University of Nottingham
UK | CHINA | MALAYSIA

LECTURE 1B

Electrical Engineering Fundamentals

Electromechanical Devices

MMME2051

Module Convenor – Surojit Sen

Learning Outcomes

- What is **Engineering**?
  - **Mechanical**
  - **Electrical** – sub-branch **Electronic engineering**
  - **Electromechanical**
  - **Computer/Software**
- Fundamentals of **Electrical Engineering**
  - **Charge**, **Current**, **Voltage** – concept of **Across** & **Through** variables
  - Resistance & **Ohm's Law**
  - Kirchhoff's Current Law (**KCL**) & Kirchhoff's Voltage Law (**KVL**)
  - **Power** & **Energy**
- Electrical **energy storage** devices – **Reactive** elements
  - **Capacitor**
  - **Inductor**

What is Engineering?

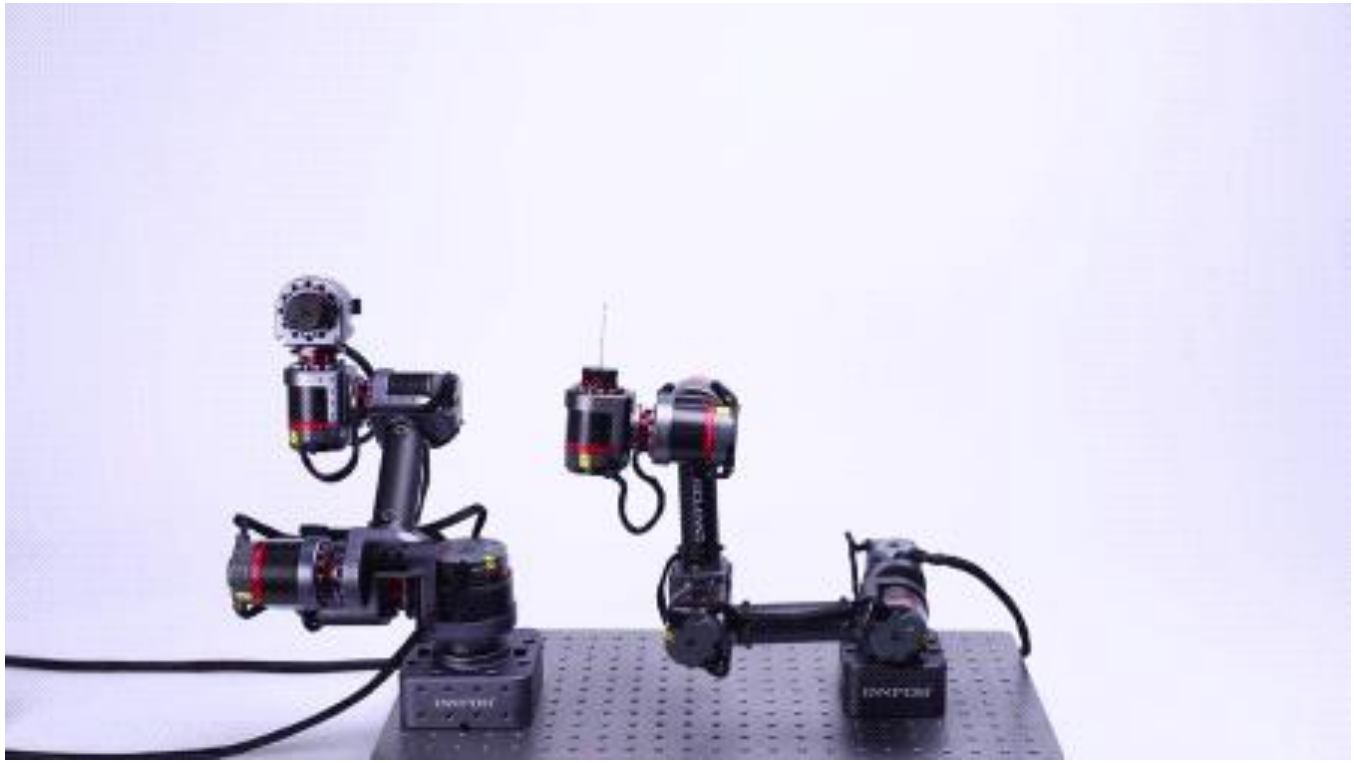
"**Creative application** of scientific principles to **design or develop structures**, **machines**, **apparatus**, **processes**; utilising them **singly** or in **combination**"

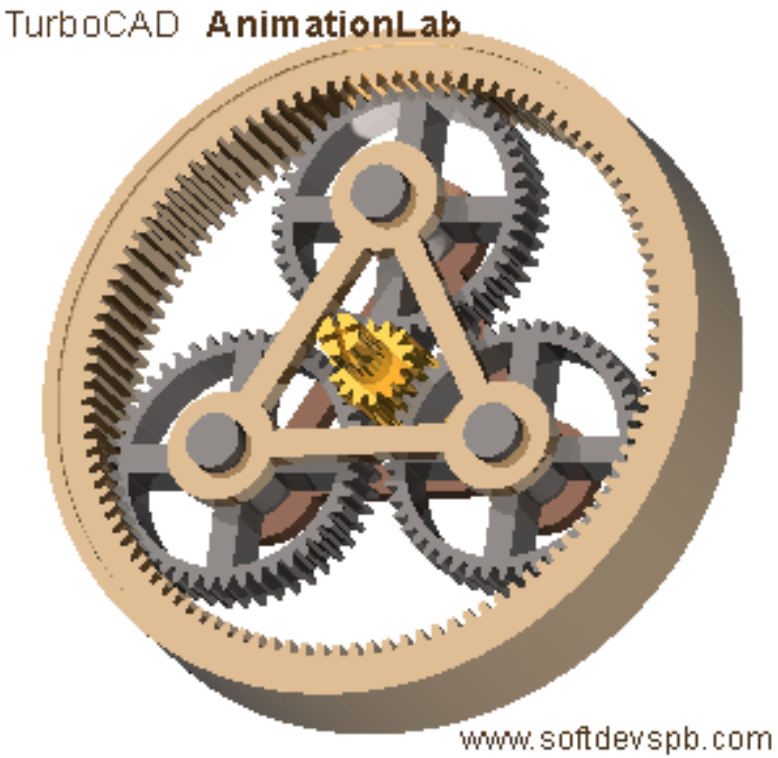
Derived from *ingenium*, meaning "**cleverness**", and *ingeniare*, meaning "to **contrive**, **devise**, **fabricate**, **invent**, **build**"

"Put together a bunch of things to do some form of useful work"

Mechanical Engineering

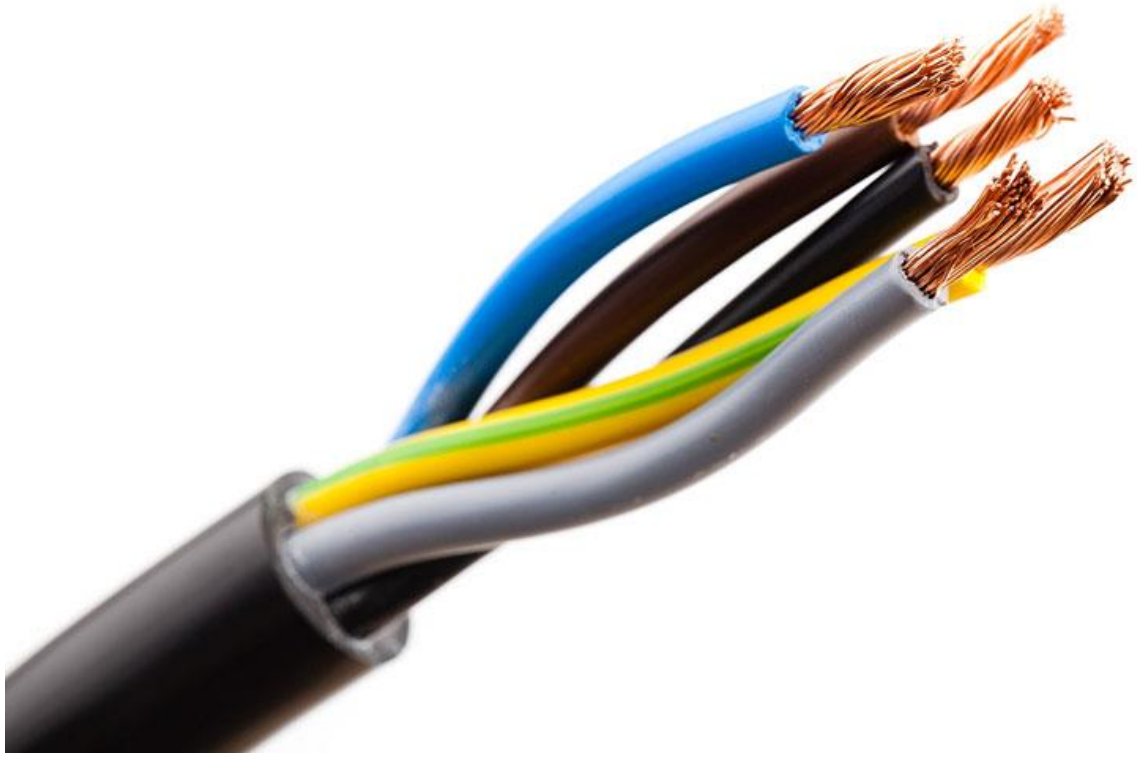
Study of **physical machines** that may involve **force** and **motion/movement**





