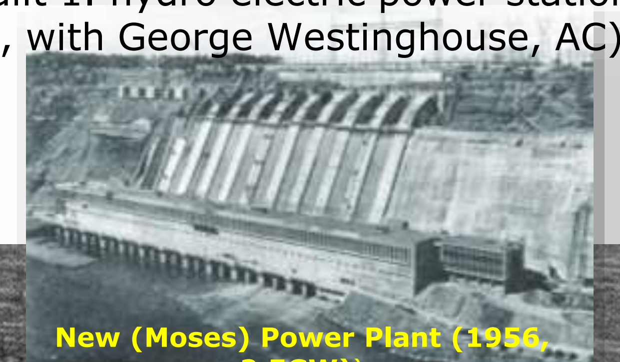


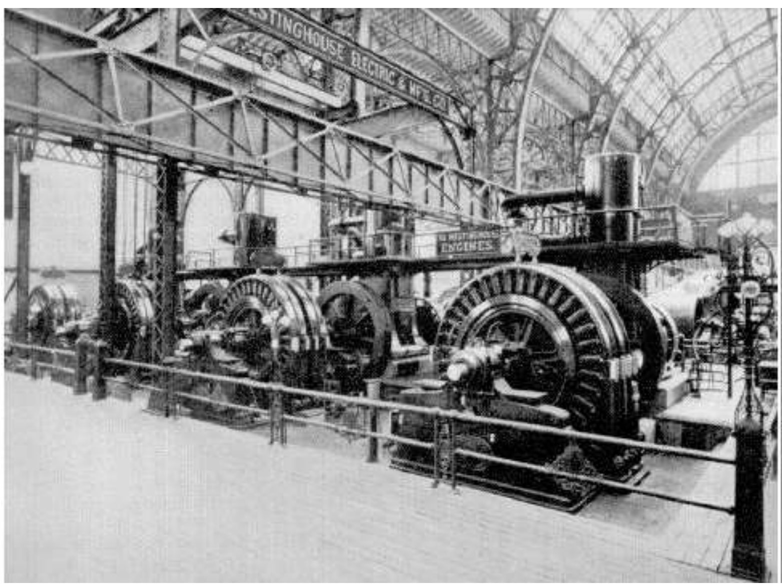


Influential inventors of DC (Edison) and AC (Tesla) electrical power transmission over large distances.

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

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





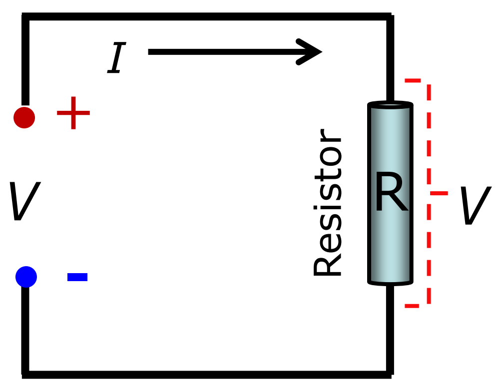
Start of new chapter in hydropower
→ many hydro-electric power plants

Components of Electrical DC Circuits: Resistors

Electric current I unit=[1 A(mpere)= 1C/s]:
e^- stream [dq/dt=#e^-/sec] transfers power through metallic wires, dissipates e^- energy→ heat. All metallic wires have intrinsic (distributed) resistivity.

→ Unidirectional (DC) electrical (e^-) current sustained by applied electric potential = Voltage differential V=constant in time.

Always finite electric conductivity σ → 1/Ohm resistance $R \neq 0$!!



