Basic concepts, energy and materials

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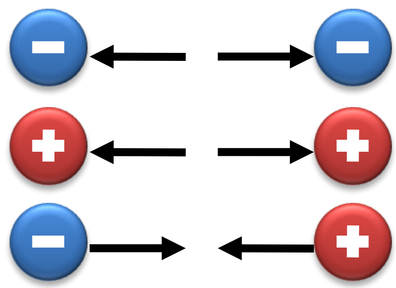
Electric Charge

Building blocks: Electron, charge -*e*

Proton, charge +*e*

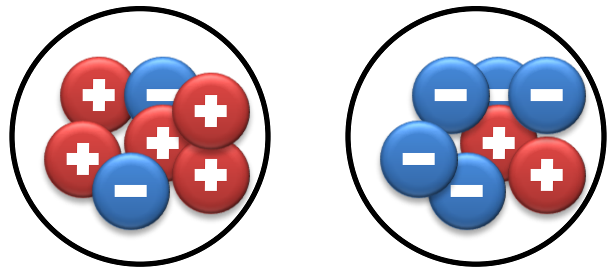
Attract/repel:



Unit: Coulomb (C)

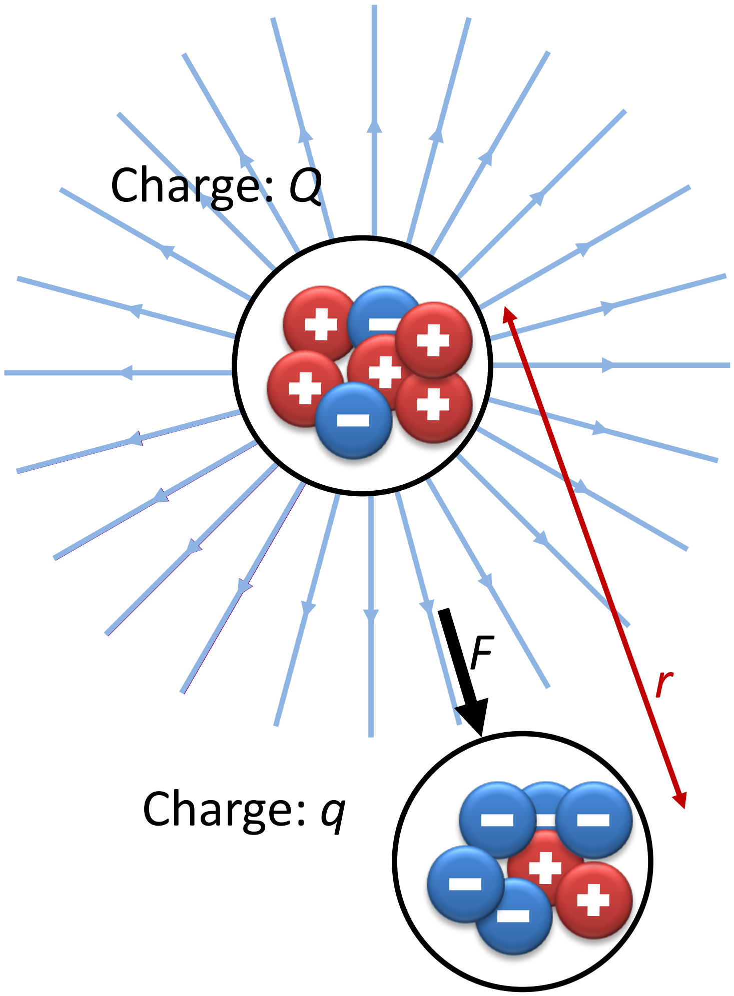
$e = 1.60 \times 10^{-19}$

Positive/negative:



Quantized: Always an integer times the **elementary charge** *e*.

Electric field



Electric field strength at distance *r* from charge *Q* :

$$E = k \frac{Q}{r^2} \quad \text{[Volt/meter]}$$

Coulombs law:
Force experienced by a charge *q* at distance *r* from charge *Q* :

$$F = k_e \frac{qQ}{r^2} \quad \text{[Newton (N)]}$$

$$k_e = 8.99 \times 10^9 \ [Nm^2/C^2]$$

QUIZ: How ”strong” are the electrical forces?

First: Heard of the 800 pound gorilla?

AFTER EXPERIENCING A BAD MOBILE CONNECTION WHILE USING HIS IPAD, THE 800 LB. GORILLA CHECKS IN

800-pound gorilla is an (American) English expression for a person or organization so powerful that it can act without regard to the rights of others or the law.

Comes from a riddle:

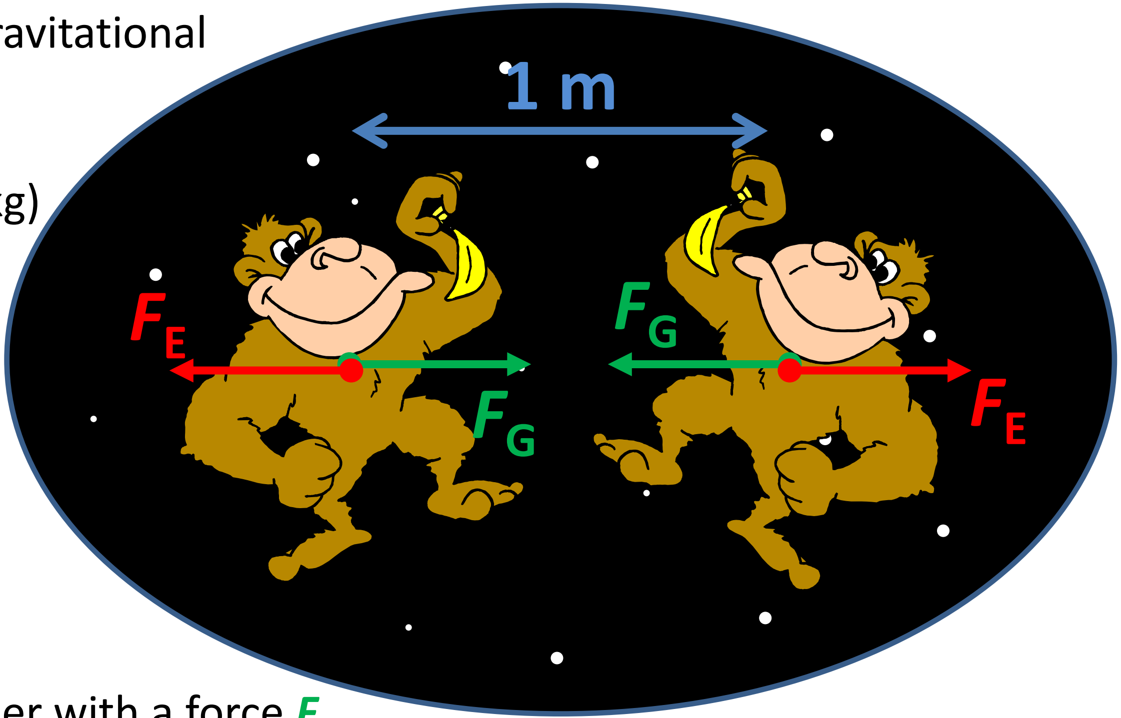
- Where does an 800-pound gorilla sit?
- Anywhere it wants to!

FACT: The heaviest gorilla ever recorded was a 586 pound silverback shot in Ambam, Cameroon.

QUIZ: How "strong" are the electrical forces?

Now: The real quiz ...

Let's compare eletrical and gravitational forces!



Two **800 pund gorillas** (363 kg) are floating around in space, 1 m from each other!

For some reason they both have about 0.01% too many electrons in their bodies.

Gravitation pulls them together with a force F_G.

Electrical forces pushes them apart with a force F_E .

Which force wins?

ANSWER: Let's calculate the forces!

NEWTON'S GRAVITATIONAL LAW

$$F_G = G\frac{mM}{r^2} = 8.8 \times 10^{-6} \ [N]$$

$$\begin{cases} G = 6.67 \times 10^{-11} \ [Nm^2/kg^2] \\ m = 363 \ [kg] \\ M = 363 \ [kg] \\ r = 1 \ [m] \end{cases}$$

COLOUMB'S LAW

$$F_E = k_e\frac{qQ}{r^2} = 2.9 \times 10^{22} \ [N]$$

$$\begin{cases} k_e = 8.99 \times 10^{9} \ [Nm^2/C^2] \\ q = ??? \ [C] \ = -1.8\times 10^{6} \ [C] \\ Q = ??? \ [C] \ = -1.8\times 10^{6} \ [C] \\ r = 1 \ [m] \end{cases}$$

How many are 0.01% too many electrons (one extra per 10 000)?

A neutral body contains an equal number of electrons and protons ... and neutrons.

One electron + one proton + one neutron weighs (0.0009+1.67+1.67)x10^{-27} = 3.34x10^{-27} [kg]

In a "normal" 363 kg gorilla, there must be something like 363/3.34x10^{-27} = 1.1x10^{29} electrons. So ... 0.01% too many electrons must be about **1.1x10^{25}** electrons per gorilla.

How much charge is 1.1x10^{25} electrons?

The elementary charge is *e* = 1.60x10^{-19} [C], and we get a charge per gorilla of

$$q = Q = -1.60 \times 10^{-19} \times 1.1 \times 10^{25} = -1.8\times 10^{6} \ [C]$$

ANSWER: Let's calculate the forces!

NEWTON'S GRAVITATIONAL LAW

$$\boldsymbol{F_G} = G\frac{mM}{r^2} = \mathbf{8.8 \times 10^{-6}}\ [N]$$

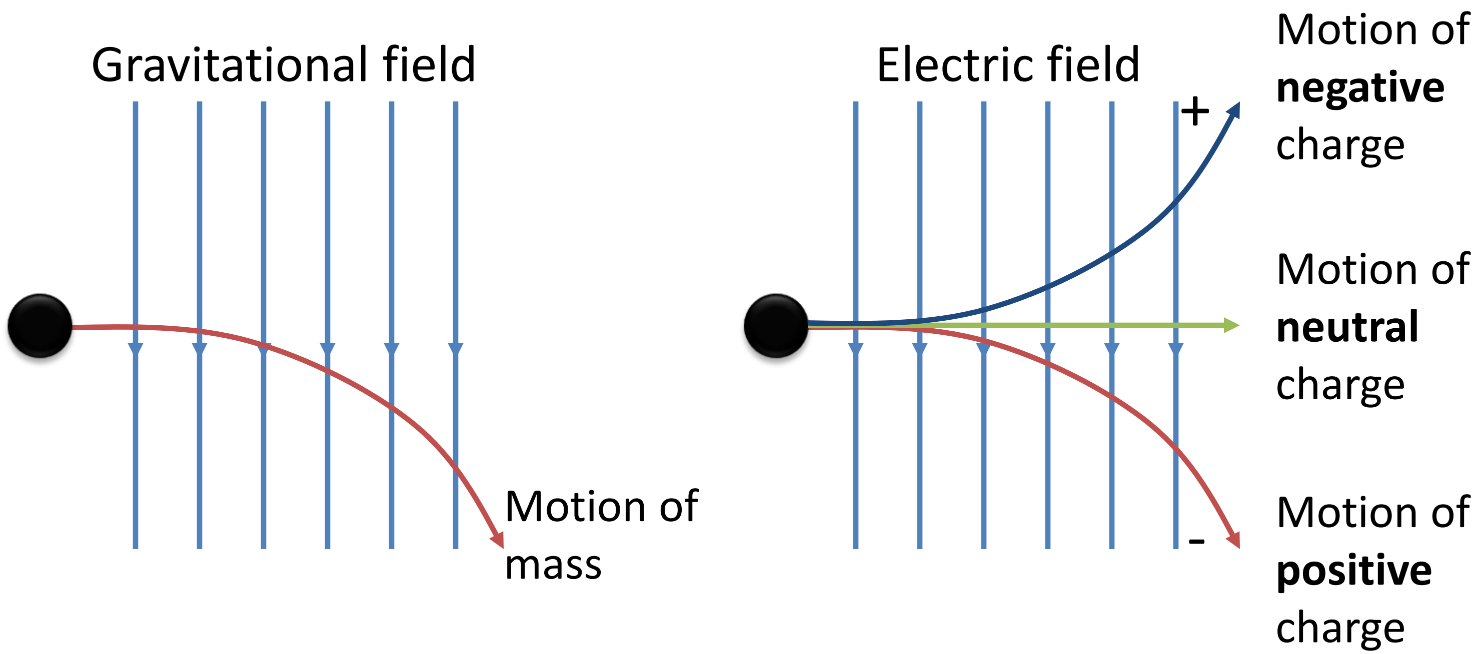
COLOUMB'S LAW

$$\boldsymbol{F_E} = k_e\frac{qQ}{r^2} = \mathbf{2.9 \times 10^{22}}\ [N]$$

Only enough to lift about 1 mg on earth

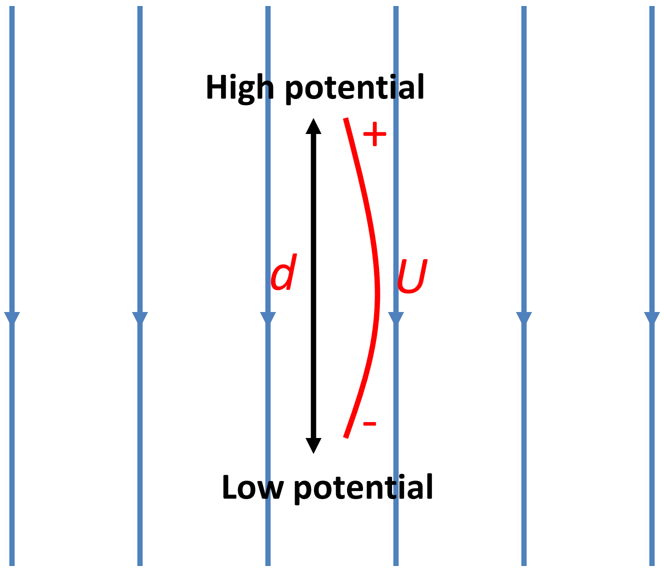
This force is more than enough to lift all water in the Pacific Ocean