Electrical Engineering

Study and application of devices that use **electricity** and **electromagnetism**

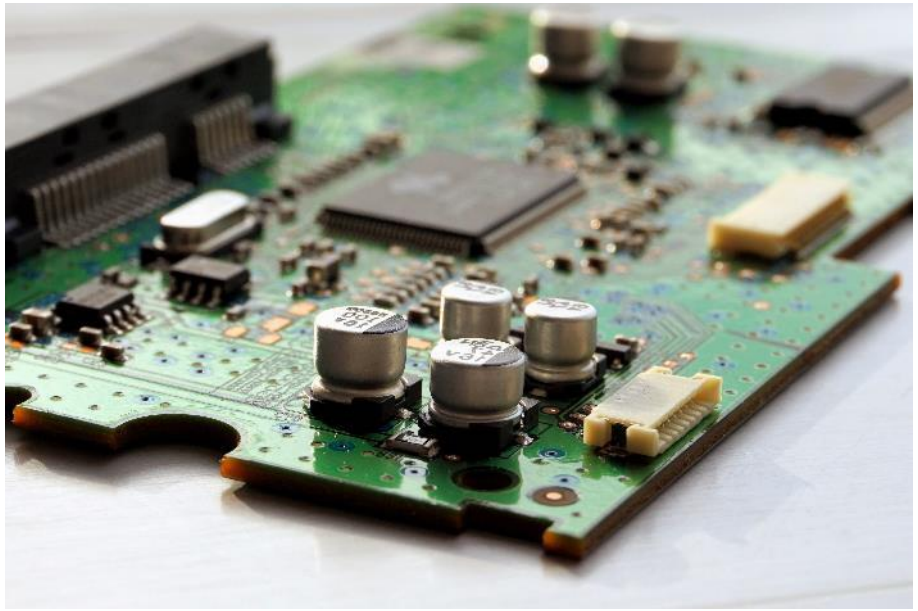


Electronic Engineering

Electrical systems that deal with **less than 5V** and **50mA**

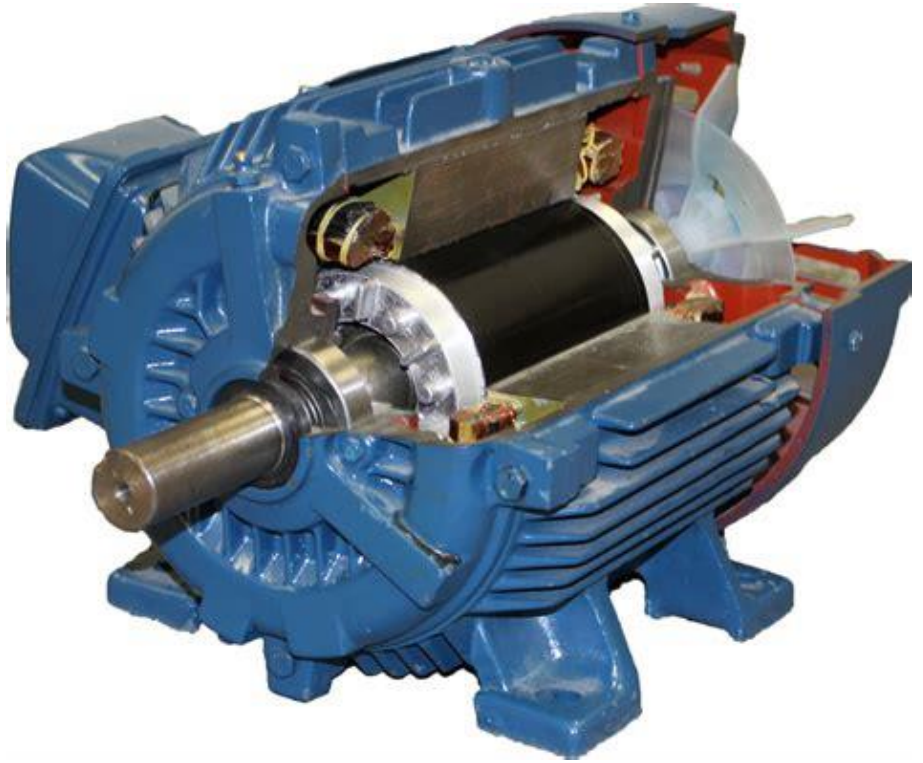
Electronics specifically employs **active devices** like **amplifiers** and **rectifiers**

Electronics with higher voltage/current and active devices are classed under **Power Electronics** – power converter in an electric car