Ohm's Law

$$I = \frac{V}{R} \rightarrow V = I \cdot R$$

$$[R] = 1\Omega\ (Ohm) = \frac{1V}{1A}$$

Power dissipated in resistor

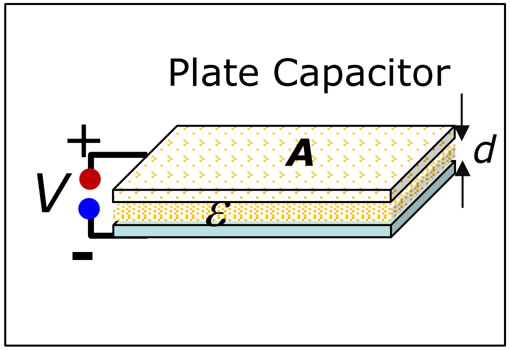
$$p = V \cdot I = I^2 \cdot R$$

$$[p] = W\ (Watt) = J/s$$

Power drained from the electric source V (battery discharged)

Commercial resistor elements are made of materials with low electric conductivity.

Components of Electrical DC Circuits: Capacitors

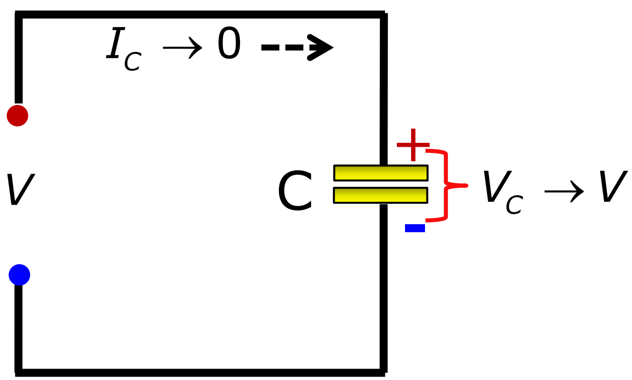


Metal plates (area *A*) separated by dielectric medium (ε) of thickness *d* form a capacitor w. capacitance

$$C = \frac{\varepsilon \cdot A}{d} \qquad [C] = F\,(Farad)$$

→Carries static charge $Q = C \cdot V$

As "load" element :



$$Switch-on\ voltage\ V \to brief\ \ current\ I_C(t)$$

$$V_C(t) = \frac{1}{C}Q(t) = \frac{1}{C}\int^{t} I_C(t')dt' \to V$$

Potential energy content W_C of capacitor C

$$W_C = \frac{1}{2}Q \cdot V = \frac{C}{2}V^2 = \frac{Q^2}{2C}$$

$$\frac{dW_C}{dt} = 0$$

A purely capacitive load in an electrical circuit does not dissipate (lose) power.

Components of Electrical DC Circuits: Inductances

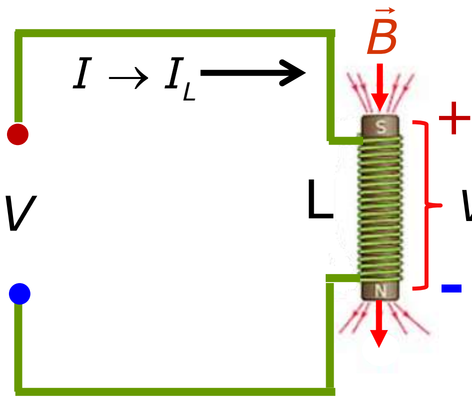
Helical coil of insolated Cu wire wound ***N** times* around plastic ("solenoid") or ferrite/carbon-iron core. Connected to electric battery it produces static axial magnetic field ("electro-magnet"). K= material and geometry factor.

Inductance $$L = \mu_0 K \left(N^2 A/\ell \right)_{coil}$$

$$[L] = H = Vs / A \ \ (Henry)$$

$$1H = 1kg \cdot m^2 \cdot s^{-2} \cdot A^{-2}$$

As "load" element in circuit:



$$V_L(t) = -L\frac{dI}{dt} \rightarrow Work \ \frac{dW_L}{dt} = -L \cdot I \cdot \frac{dI}{dt} \rightarrow 0$$

Potential energy content W_L stored in inductor L

$$W_L = \frac{1}{2} L \cdot I_L^2$$

$$\frac{dW_L}{dt} = 0$$

A purely inductive load in an electric circuit does not dissipate electric energy.