Compare: Gravity and electric field



Voltage

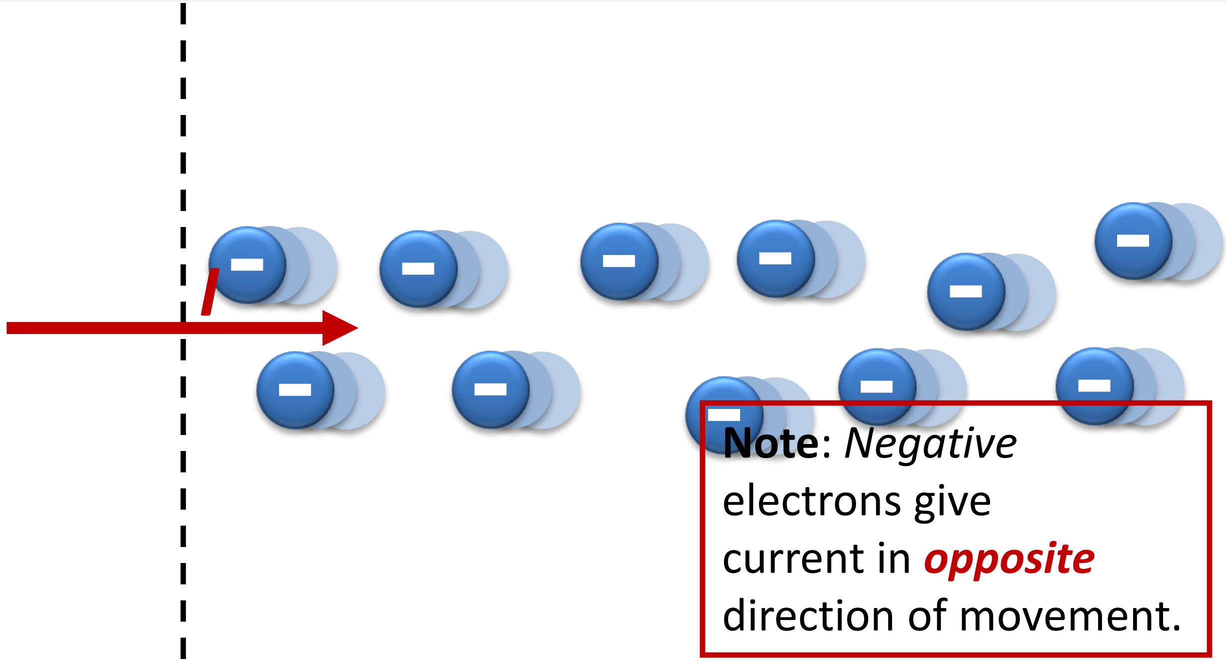
Electric field – E [V/m]



Voltage = difference in electric potential

$$U = E \times d$$ [Volt]

Current

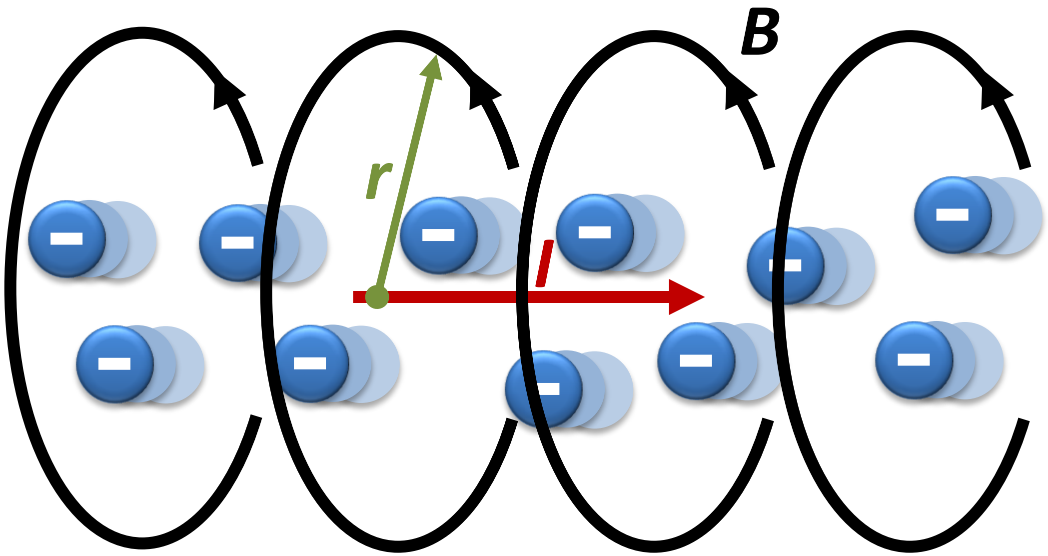


Note: *Negative* electrons give current in ***opposite*** direction of movement.

Current is defined as the amount of charge [Coulomb] that passes by per time unit [second].

$$I = \frac{\text{charge}}{\text{time unit}} = \frac{dQ}{dt}$$ [Coulomb/second = Ampere (A)]

Magnetic field

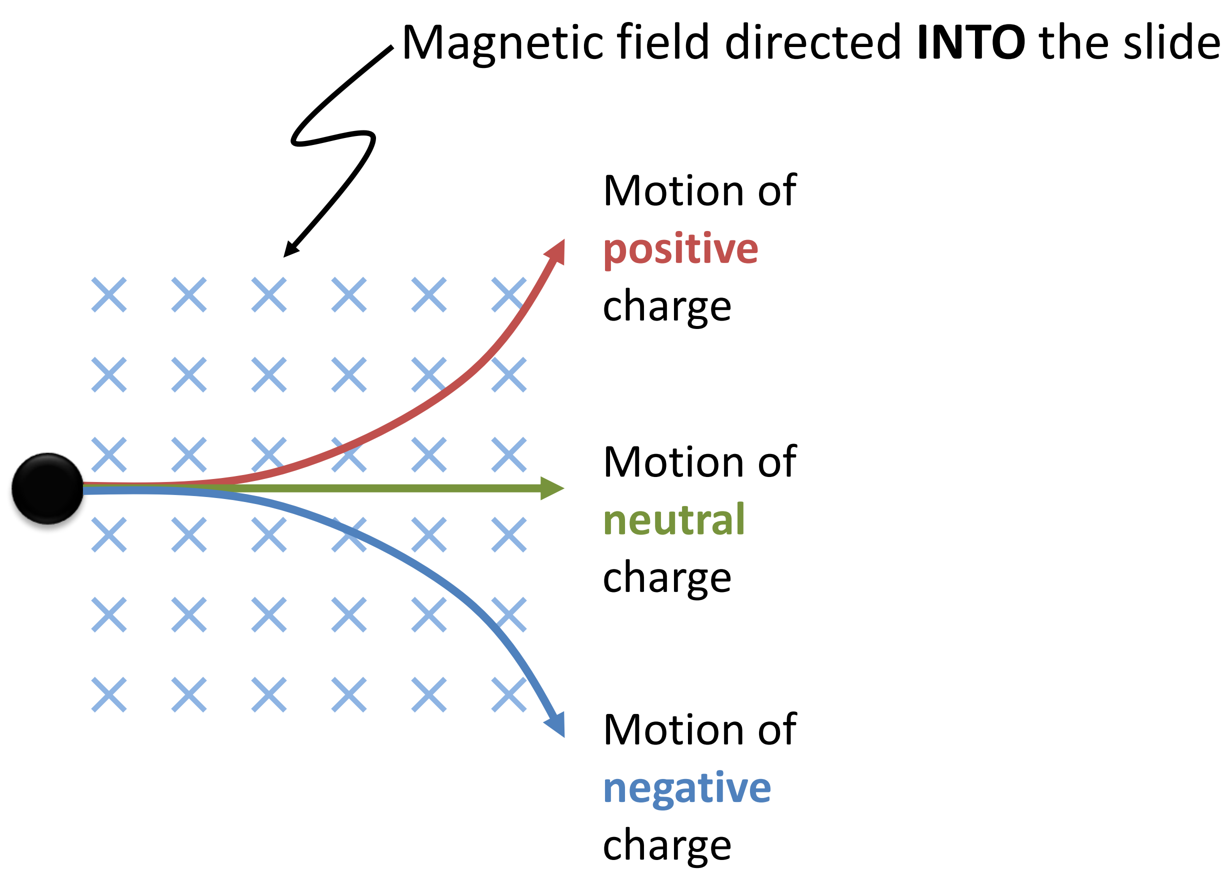


Strength of magnetic field at distance *r* from a "long" straight current:

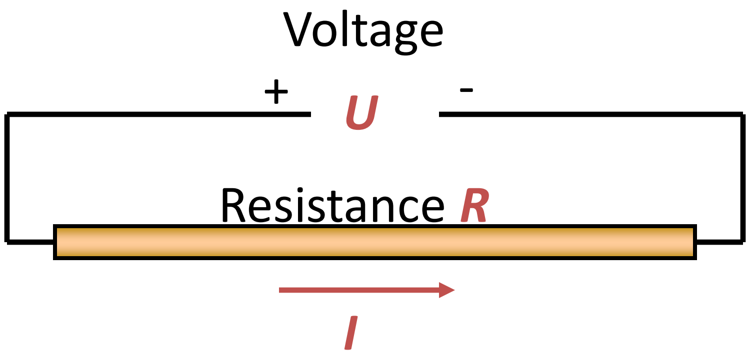
$$B = \mu_0 \frac{I}{2\pi r} \quad \text{[Tesla (T)]}$$

$$\mu_0 = 4\pi \times 10^{-7} \quad \text{[Tm/A]}$$

Magnetic field and forces

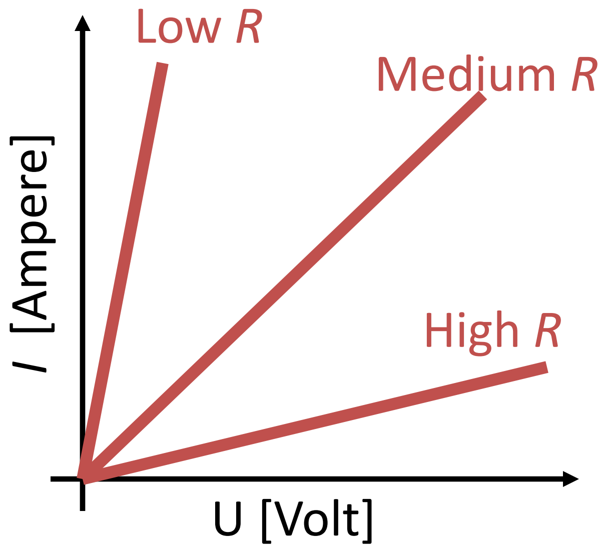


Resistance

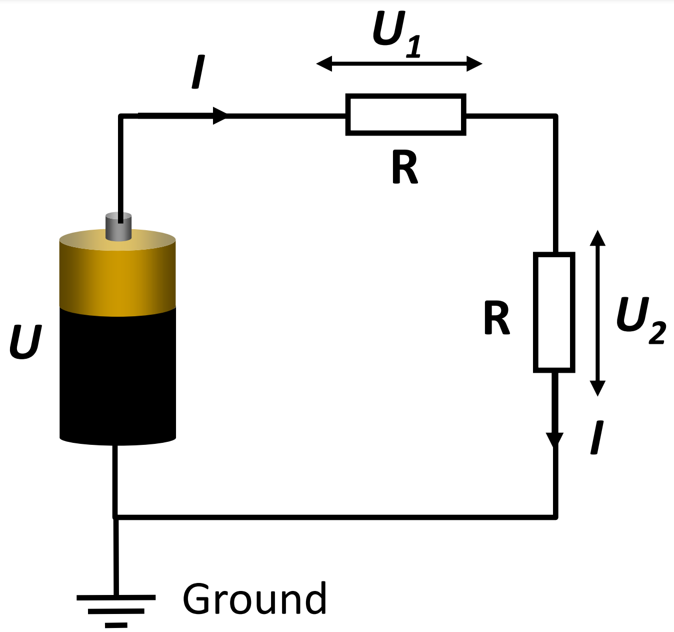


Ohm's law:
The resistance is the proportionality of the amount of voltage *U* needed to obtain a certain current *I* :

$$R = \frac{U}{I}$$ [Volt/Ampere = Ohm]