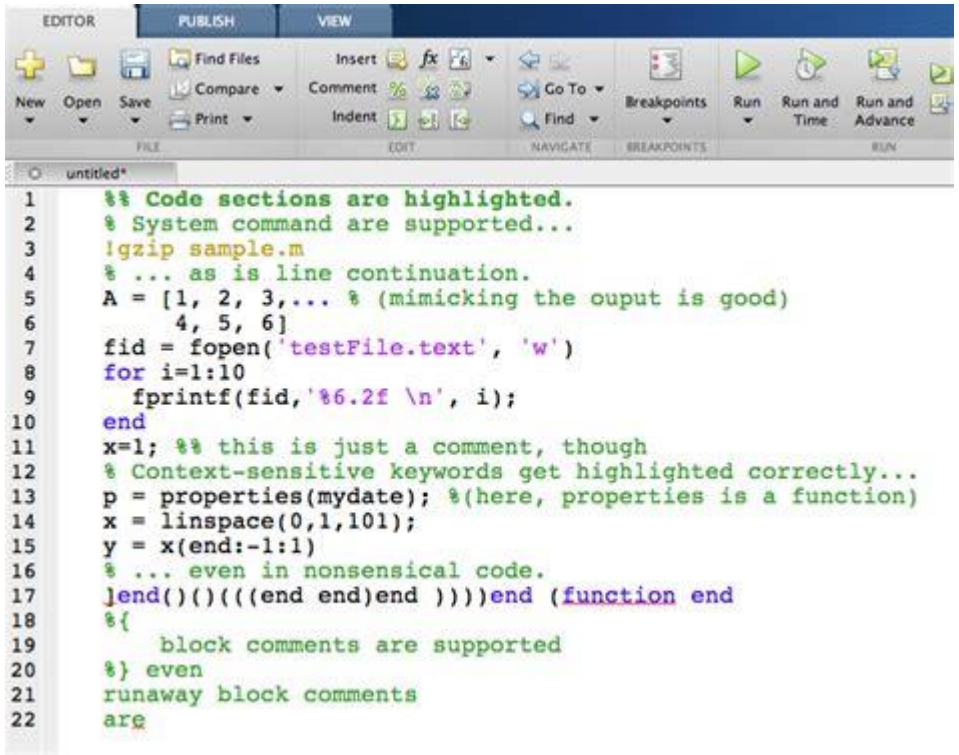
Electromechanical Engineering

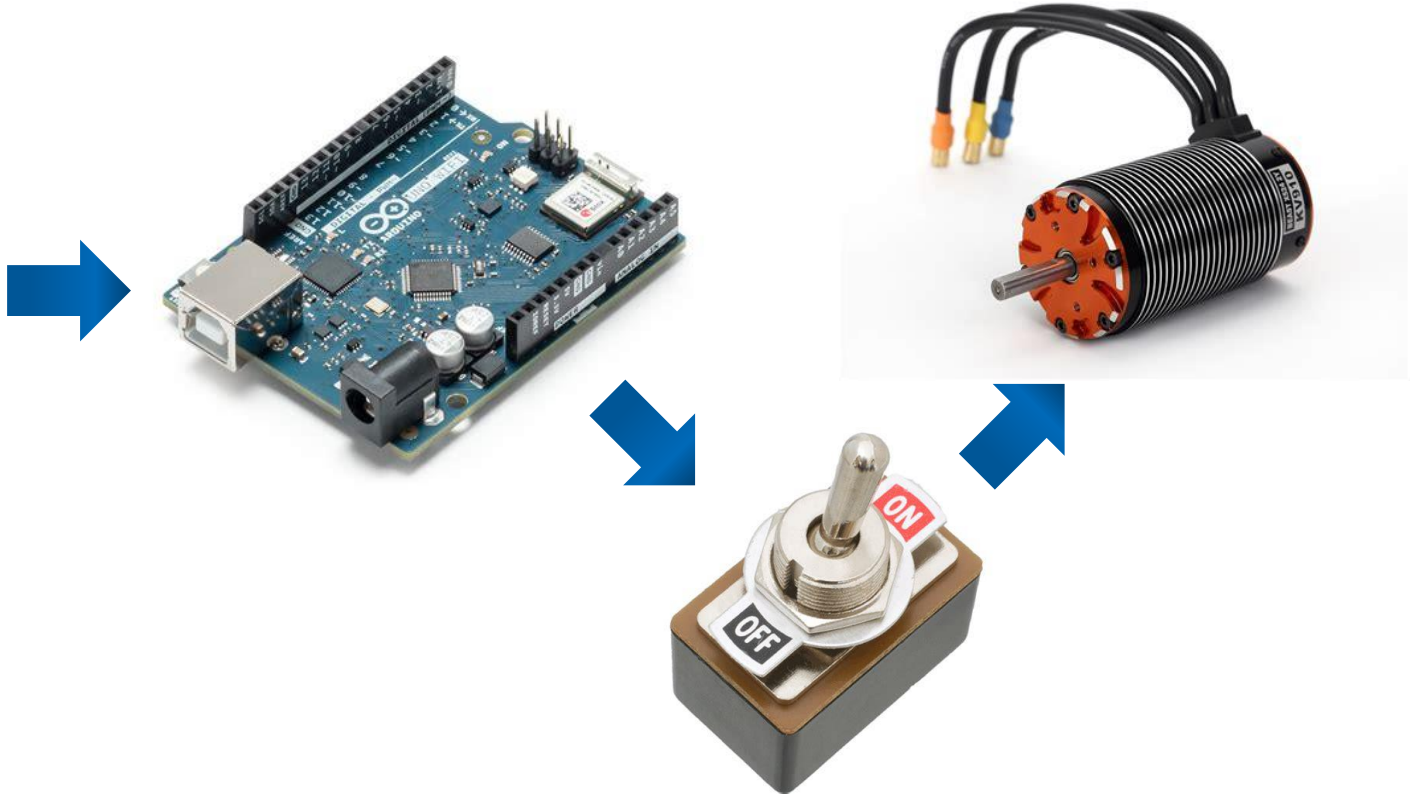
Study of ways to use **electricity to turn or move something**, or use force or movement to **generate electricity**



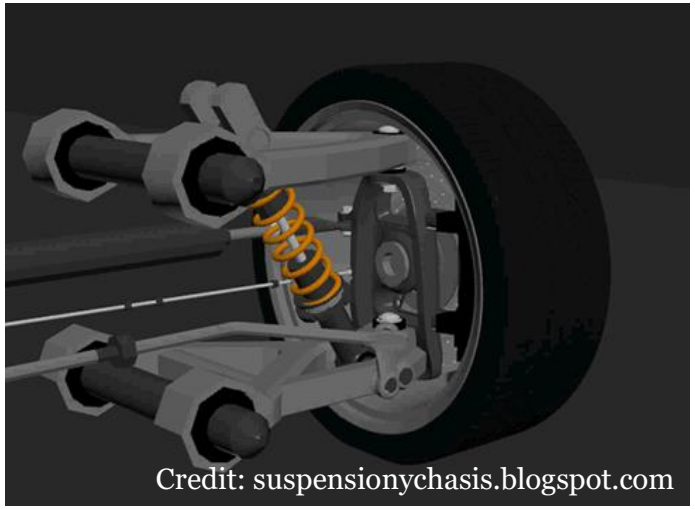
Computer/Software Engineering

Systematic “writing” of “instructions” to operate an electronic system like a **computer** to do a specific set of tasks in a downstream system





Engineering Application – Tesla Model S


Credit: suspensionychasis.blogspot.com

Suspension & **chasses**
Mechanical Engineering


Credit: pinterest.com

Vehicle Control Unit (VCU) that sends signals/commands to drive/stop the car
Electronic Engineering

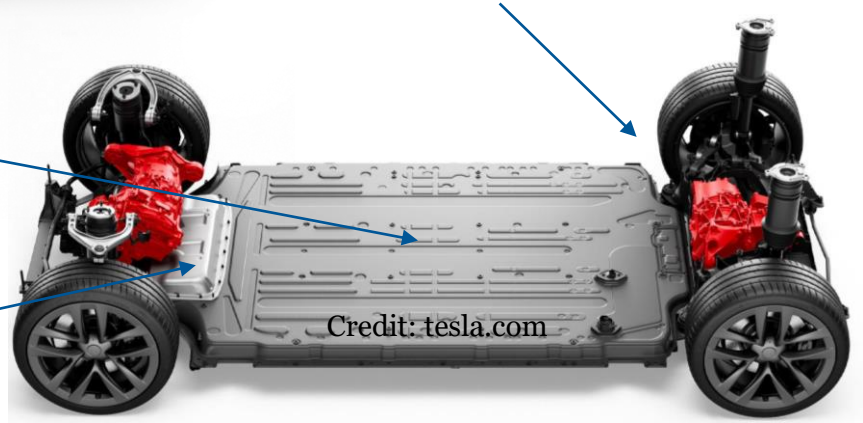
Code written to program the VCU
Computer/Software Engineering


Credit: tesla.com

Motor that converts electrical power from battery to mechanical motion
Electromechanical Engineering