Components of Electrical AC Networks: Resistors

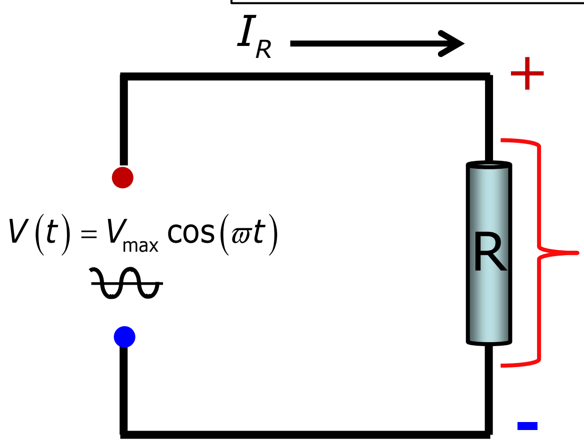
Transfer of electrical power through metallic wires → Electric conductivity σ → Electrons dissipate kinetic energy through scattering
→ Ohm resistance $R \sim 1/\sigma \quad [R] = \Omega\ (Ohm)$ Extension: R=generic workload

$$Applied\ \ AC\ voltage\ \ [V] = V\ (Volt)$$

$$V(t) = V_{\max}\cos(\varpi t) \rightarrow effective\ V = \langle V(t)\rangle = V_{\max}/\sqrt{2}$$

$$effective\ \ I = \langle I(t)\rangle = I_{\max}/\sqrt{2}$$

Averaged over 1 period



$$I_R(t) = I_{\max}\cos(\varpi t); \quad I_{\max} = \frac{V_{\max}}{R}$$

Ohm's Law

$$Current\ \ I_R(t)\ \{[I] = A\ (Ampere)\}\ \ in\ phase\ with\ V(t)$$

Power dissipated in resistor $[p] = W\ (Watt)$

$$p_R(t) = V(t)\cdot I_R(t) = V_{\max}I_{\max}\cos^2(\varpi t)$$

$$= \frac{1}{2}V_{\max}I_{\max}\{1+\cos(2\varpi t)\} = V\cdot I_R\{1+\cos(2\varpi t)\}$$

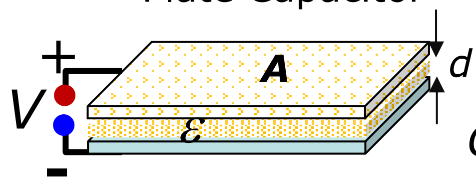
effective

$$Effective\ dissipated\ power\ \ \langle p_R(t)\rangle = V\cdot I_R = \frac{V^2}{R} = I_R^2\cdot R$$

This is real power loss.

Components of Electrical AC Networks: Capacitors

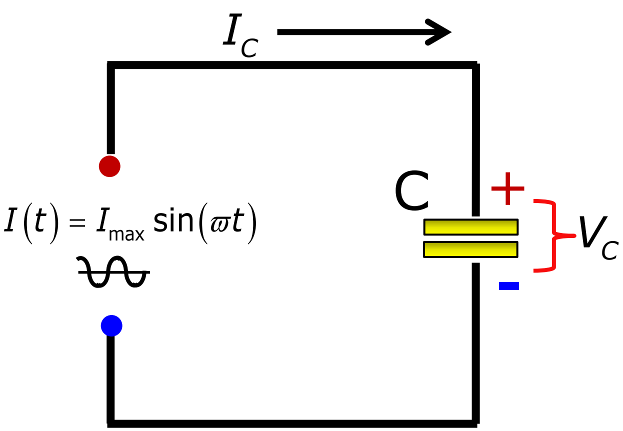
Plate Capacitor



Metal plates (area *A*) separated by dielectric medium (ε) of thickness *d* form a capacitor w. capacitance

$$C = \frac{\varepsilon \cdot A}{d}; \left[C\right] = F\left(Farad\right)$$ →Carries static charge $Q = C \cdot V$