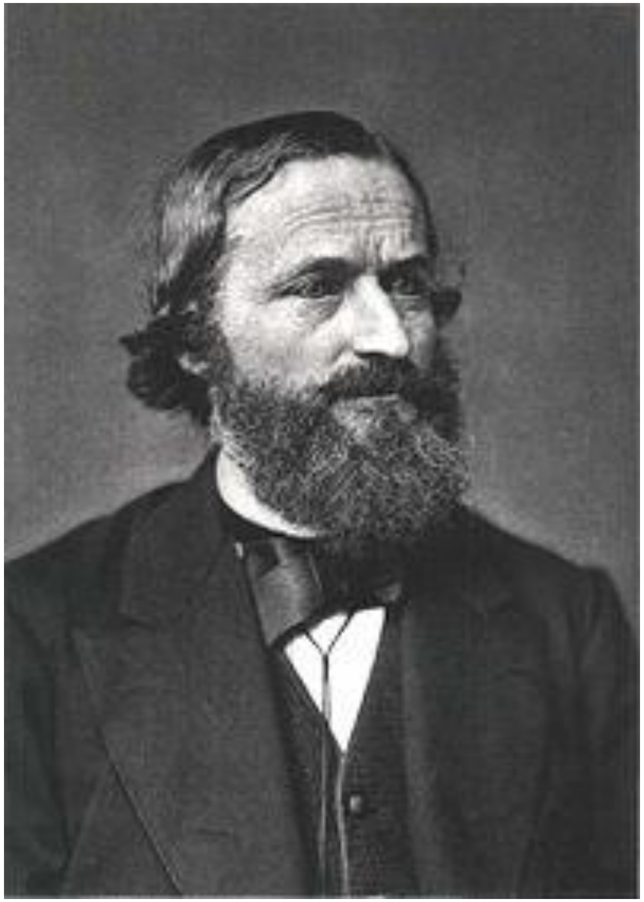
Serial resistors



Kirchhoff's Voltage Law:
The sum of the voltages around any closed loop is zero

$$\Rightarrow U = U_1 + U_2$$

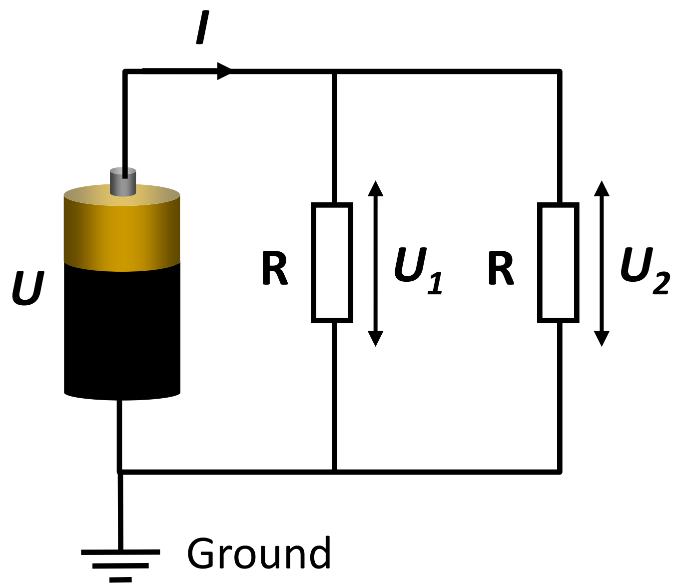
Kirchhoff

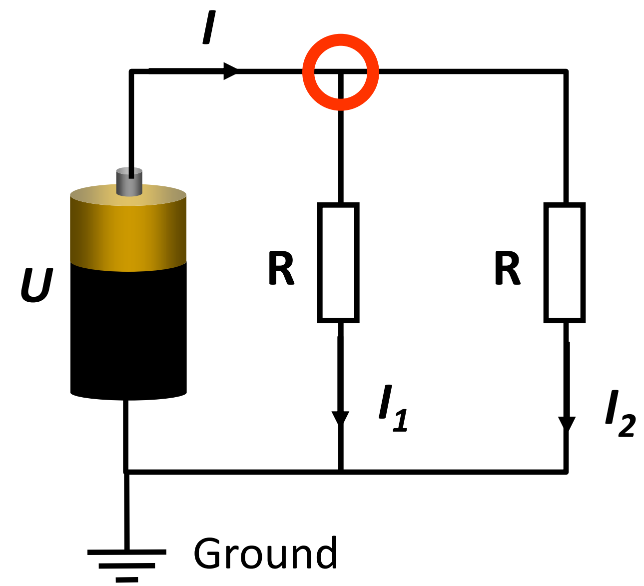


Gustav Robert Kirchhoff (1824 – 1887) was a German physicist who contributed to the fundamental understanding of electrical circuits, spectroscopy, and the emission of black-body radiation by heated objects.

Kirchhoff formulated his circuit laws, which are now ubiquitous in electrical engineering, in 1845, while still a student. He completed this study as a seminar exercise; it later became his doctoral dissertation.

Parallel resistors





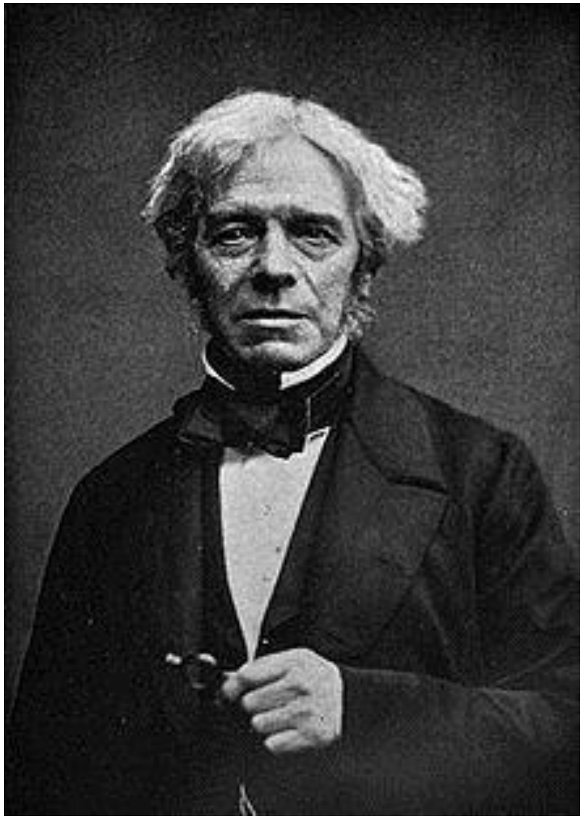
Kirchhoff's Voltage Law:
The sum of the voltage changes around any closed loop is zero

⇨ $U = U_1 = U_2$

Kirchhoff's Current Law:
The sum of all currets flowing into a node must be equal to the ones flowing out

⇨ $I = I_1 + I_2$

Michael Faraday



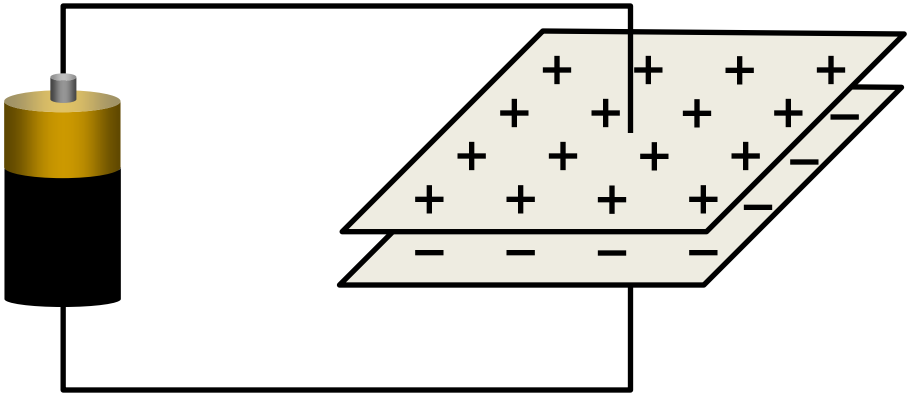
Michael Faraday, (1791 – 1867) was an English scientist who contributed to the fields of electromagnetism and electrochemistry.

Faraday received little formal education but still he is one of the most influential scientists in history.

His inventions of electromagnetic rotary devices formed the foundation of electric motor technology, and it was largely due to his efforts that electricity became practical for use in technology.

A Faraday cage is an enclosure formed by conducting material or by a mesh of such material. Such an enclosure blocks external static and non-static electric fields.

The Capacitor

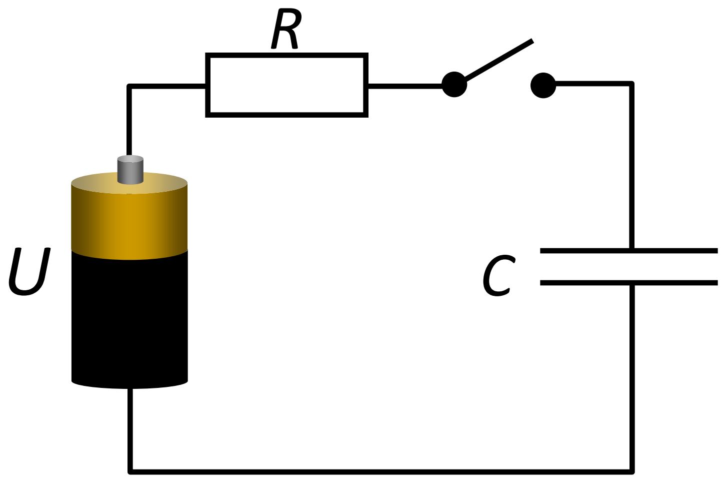


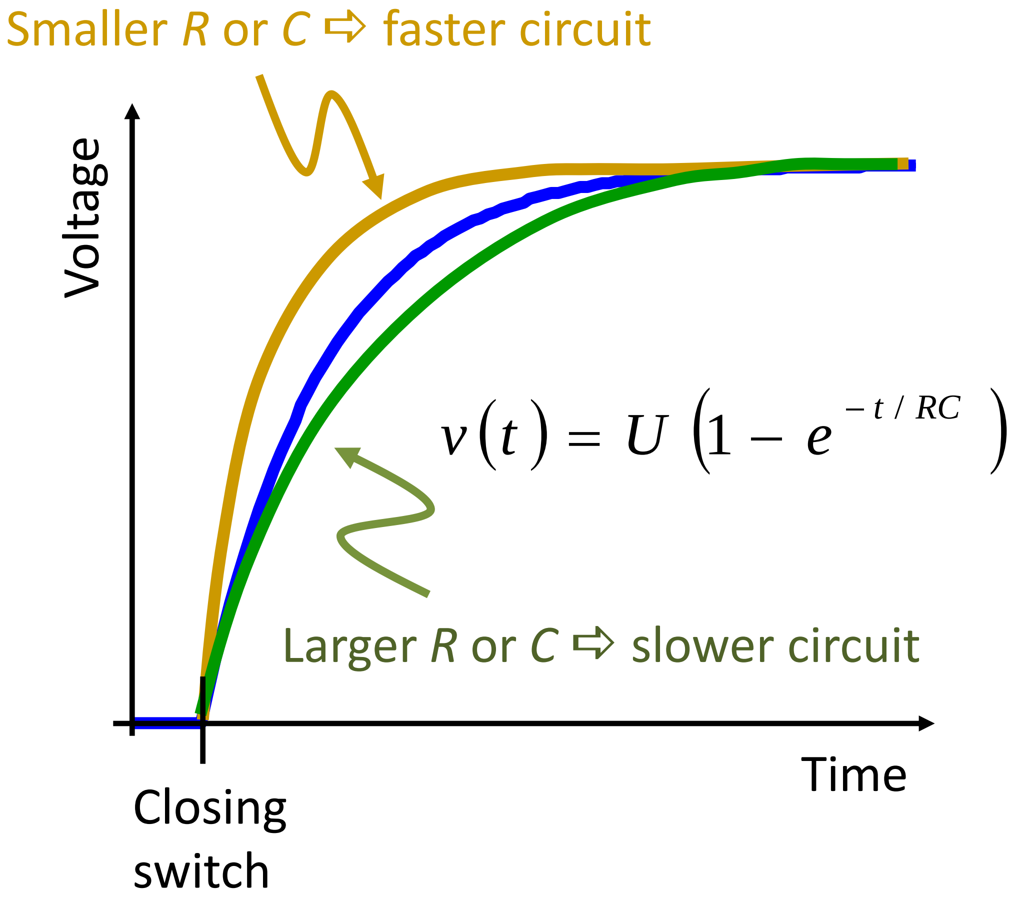
A battery will transport charge between the plates until until the voltage produced by the charge is equal to the battery voltage