Battery that supplies power to drive the motor
Electrical Engineering

Power Converter that controls the flow of electrical power between battery and motor
Power Electronics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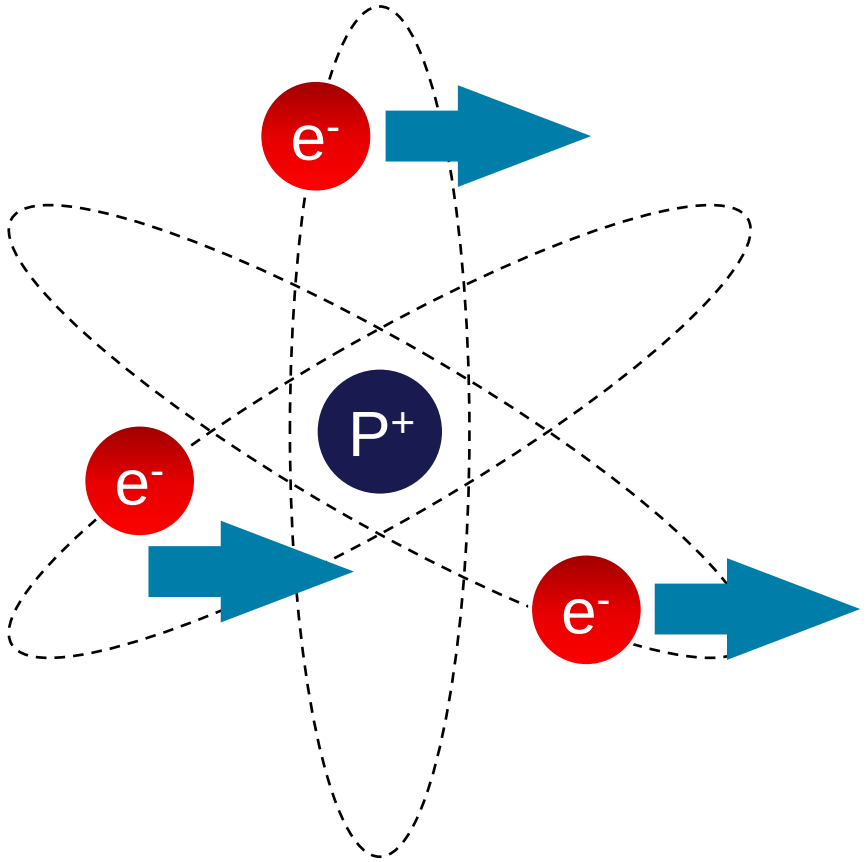
Electricity

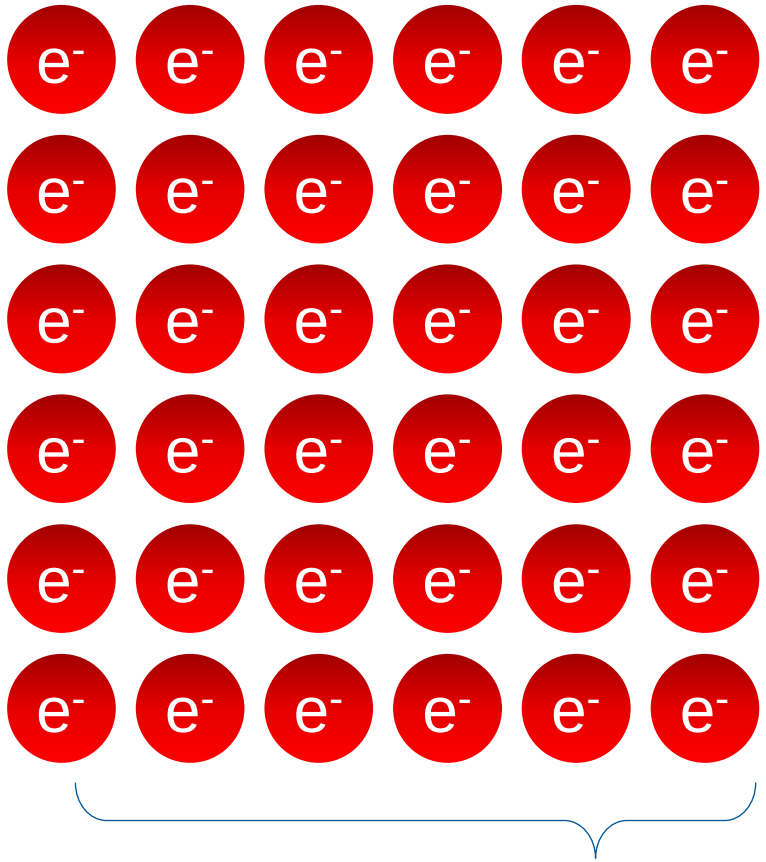


Is it the **electrons**?
No, electrons are everywhere!

Is it **free** electrons?
No, **free electrons** are present in electrical **conductors**, like all metals you see around.

A **cumulative flow** of electrons in a **particular direction consistently**, is **electricity**!

Charge



An electron has a charge of $-1.6022 \times 10^{-19}\ C$ (coulomb)

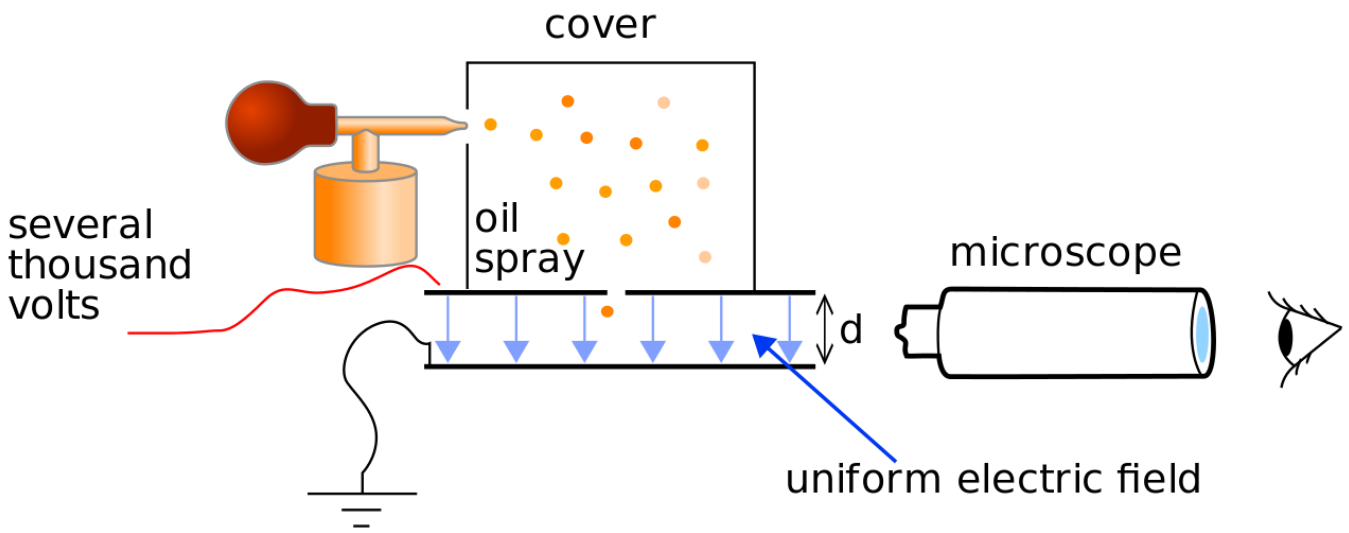
Charles-Augustin de Coulomb, French engineer who did some studies to figure out the force of attraction/repulsion between charged particles in late 1700s. The SI unit is named after him.

If there were $\frac{1}{1.6022 \times 10^{-19}} = 6.2 \times 10^{18}$ electrons together, they would hold $-1C$ charge

Millikan Oil Drop Experiment

A quick worthwhile detour!