As "load" element in AC (frequency ω) circuit:



$$V_C\left(t\right) = \frac{1}{C}Q\left(t\right) = \frac{1}{C}\int^{t} I_C\left(t'\right)dt' = \frac{I_{max}}{\varpi C}\cos\left(\varpi t\right)$$

$$= V_{max}\cos\left(\varpi t\right) \rightarrow \boxed{V_{max} = I_{max} \cdot X_C}$$ Ohm's Law

Reactance $\left|X_C\right| = \frac{1}{\varpi C}$

Current leads voltage : phase difference $+\frac{\pi}{2}$

Power in capacitor

$$p_C\left(t\right) = V\left(t\right) \cdot I_R\left(t\right) = V_{max}I_{max}\sin\left(\varpi t\right) \cdot \cos\left(\varpi t\right)$$

$$= \frac{1}{2}V_{max}I_{max}\left\{\sin\left(2\varpi t\right)\right\} \rightarrow \boxed{\left\langle p_C\left(t\right)\right\rangle = 0}$$

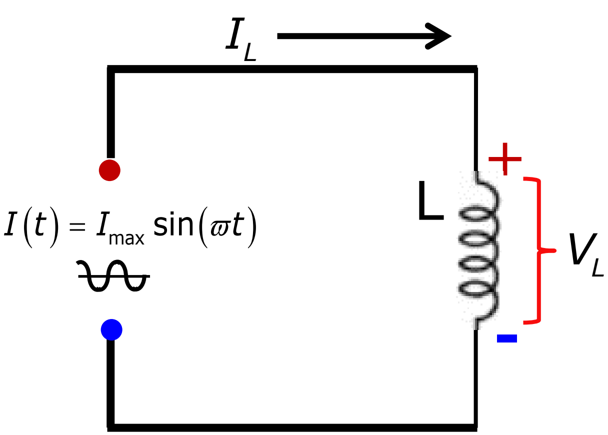
A pure capacitive load in an AC circuit does not dissipate (lose) power, it moves energy between electron currents and electric field and changes relative phase of current vs. voltage → reactive power

Components of Electrical AC Networks: Inductors

Helical coil insolated Cu wire wound around plastic ("solenoid") or ferrite/carbon-iron core. Connected to electric battery it produces static axial magnetic field ("electro-magnet")

Inductance L, $L_{solenoid} = \mu_0 K\left(N^2 A/\ell\right)_{coil}$ [L]=H=Vs/A (Henry)

As "load" element in AC (frequency ω) circuit:



$$V_L(t) = -L\frac{dI}{dt} = -\varpi L \cdot I_{\max}\cos(\varpi t)$$

$$= V_{\max}\cos(\varpi t) \rightarrow \boxed{V_{\max} = I_{\max}\cdot X_L}$$ Ohm's Law

Reactance $|X_L| = \varpi L$

$$\textit{Current lags voltage : phase difference} -\frac{\pi}{2}$$

Power in inductor

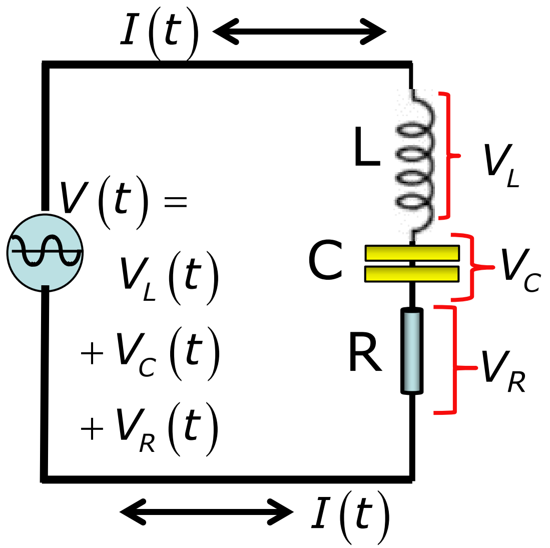
$$p_L(t) = V_L(t)\cdot I(t) = -V_{\max}I_{\max}\sin(\varpi t)\cdot\cos(\varpi t)$$

$$= -\frac{1}{2}V_{\max}I_{\max}\left\{\sin(2\varpi t)\right\} \rightarrow \boxed{\langle p_L(t)\rangle = 0}$$