Capacitance is the amount of charge which can be stored per unit voltage applied to the device.

$$C = \frac{Q}{U}$$ [Coulomb/Volt = Farad (F)]

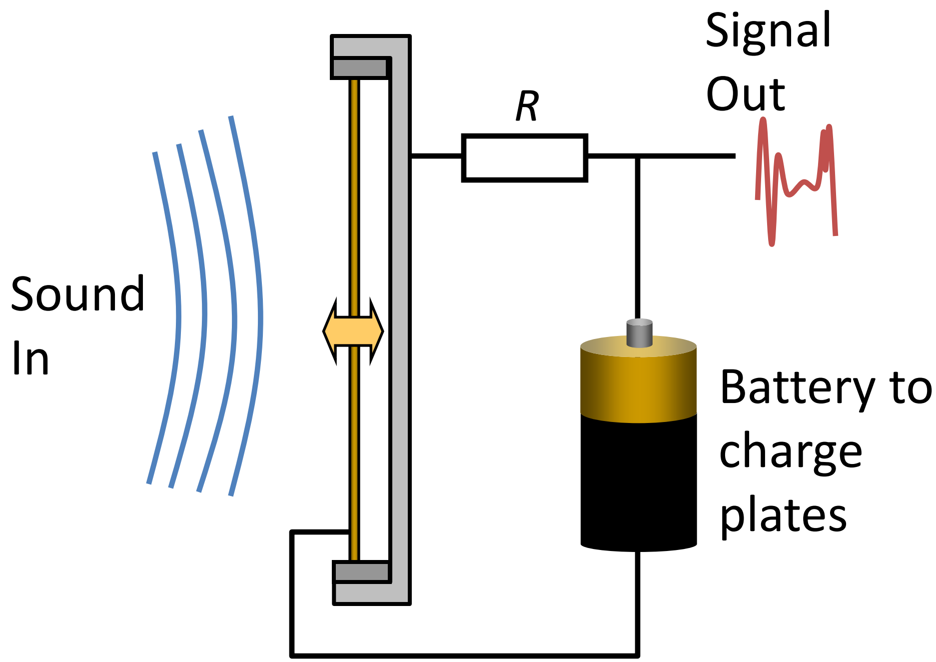
Charging a Capacitor





A ”real” capacitor CANNOT change its charge momentarily!

Application: Condenser microphone



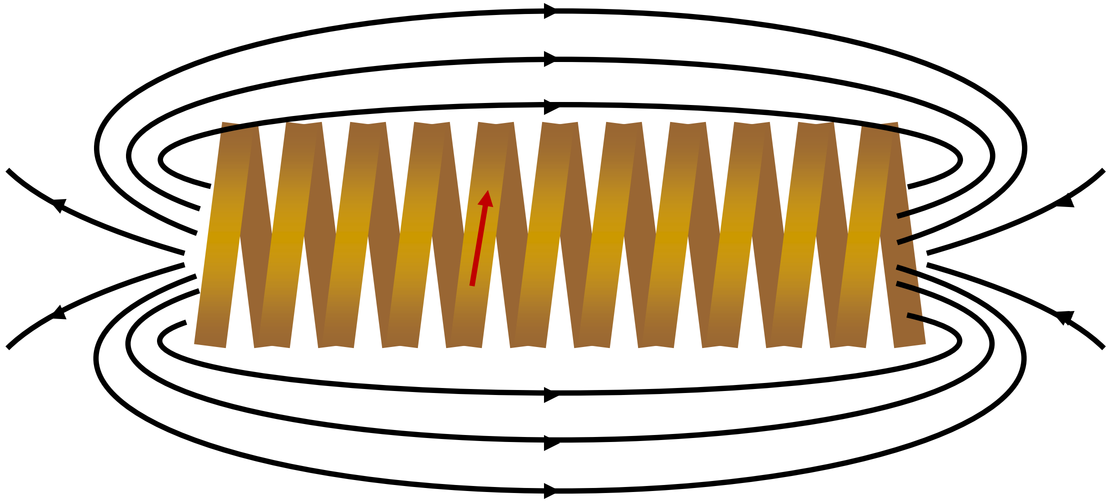
Principle: Sound pressure changes the spacing between a thin metallic membrane and the stationary back plate and thus the capacitance.

$$C = \varepsilon \frac{A}{d}$$

This will cause a change in charge Q and force a current through the resistance, R. This current "images" the sound pressure.

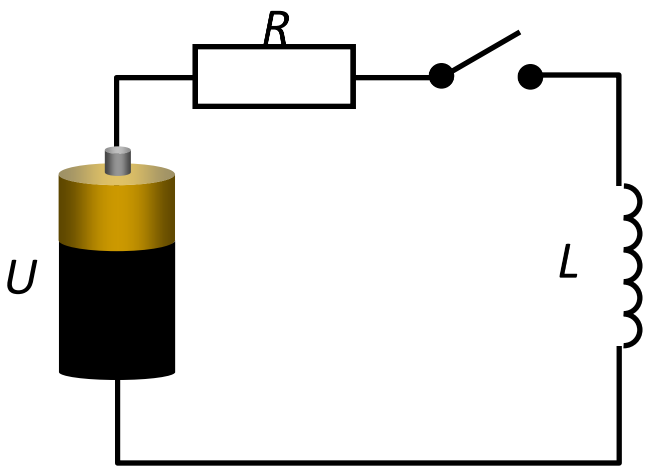
Coil

If we make a coil, we get a stronger magnetic field for each winding without increasing the current.

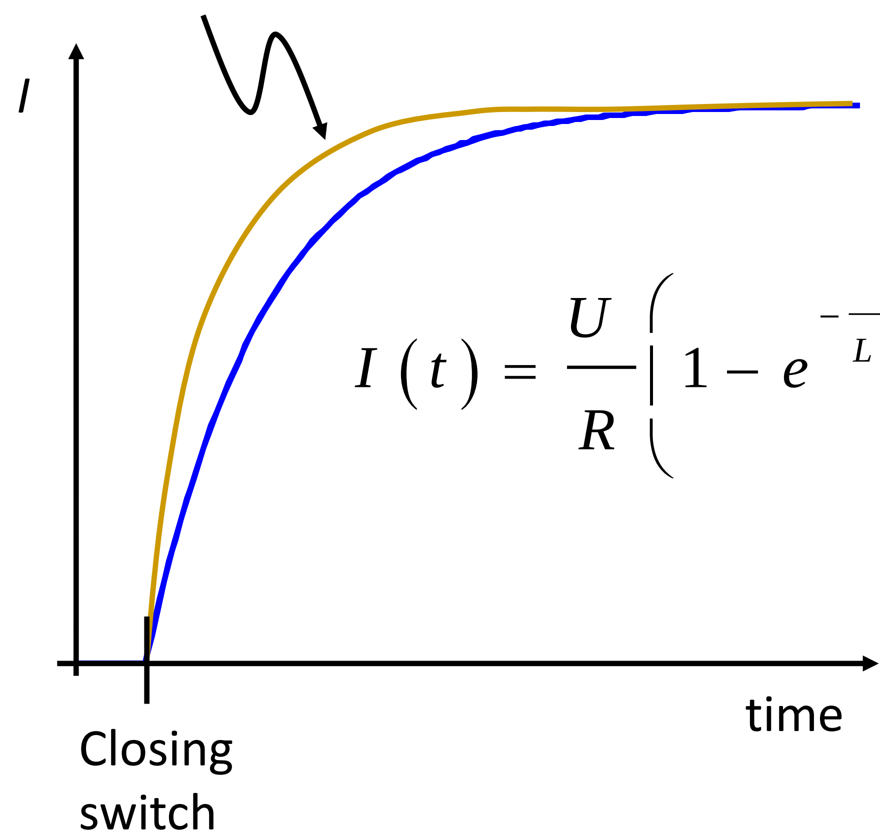


A coil will resist any changes in the current. The more windings, the stronger the resistance to changes in the current. This resistance to current change is called **inductance** and measured in the unit **Henry**.

Inductance



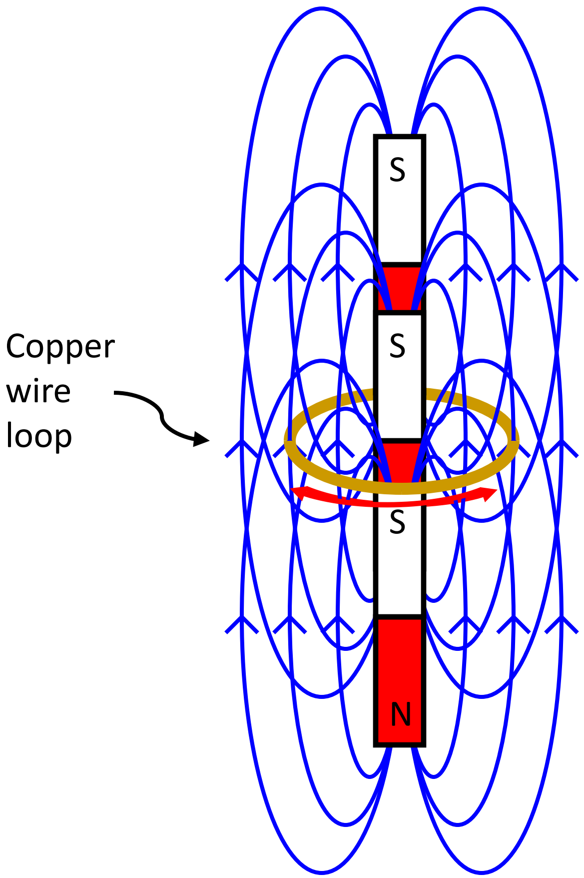
Smaller L ⇨ faster circuit



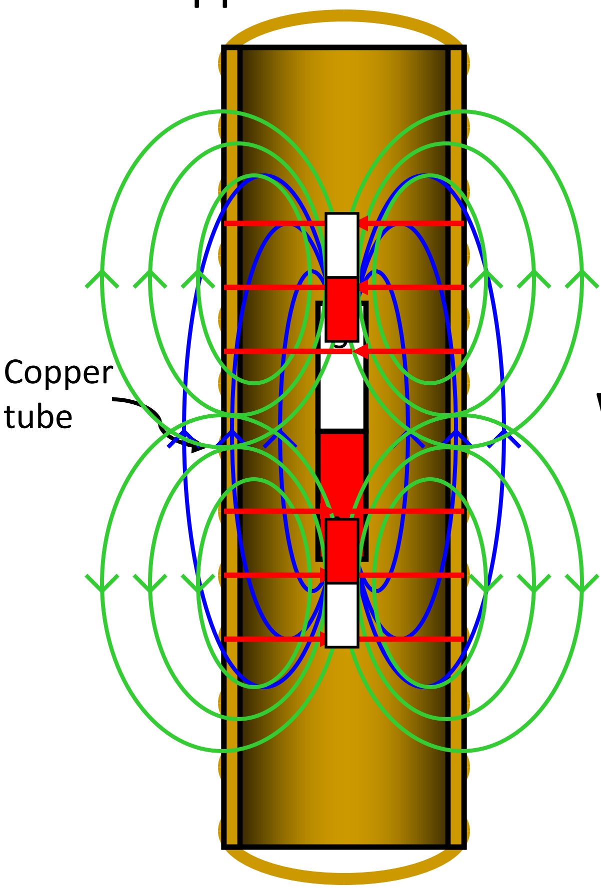
$$I(t) = \frac{U}{R}\left(1 - e^{-\frac{t}{L/R}}\right)$$

Eddy currents – an interesting effect

The principle



Magnet falling inside a copper tube



What happens?