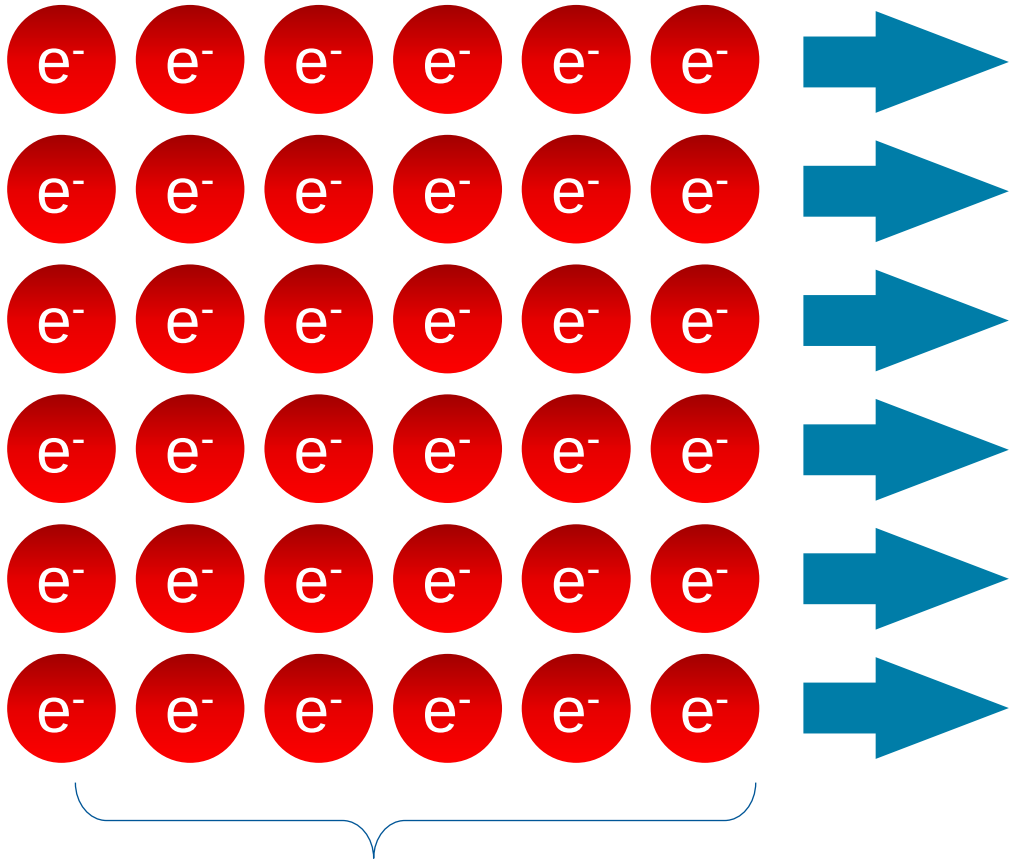
This scientist called *Rob Millikan* in early 1900s wanted to identify the charge of a single electron. The setup was very interesting!



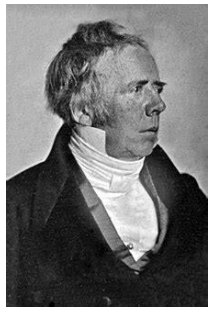
- A mist of **aerosolised oil droplets** were ionised using X-Ray in the top chamber.
- An **electric field applied** and adjusted to **hold** the "charged clusters of electrons" dead in space.

It was deduced (with different field and charge settings) that all droplets were an **integral multiple of a single value**, i.e., $\mathbf{-1.6022 \times 10^{-19}}\ C$

Current



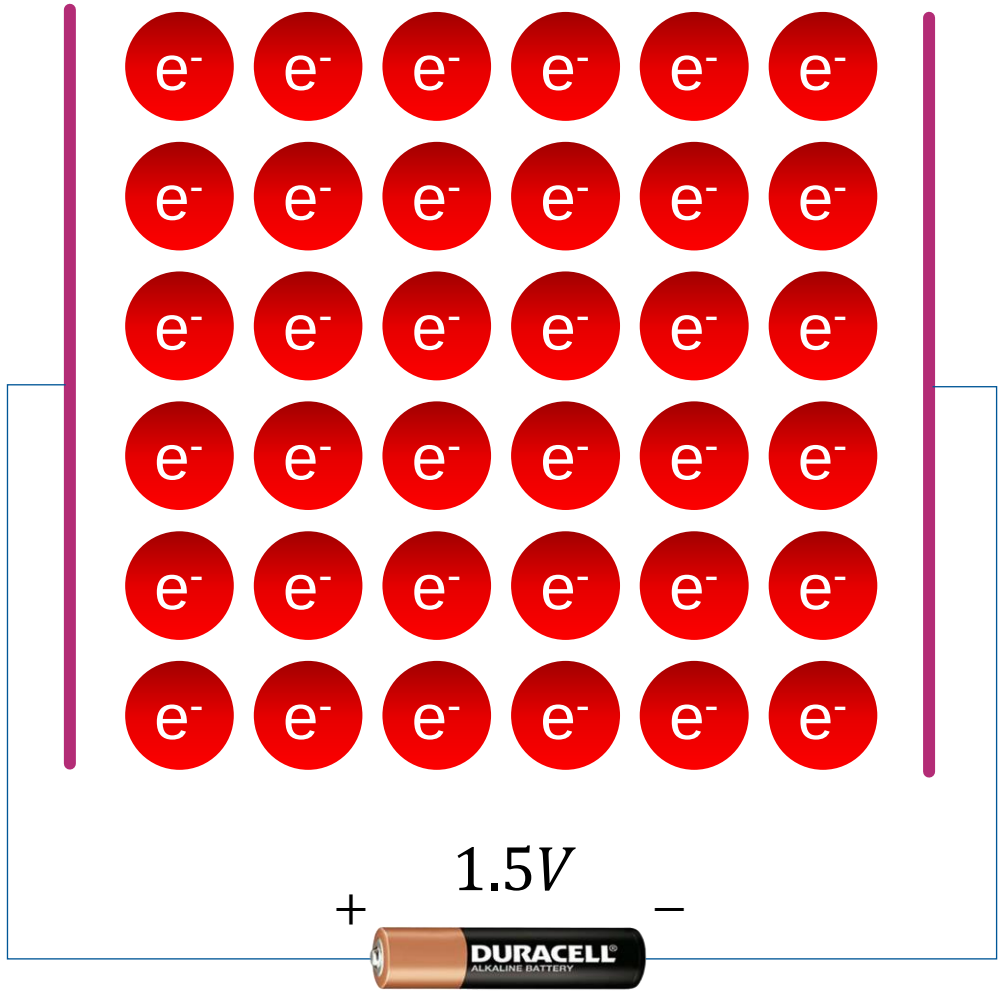
When $1C$ **of charged particles** cumulatively pass through a surface area **every second**, that is $1A$ **(ampere) of current**



André-Marie Ampère, French physicist and mathematician conducted ground-breaking experiments with Danish physicist *Hans Christian Ørsted* to bring together electricity and magnetism in early 1800s.

If 6.2×10^{18} electrons moved together from **left to right**, we would say 1A current is flowing **right to left** (notice the polarity of an electron!)

Voltage



So how can we **push these electrons** to create current?

We do so by creating a **potential difference** between two points, or **voltage** (between two points)

Alessandro Volta, Italian physicist and chemist was the inventor of the first battery in 1800. He was the pioneer of the novel field of electrochemistry.

Think of voltage as **electric pressure**
The battery is an **electric pump**

Electric-Hydraulic Analogy

Volume of Water
(Litre)

Flow Rate of Water
(Litre/sec)

Water Pressure
(Pascal)

Charge
(Coulomb)

Current
(Ampere)

Voltage
(Volt)

Electric-Hydraulic Analogy

What is this new thing?

This is **impedance**, something that **hinders** or **impedes** the **flow** of water/electrons

Nothing is free! If you want some work done (turbine turned or lightbulb lit), you need to apply pressure/volts!

Mechanical work done

Water flows

Water Pressure applied

Pipe filled with water

Bulb lights up

Current flows

Voltage applied

+

$1.5V$

−

Copper wire (filled with electrons!)

Concept – Across v Through Variables

Across Variable

Appears **across the two terminals** of an element

Measured **relative to a reference** point

"Pressure applied by the water pump is 25 Pascals (at the outlet w/r/t inlet)"

"I am driving on the highway at 60 mph (w/r/t the ground)"

"This battery when fully charged applies 1.5 Volts (at the + terminal w/r/t the – terminal)"

Through Variable

Passes through, or acts through an element

Value is **same at both terminals** of the element

"10 L/min of water is flowing through the water pipe"

"I am applying a force of 100 N"

"There is 5 Amperes of current flowing through the lightbulb"

Ohm's Law

We talked about **flow of charge** (current) as a consequence of application of a **potential difference** (voltage) **between two points**

Ask yourself, what defines **how much current** would flow when **an amount of voltage** is applied?