A pure inductive load in an AC circuit does not dissipate (lose) electric power, it moves energy between electron currents and magnetic field and changes relative phase of current vs. voltage → reactive power

Basic Electrical Circuit Laws

Ohm's Law $V(t) = Z \cdot I(t)$ $(\Delta\phi_I = \textit{phase difference } I \textit{ rel } V)$

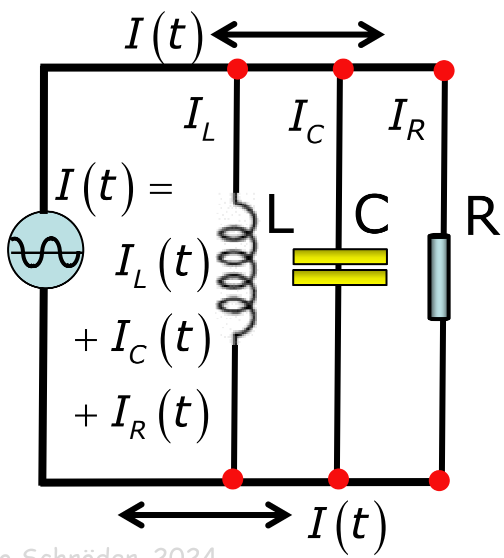


1. Ohm resistance R
1. Capacitive reactance $X_C = -1/\omega C$ $(\Delta\phi_I = +90^0)$
2. Inductive reactance $X_L = \omega L$ $(\Delta\phi_I = -90^0)$

Kirchhoff's Loop (or mesh) Rule

The directed sum of the potential differences (voltages) around any closed loop is zero.

$$V(t) = V_L(t) + V_C(t) + V_R(t)$$

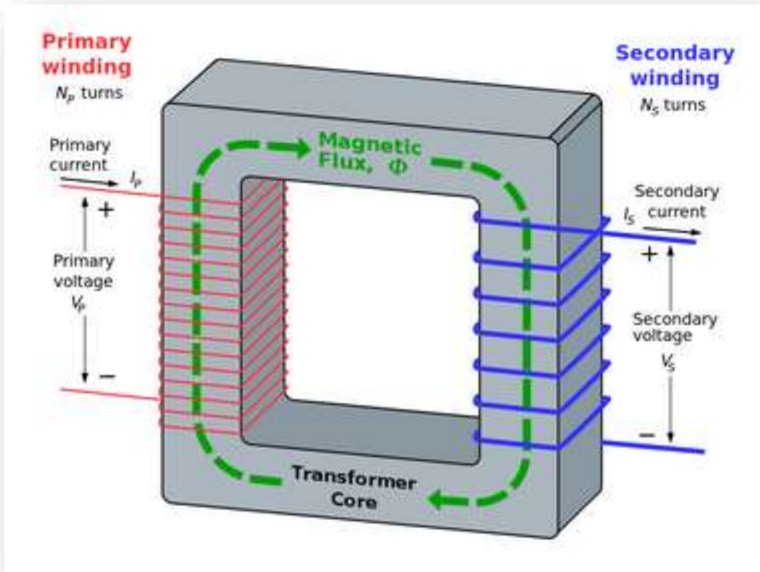


Kirchhoff's Junction Rule (Parallel Loops)

The algebraic sum of currents in a network of conductors meeting at a point is zero.