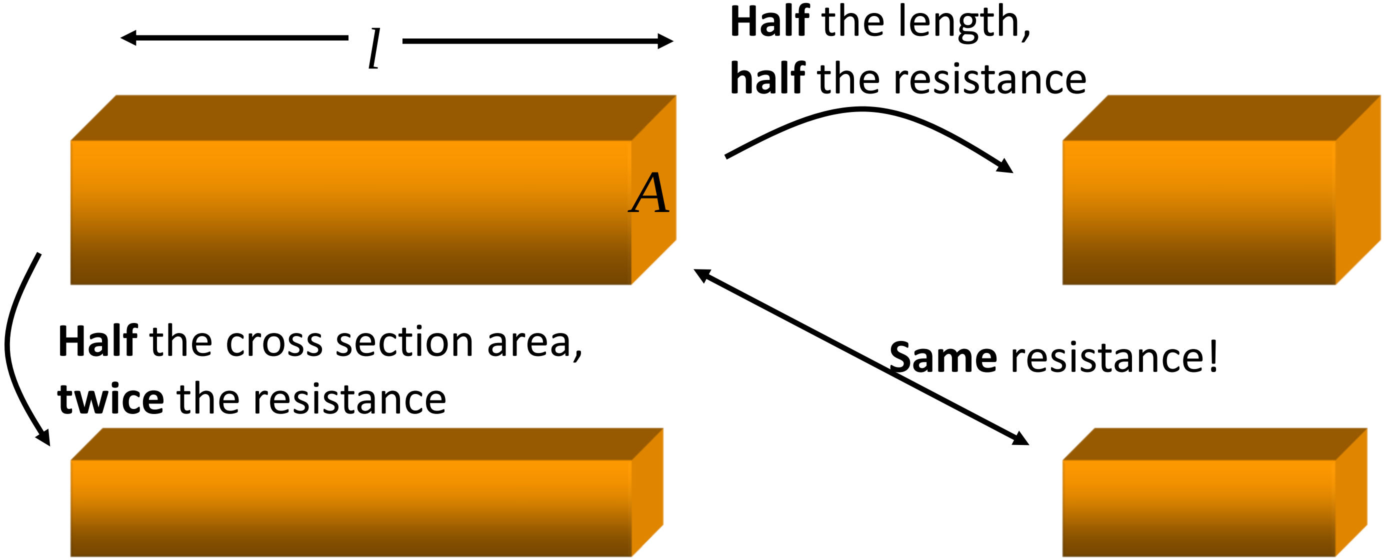
Resistivity

Resistivity is a material property describing the ”resistance”:

Cross section area
Length

ρ [ohm*m²/m = ohm*m]

$$R = \frac{\text{resistivity} \times \text{length}}{\text{cross section area}} = \frac{\rho \times l}{A} \quad \text{[ohm]}$$



Conducting materials

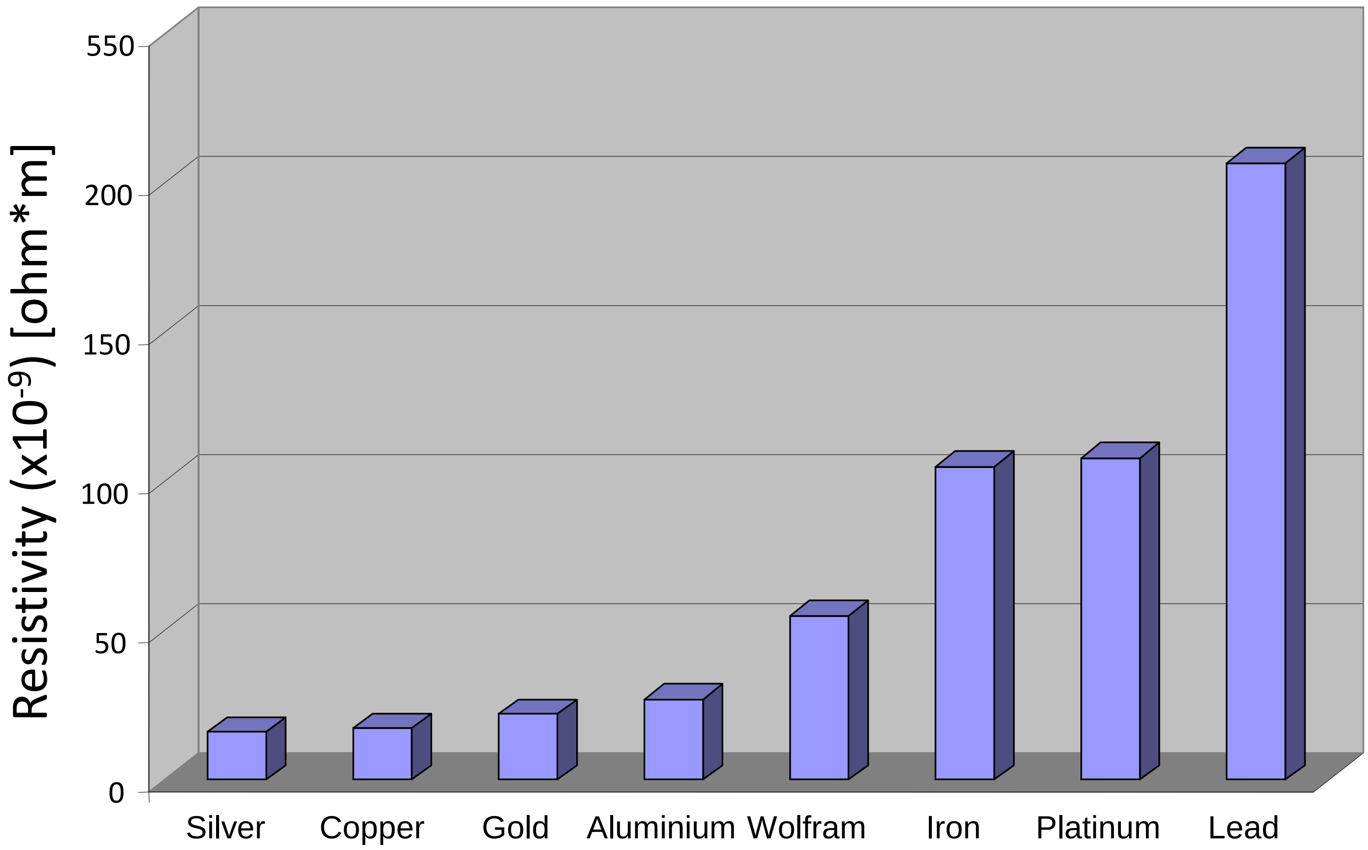
In practice, all materials are conducting.

There are however **VERY** large differences in resistivity!

Example:	Silver	15.9×10^{-9} ohm*m
	Quartz glass	$10^{12} - 10^{16}$ ohm*m

A difference of up to 24 orders of magnitude!

Conductors



Resistivity (x10-9) [ohm*m]
550
200
150
100
50
0
Silver
Copper
Gold
Aluminium
Wolfram
Iron
Platinum
Lead

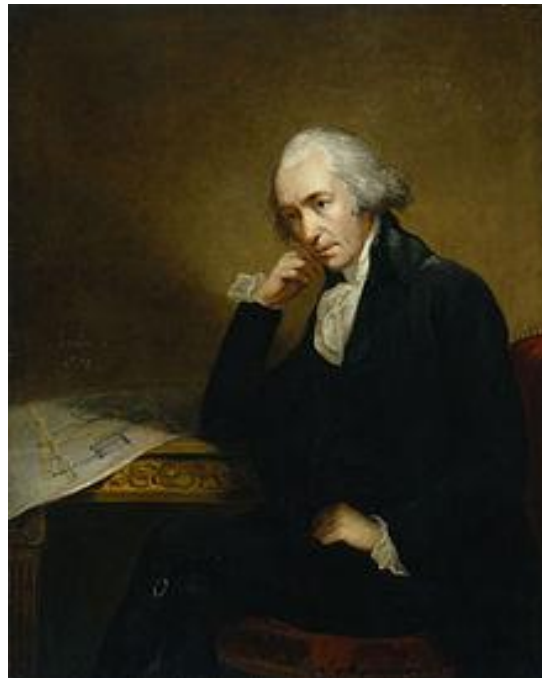
ENERGY

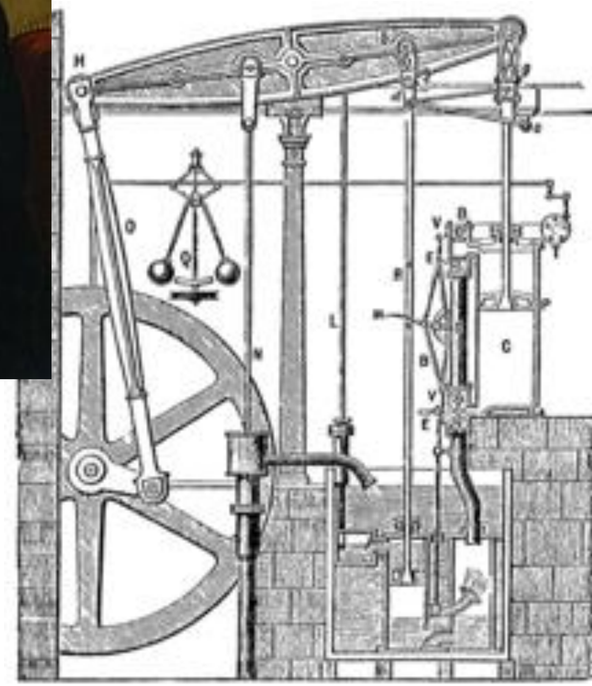
James Watt

James Watt (1736 – 1819) was a Scottish inventor and mechanical engineer whose improvements to the Newcomen steam engine were fundamental to the changes brought by the Industrial Revolution.

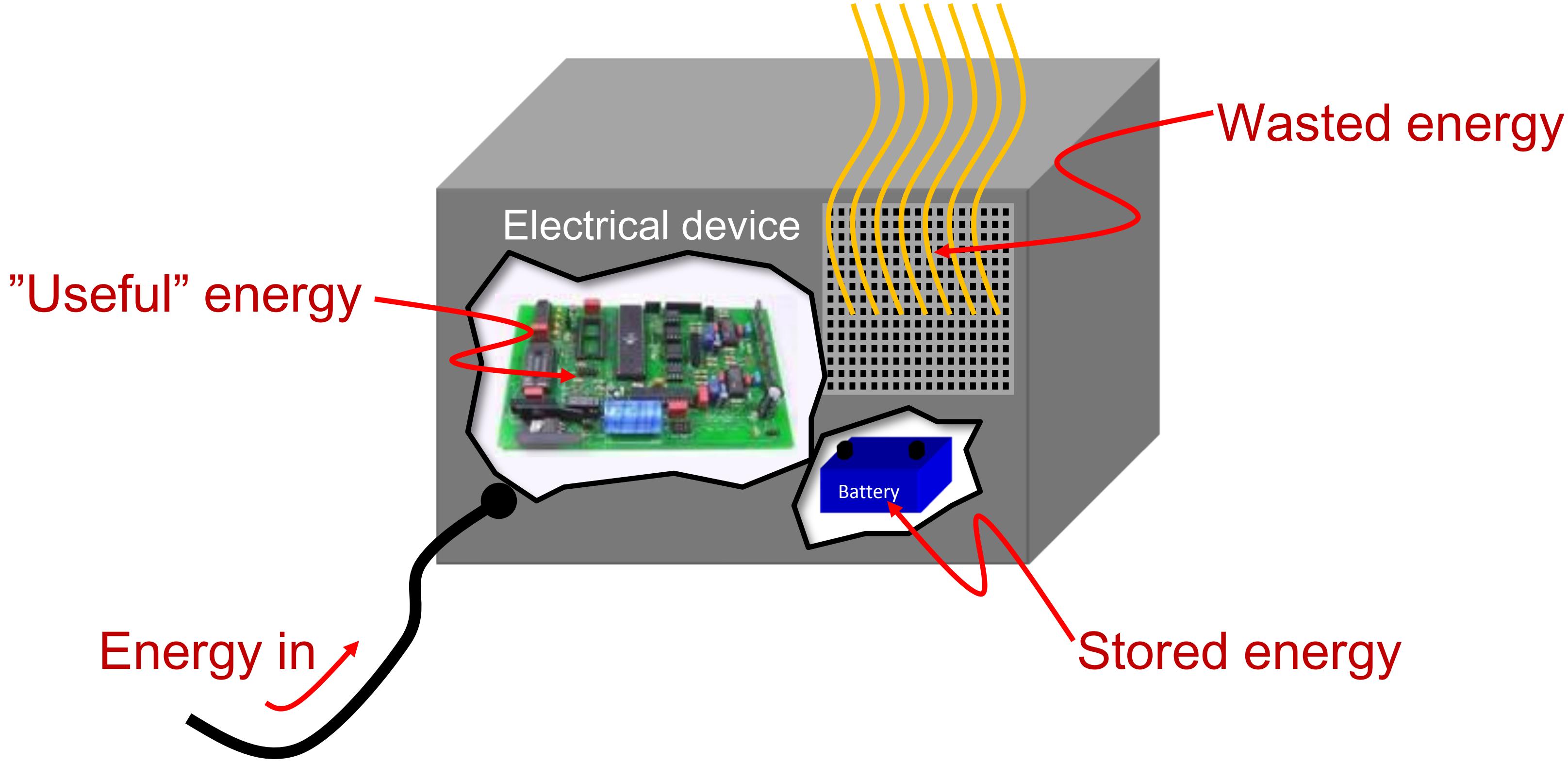
He developed the concept of horsepower, to compare the output of steam engines with the power of draft horses, and the SI unit of power (Watt) was named after him.