For all practical purposes, **voltage & current** follow a **linearly proportional** relationship

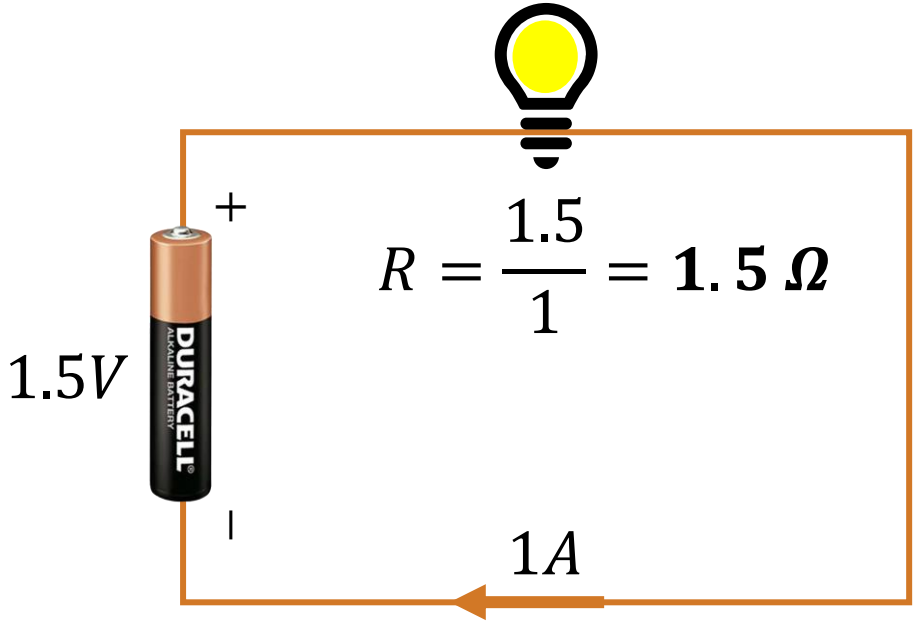
This is called the **Ohm's Law**

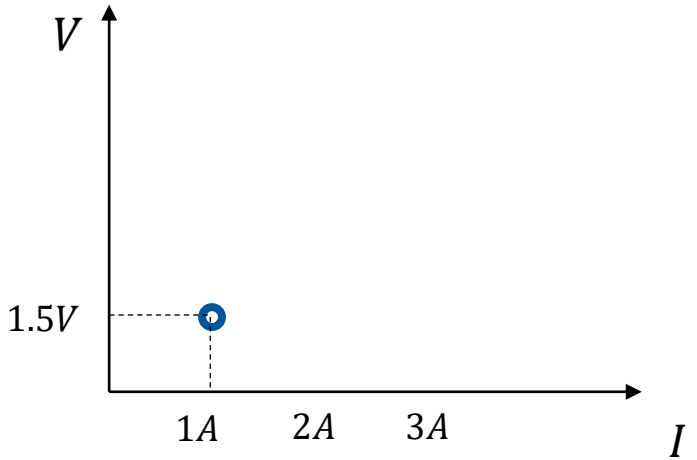
$$V \propto I$$

$$V = IR$$

Voltage, Current, Resistance

Georg Simon Ohm, German physicist began his research with Alessandro Volta's electrochemical cell in mid 1800s to define this law.





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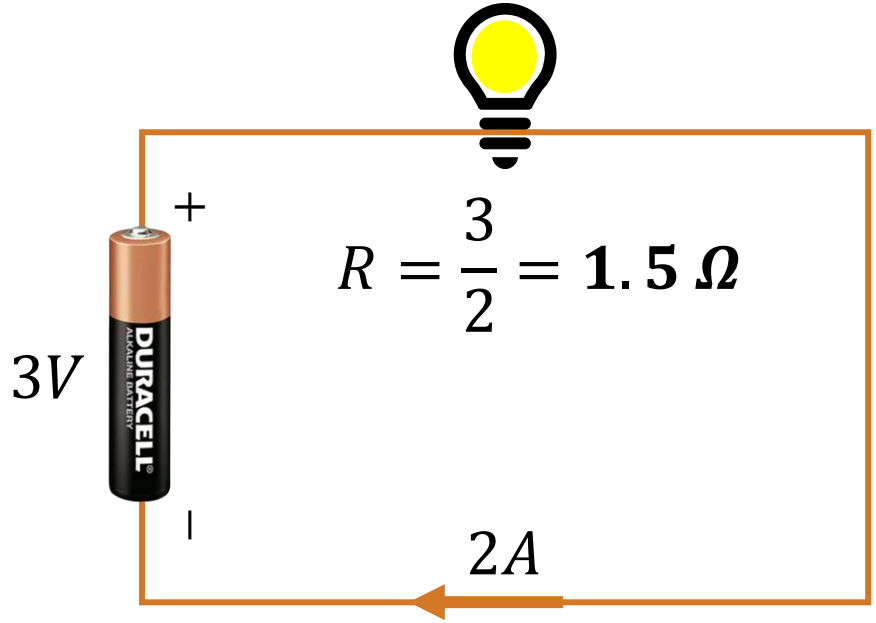

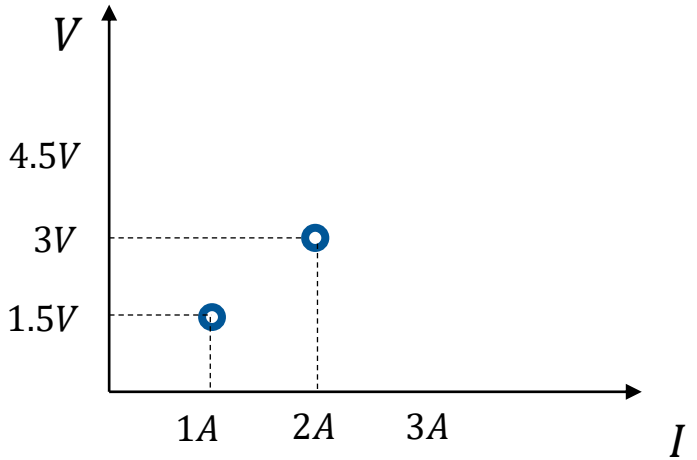

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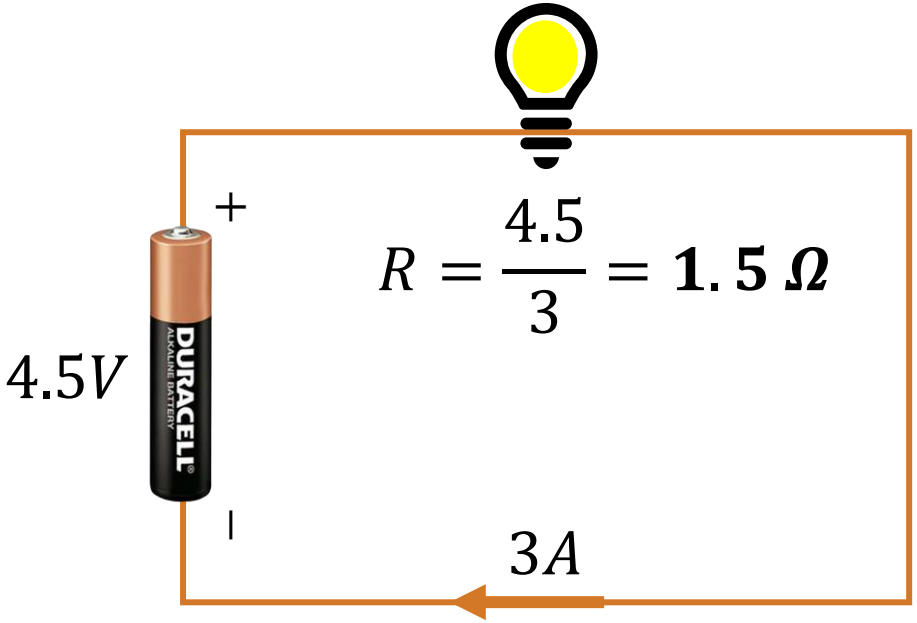
Voltage → V, Current → I, Resistance → R



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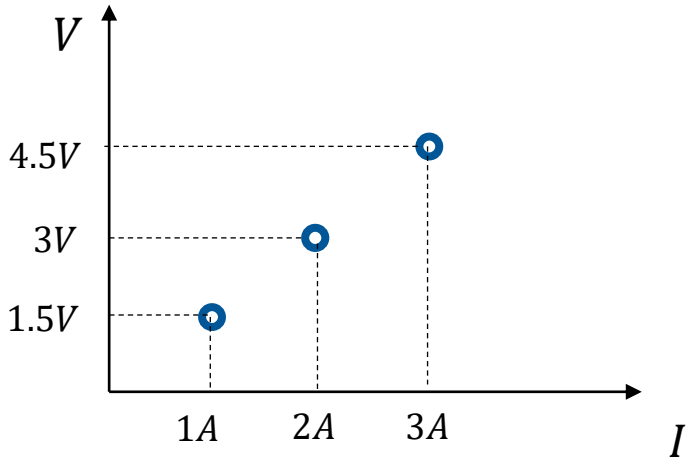