$$I(t) = I_L(t) + I_C(t) + I_R(t)$$

AC Transformers

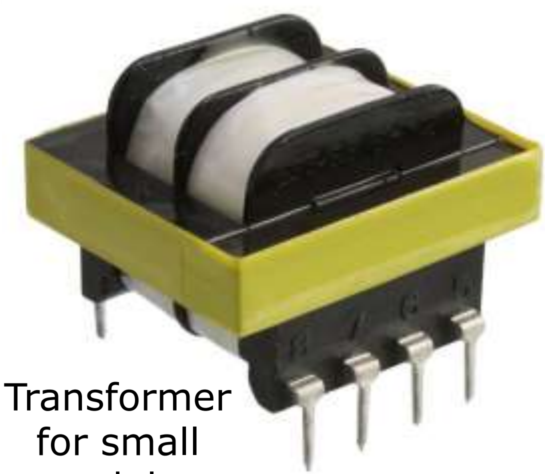


$$V_{primary} = -N_{primary}\, d\Phi/dt$$
$$V_{secondary} = -N_{secondary}\, d\Phi/dt$$
$$V_{secondary}/V_{primary} = N_{secondary}/N_{primary}$$
$$Changes\ load\ impedance\ Z_{primary}$$

Laminated or toroidal transformer cores.

Iron/steel laminations prevent eddy currents. Insulated with a nonconducting material, such as varnish or epoxy.

Toroidal: coils wrapped around cylindrical core.



Transformer for small modular electronics

Cooled power transformer on national e-grid

Complex Notation

Phase differences are conveniently handled in complex notation *V(t), I(t)*

$$V(t)=|V(t)|\cdot e^{i\cdot(\varpi\cdot t+\phi_V)};\quad I(t)=|I(t)|\cdot e^{i\cdot(\varpi\cdot t+\phi_I)}$$

Amplitudes and phases are determined from initial conditions, *V(t=0), I(t=0).*
Example:

$$V(t=0)=V_0\rightarrow V(t)=V_0\cdot\cos(\varpi\cdot t)$$

Ohm's Law $V(t)=Z\cdot I(t)$ *at all times*

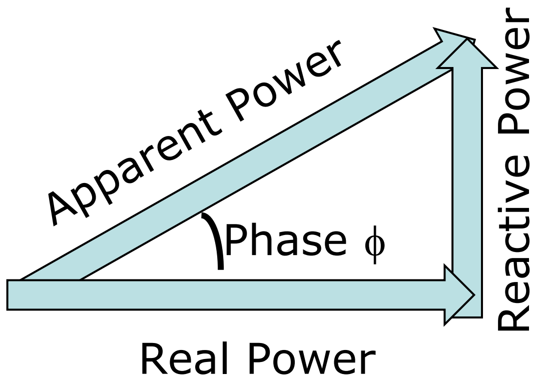
Impedance $Z = R + i\cdot[X_C(\omega) + X_L(\omega)]$ $(i:=\sqrt{-1})$

1. Ohm resistance *R*
1. Capacitive reactance $X_C= -1/\omega C$ $(\Delta\phi_I = +90^0)$
2. Inductive reactance $X_L = \omega L$ $(\Delta\phi_I = -90^0)$

$$Euler's\ Formula: i=e^{i\cdot\pi/2}=\cos(\pi/2)+i\cdot\sin(\pi/2)$$

Real and Reactive Power

Power $P(t) = V(t) \cdot I(t)$ *or, in complex notation* $P = V \cdot I^*$ $(* = \text{complex conjugate})$



Purely resistive loads : $P_R = V_R \cdot I = V^2/R = I^2 \cdot R$

Real power $P_R(t) = V_R(t) \cdot I(t)$

Apparent power : $P_A(t) = \sqrt{P_R^2(t) + P_{LC}^2(t)}$

Real power $P_R(t) = P_A(t) \cdot \cos\phi$

Power Factor $= P_R / P_A$

Real and reactive power are "out of phase"

Apparent power : $P_A^2(t) = P_R^2(t) + \left[P_C^2(t) + P_L^2(t)\right]$

Oscillating reactive power $P_C(t) \rightleftarrows P_L(t)$

Reactive power $P_{LC}(t) = P_A(t) \cdot \sin\phi$ "var" *voltage – ampere – ractive*

Actual loads on the power supply (e-grid) like an e-motor are always complex (Ohm + capacitive + inductive) → have feedback effect on supply → Affect power factor (available power) and frequency.
→ General effect on stability of grid.