- 1 hp = 746 Watts





Energy – The big picture

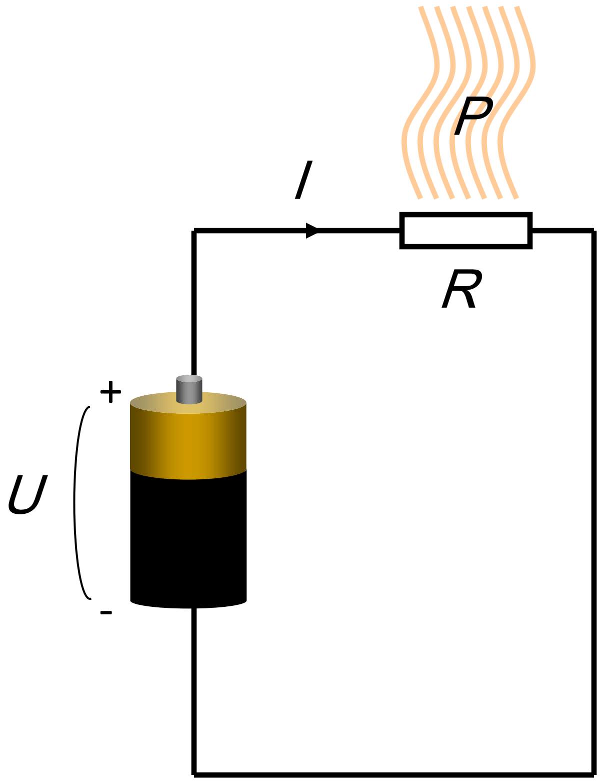


Why reduce power consumption?

- Save resources
- Less pollution
- Save money
- etc

- Increased battery life
- Less heat ⇨ increased reliability
- Less heat ⇨ less cooling, which is expensive and bulky

Power

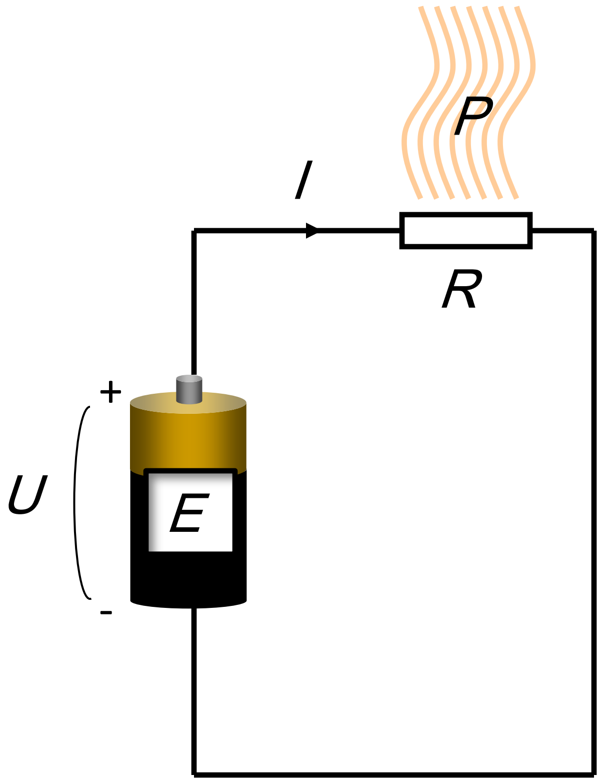


When current flows
through a resistor
the ”friction” will cause
a certain power to be
dissipated (it gets warm).

Power:

$$P = U \times I = \frac{U^2}{R} \quad \text{[Watt]}$$

Energy



How long will the battery last?

A battery contains a certain amount of energy *E* [Joule].

Power is energy per time unit [Joule/second = Watt]

$$P = \frac{\text{energy}}{\text{time}} = \frac{E}{T}$$

$$\Rightarrow T = \frac{E}{P}$$

Energy sources for electricity production

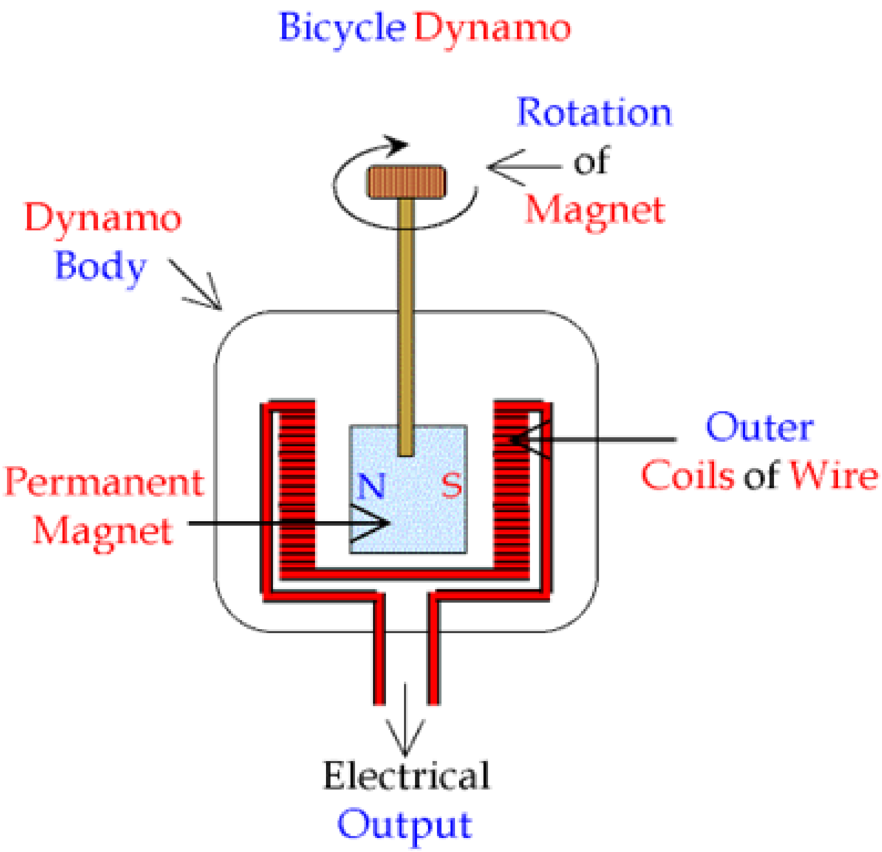
Large scale production

Hydro-electric
Coal/oil/gas
Nuclear
Wind
Solar cells
Fuel cells
Thermoelectric module
Energy scavenging

Sliding scale

Local production

Generators – Bicycle Dynamo



A wire in a fluctuating magnetic field will have an induced current!

Often integrated in the hub.

Generators – Flashlights

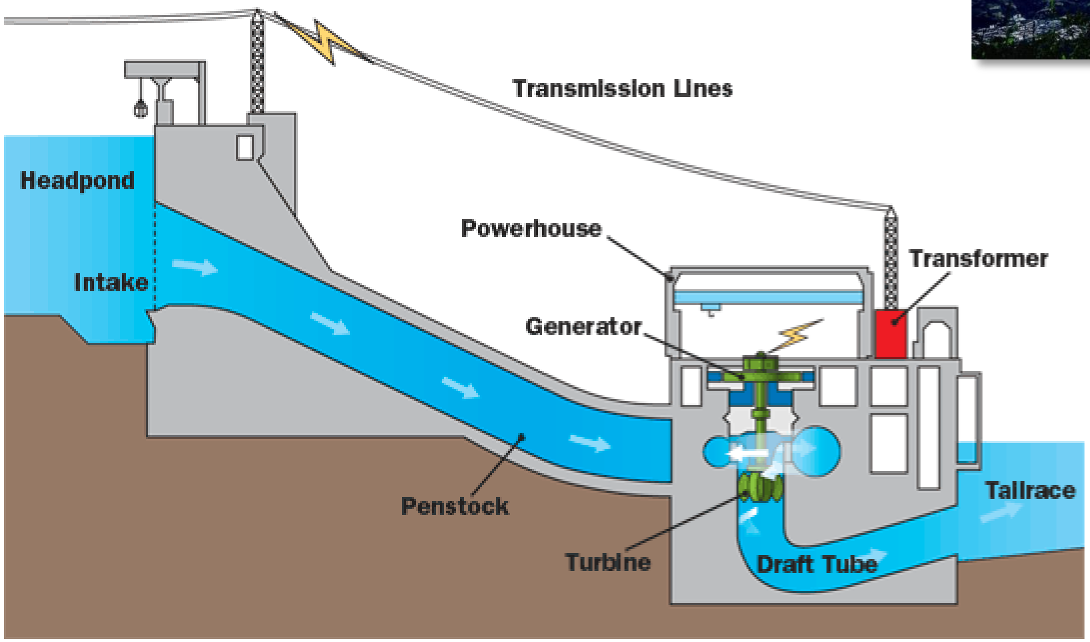
”Pump”

Shake

Turn

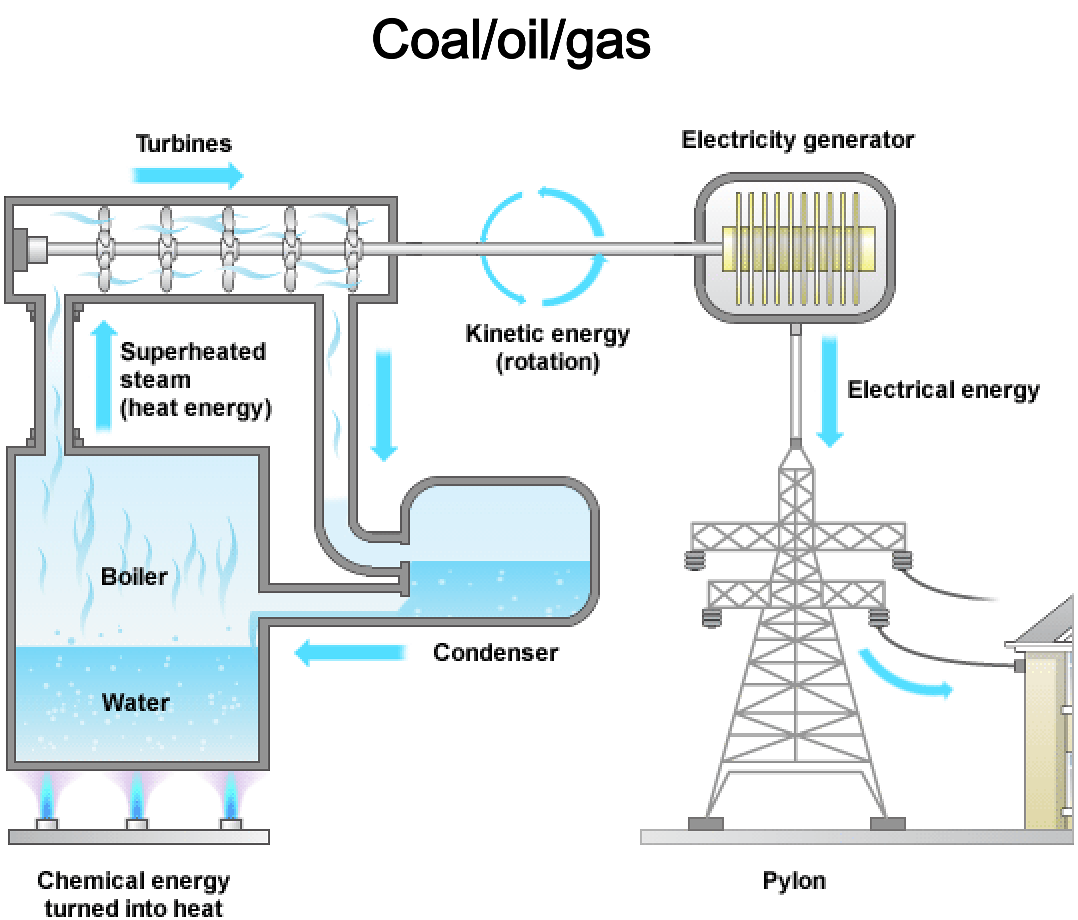
Large scale power plants

Hydroelectric

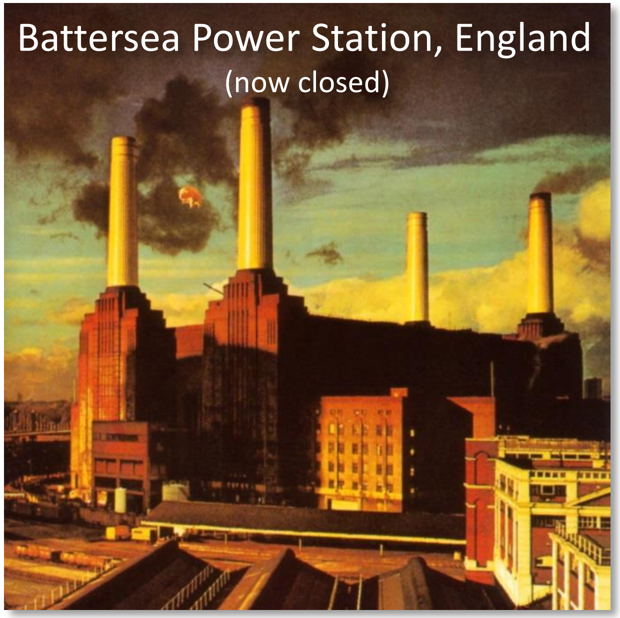


http://www.nbpower.com

Large scale power plants (cont.)