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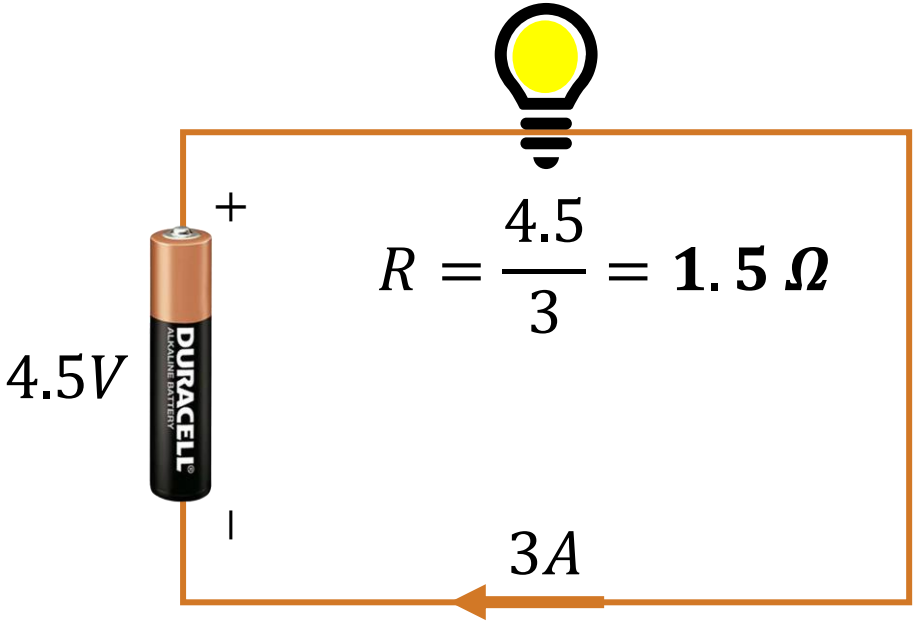

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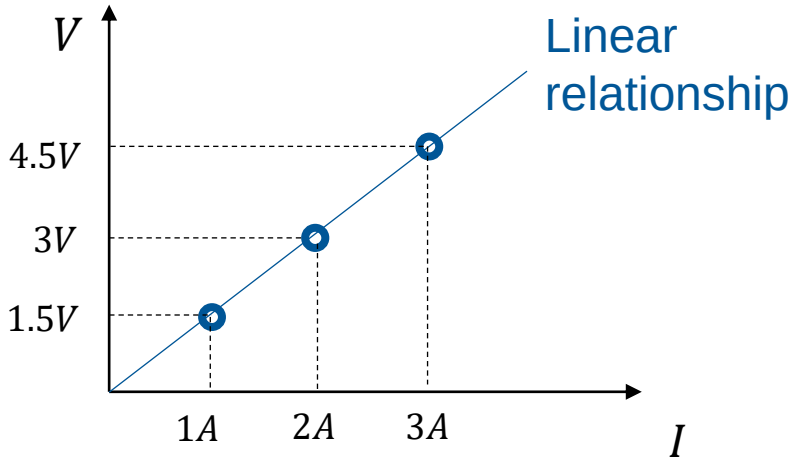
Voltage → V; Current → I; Resistance → R



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Resistance or Impedance?

Impedance is the **generic** term, of which **Resistance** is a **special case**

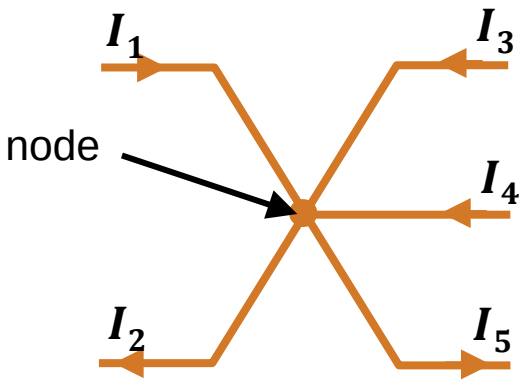
Impedance is used when there **are energy storage elements** (like **capacitor** or **inductor** – we will discuss them in the next section) in the circuit

Resistance is used for non-energy-storage elements, like a **resistor**

Kirchhoff's Laws

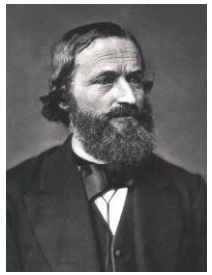
Kirchhoff's Current Law

Algebraic sum of current entering a node is zero



$$I_1 + I_3 + I_4 = I_2 + I_5$$

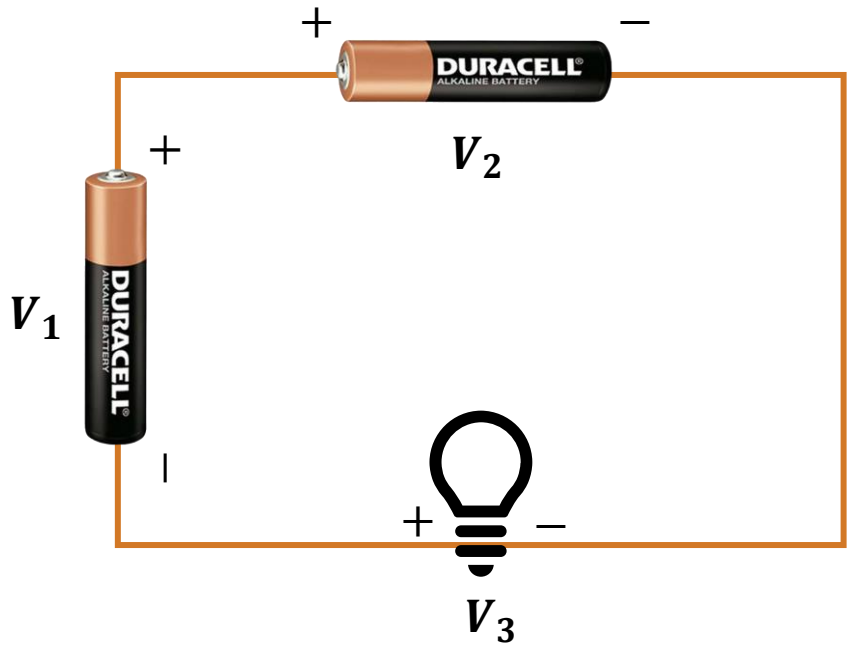
$$\boldsymbol{I_1 - I_2 + I_3 + I_4 - I_5 = 0}$$



Gustav Kirchhoff, German physicist contributed to the fundamental understanding of electric circuits in mid 1800s. He also contributed to spectroscopy and black-body radiation.