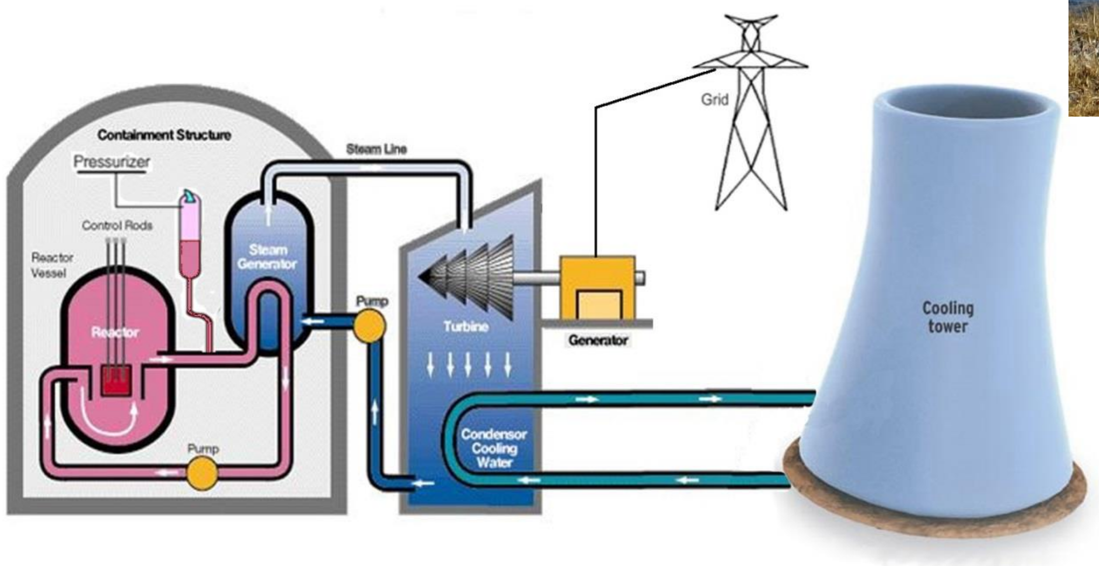
http://www.bbc.co.uk



Picture famous from ... ?

Large scale power plants (cont.)

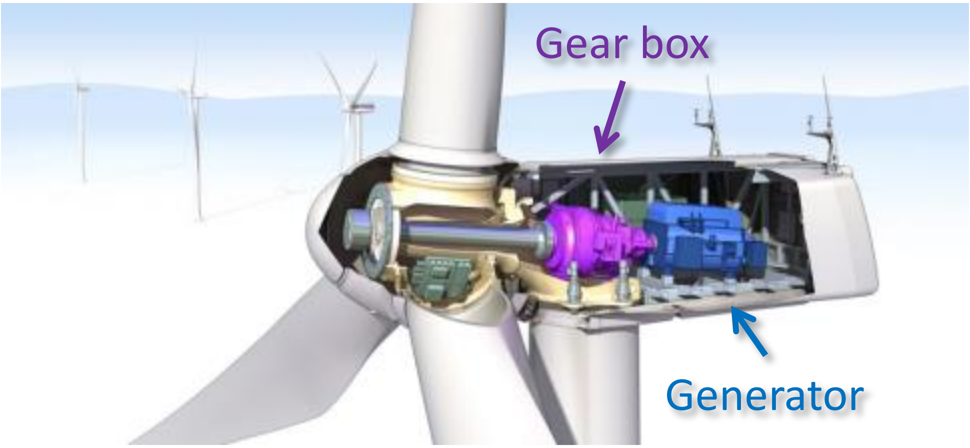
Nuclear



Where is the cooling tower?

Large scale power plants (cont.)

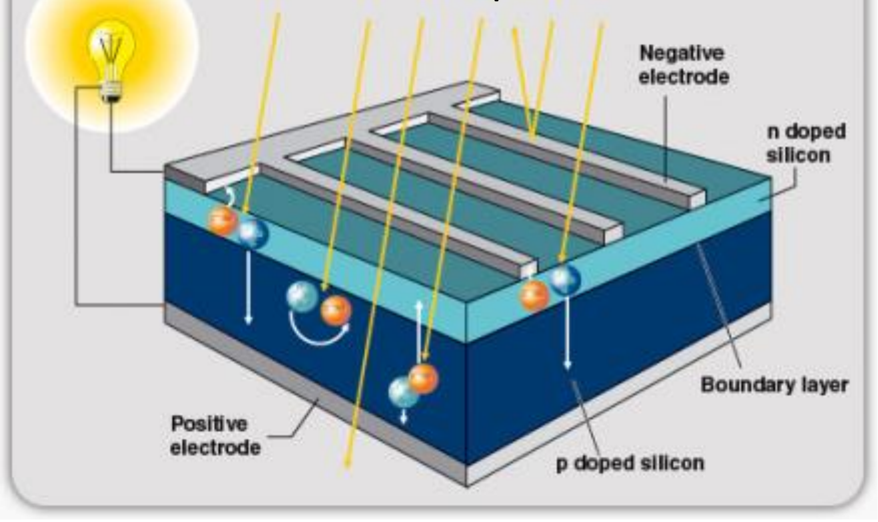
Wind



Local production

Solar cells (photovoltaic)

Principle

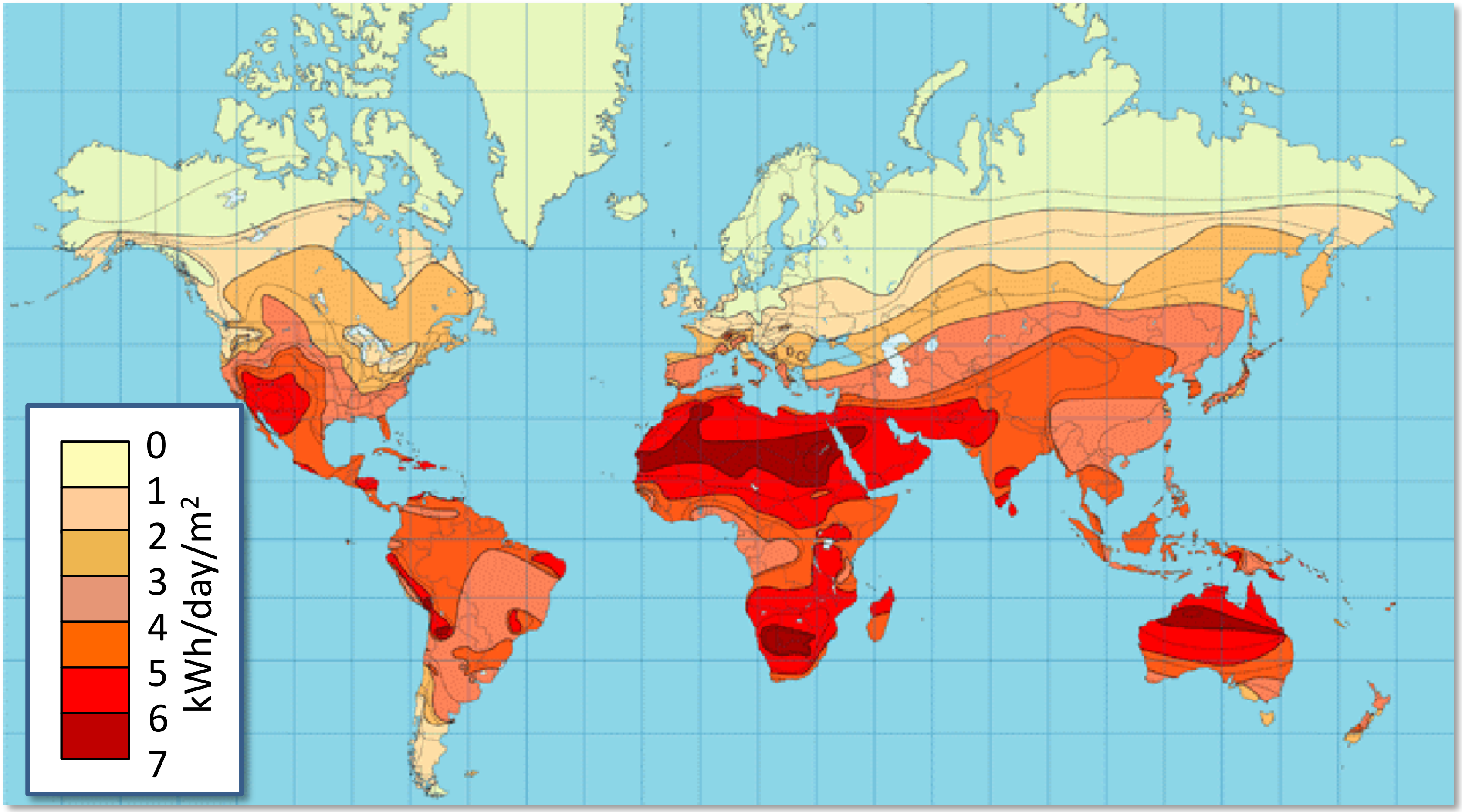


Have many practical uses, but relies on available (sun)light to produce electricity.

In most applications we are depending on good storage.

Local production

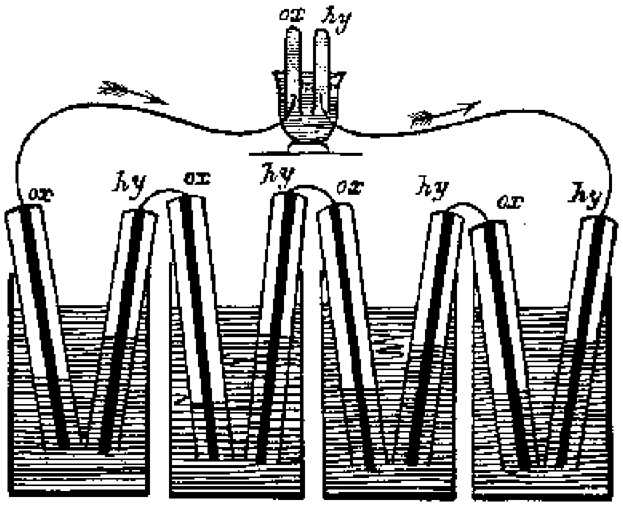
Available solar power (average)

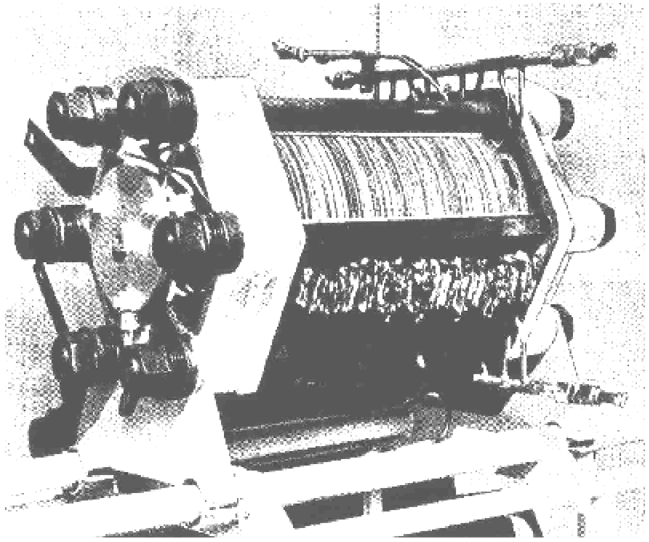


Local production (cont.)

Fuel cells

In 1839 Sir William Grove built the first fuel cell





First practical use: Apollo program 1966

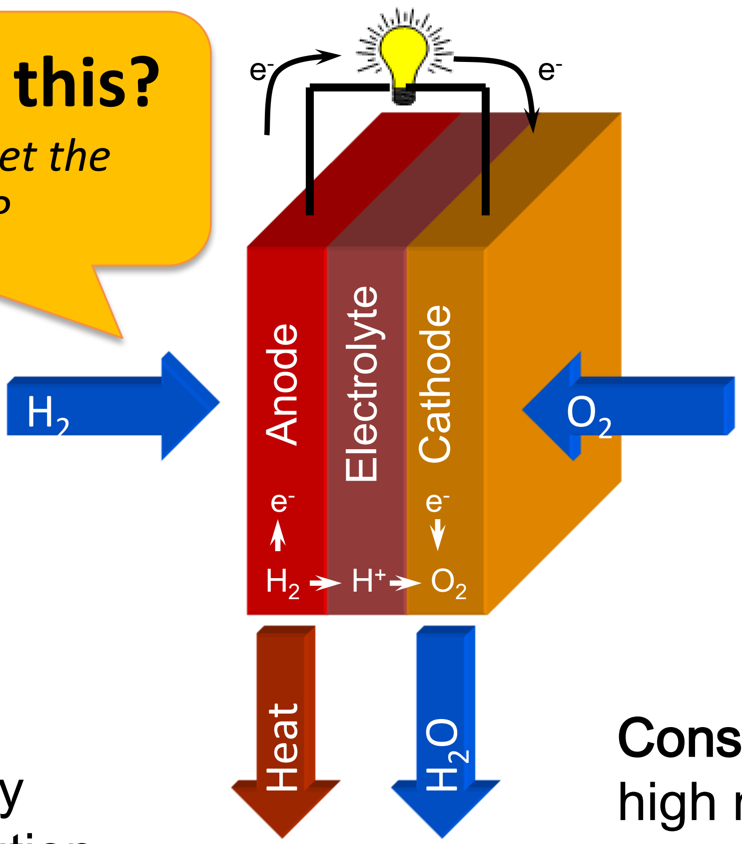
Voltage	27 -31 V
Power	1.4 kW
Diameter	57 cm
Weight	100 kg

Local production (cont.)

Fuel cells – Hydrogen cell principle

How ”clean” is this?

Hint: *Where do we get the hydrogen from?*



Pros

high efficiency

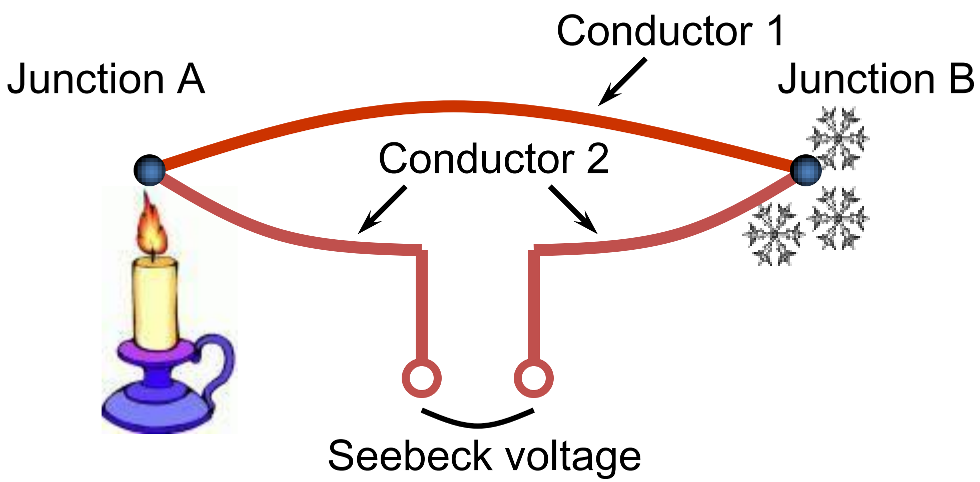
very low pollution

Cons

high material cost

high production cost

Seebeck effect

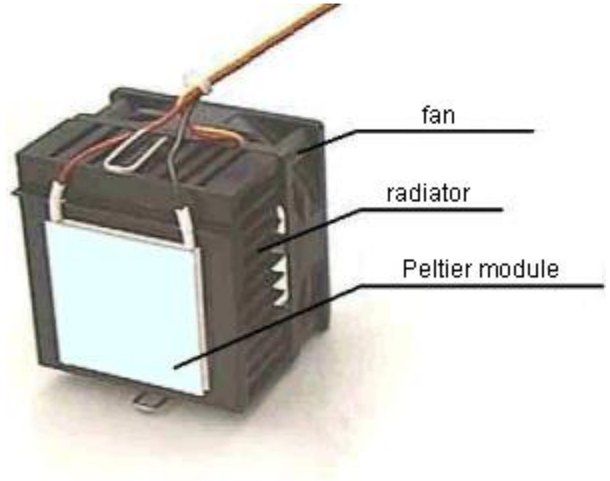


Thomas Johann Seebeck
(1770-1831)

T.J. Seebeck found out in 1821 that two different conductors joined together, where the two junctions are kept at different temperatures, can produce a voltage and, in a closed circuit, an electric current.

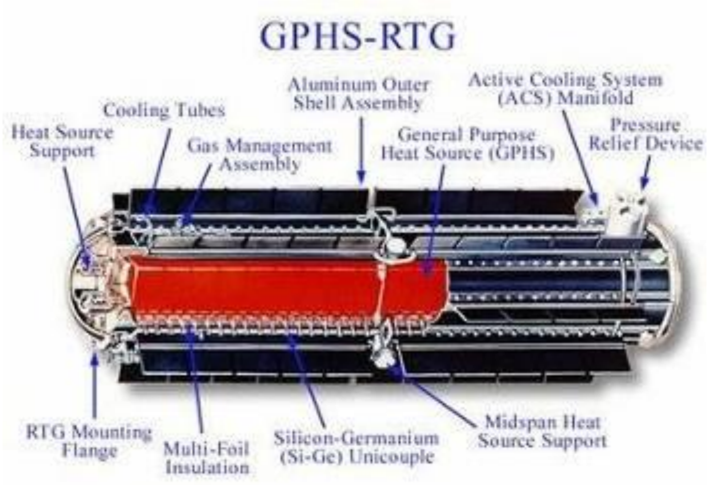
Peltier effect

The Peltier effect, discovered by a watchmaker by the name Pelitier, in 1834 is the opposite of the Seebeck effect. By introducing an electrical current in a circuit made of two different conductors it is possible to produce a thermal difference between the junctions.



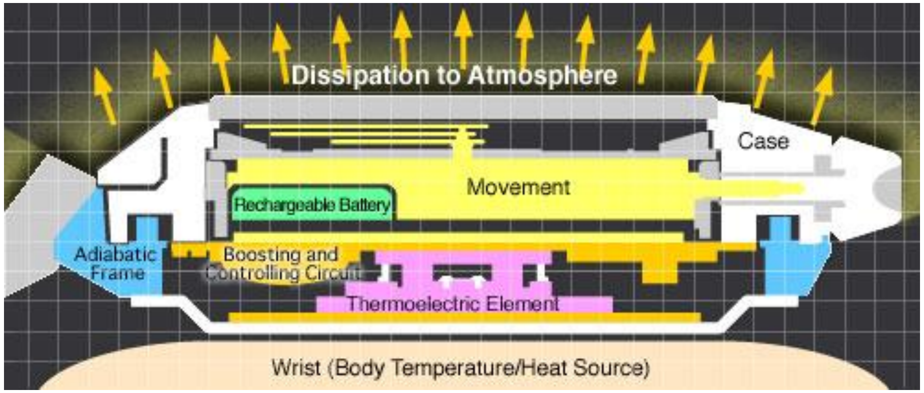
Thermoelectric applications

Radioisotope Thermo-electric Generator



This type of very reliable energy source has been used in many space applications. The radiation hazard limits its use in most other environments.

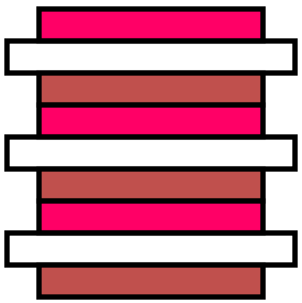
Thermoelectric watch



Even if there is only a minor temperature difference between the wrist and the atmosphere (usually as low as 1-3 deg. C) the low energy requirement of a quartz watch (about 1.5 uW) makes it possible.

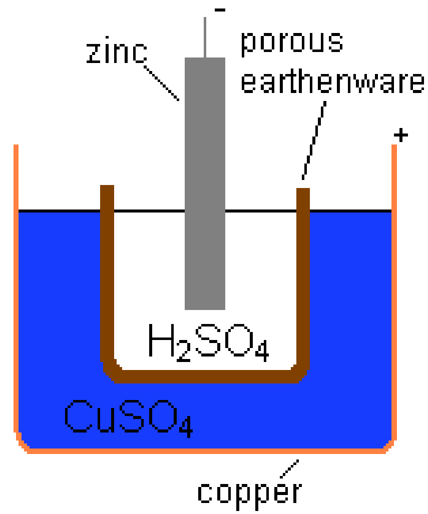
Brief History of Battery

The first battery was created by Alessandro Volta in 1800



- silver
- zinc
- papper socked in salt water

The current produced electrolysed the electrolyte solution, resulting in a film of hydrogen bubbles forming on the copper, which steadily increased the internal resistance of the battery.



Danielle cell

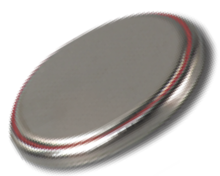
In 1836 a british chemist named John Frederic Daniell invented e Danielle cell to overcome this problem. The earthenware barrier was porous, which allowed ions to pass through but kept the solutions from mixing.

Application: Battery energy

You usuall find the energy contents described in terms of **ampere hours**. What is this?

Current x time (I x T) not enough!
Energy = Power x time = U x I x T

Examples:

		Capacity	Voltage	Energy
	Car battery (lead/acid)	60 Ah	12 V	2.6 MJ
	AAA battery (alkaline)	1150 mAh	1.5 V	6.2 kJ
	Glucose Measure (Lithium)	220 mAh	3 V	2.4 kJ
	Mobile Phone (Li-Polymer)	950mAh	3.6 V	12.3 kJ

3600 seconds per hour: $\text{Energy} = \text{Voltage} \times \text{Ampere hours} \times 3600$ [Joule]

Batteries - Considerations



- Amount of stored energy?
- Size?
- Rechargable?
- Voltage?
- Max current?
- Speed of discharge?
- Cost
- ...?

What has happened?

25 years of development

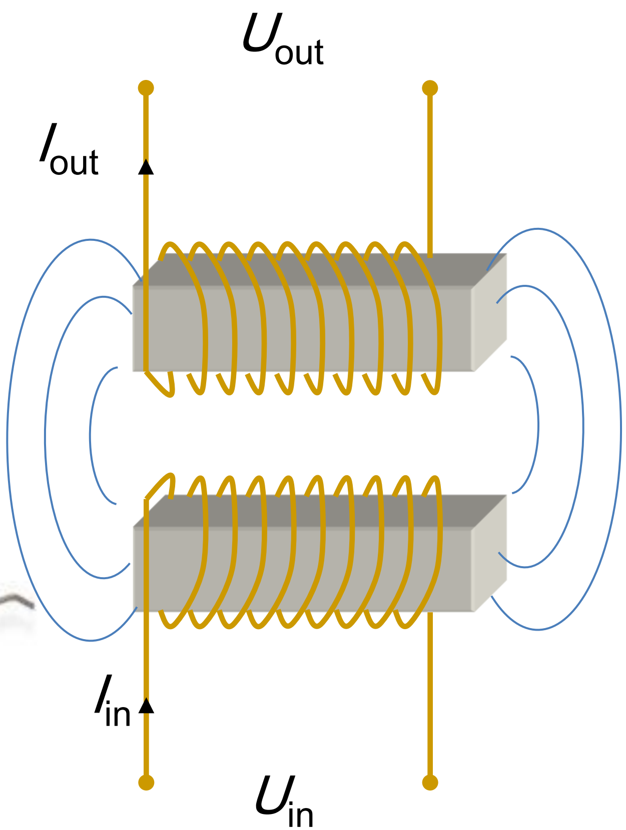
4 kg

0.092 kg

From simple phones with a **few hours** of battery time to
(by comparison) extremly complex phones with **many days** of battery time!

Much better batteries in modern phones?

Electric toothbrush.
No contact. How is it charged?

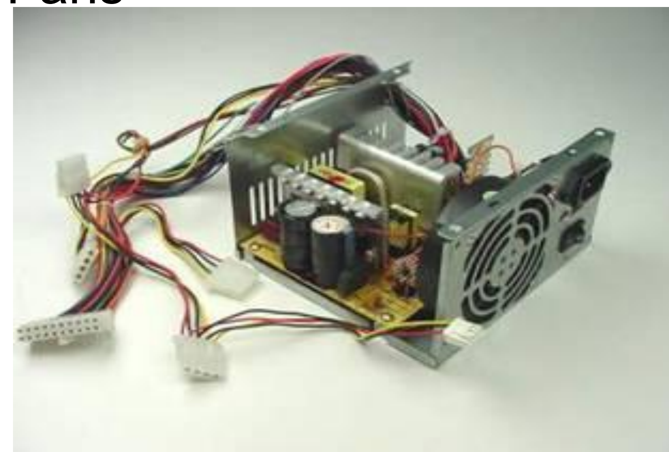


Inductive charging

Getting rid of the heat

Water/liquid

Fans



Heat sinks

Design or functionality?