Kirchhoff's Voltage Law

Algebraic sum of voltages around a closed loop is zero



$$\boldsymbol{V_1 - V_2 + V_3 = 0}$$

Kirchhoff's Laws

Kirchhoff's Current Law

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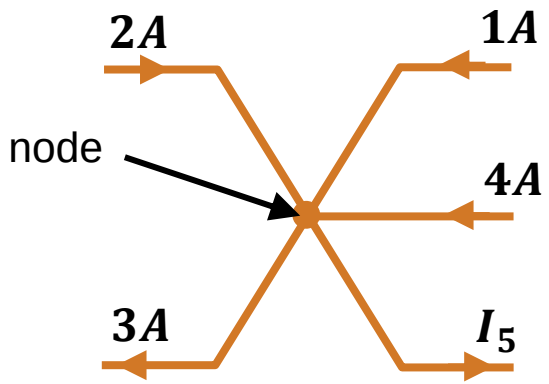
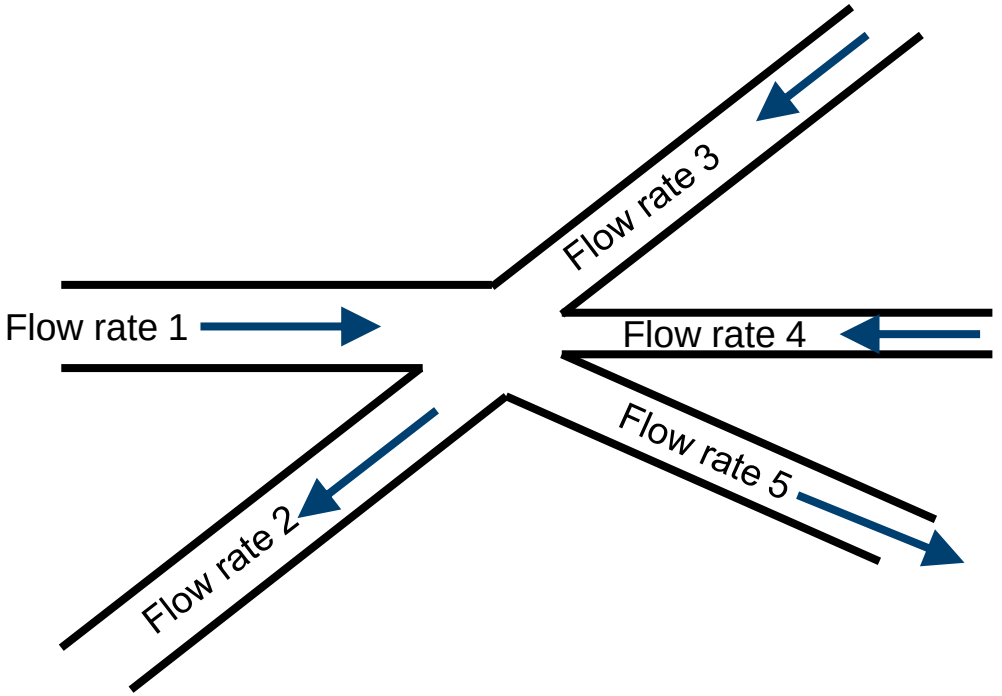


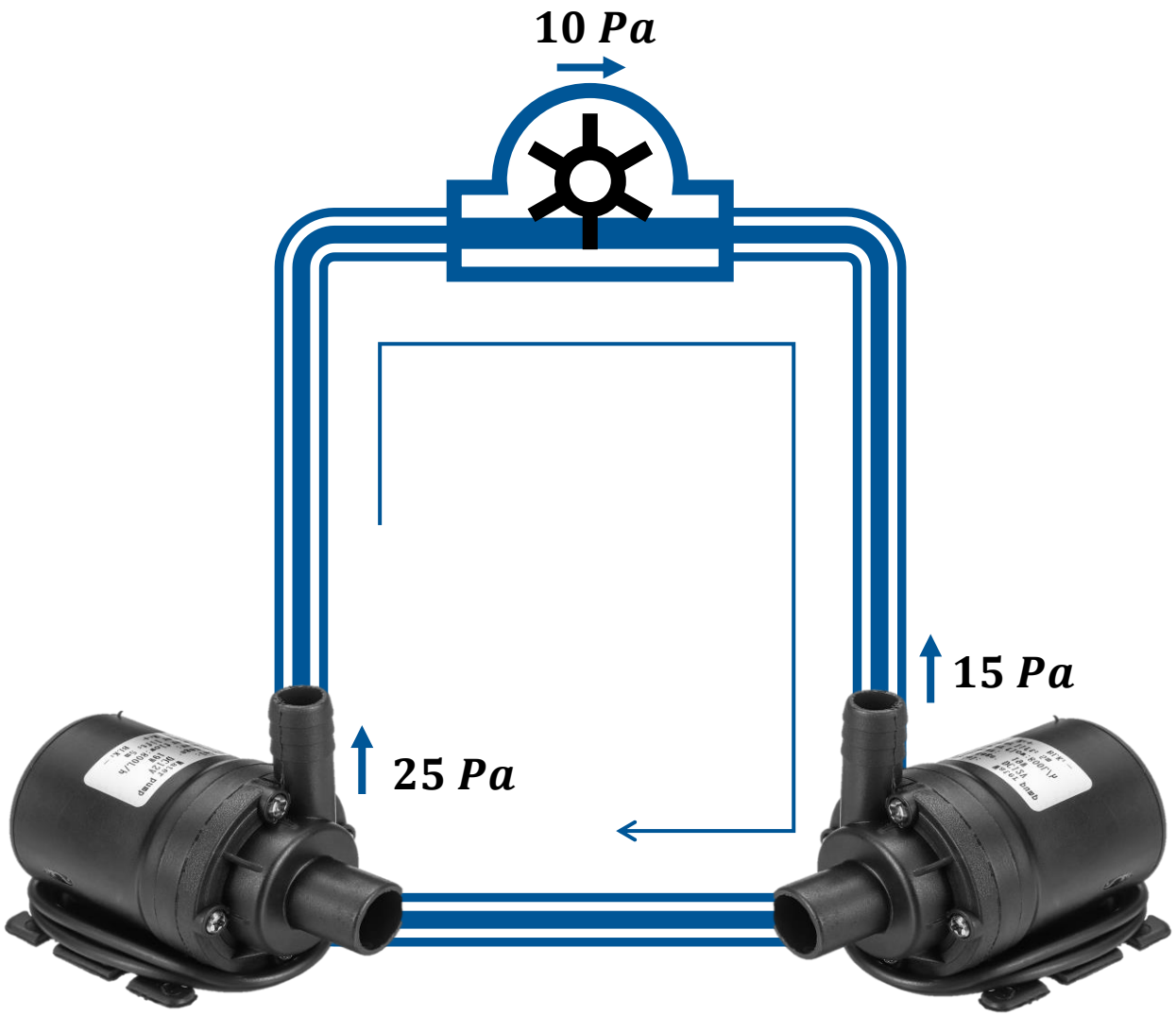


$$2 - 3 + 1 + 4 - I_5 = 0$$

$$2 - 3 + 1 + 4 = I_5$$

$$4A = I_5$$

Kirchhoff's Laws



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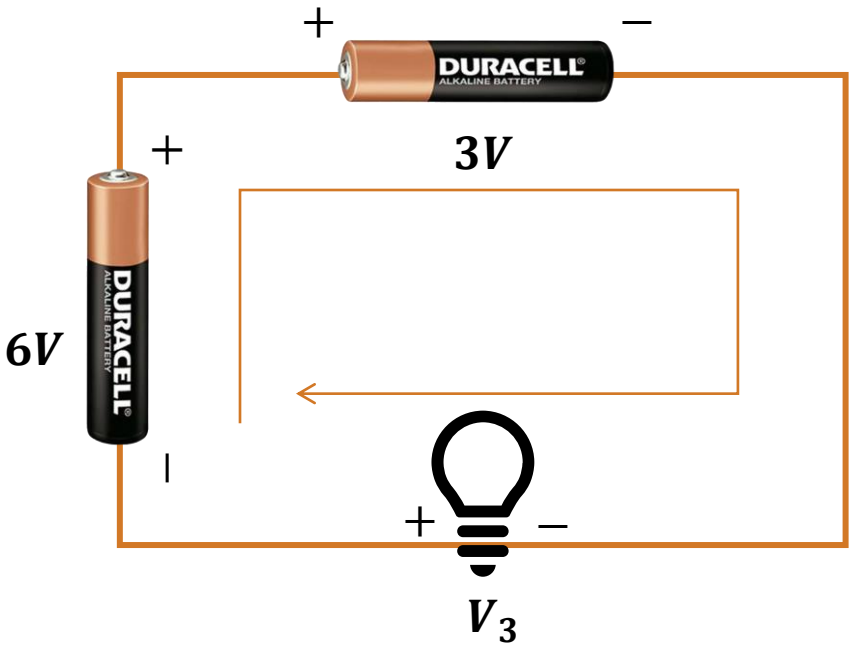

$$6 - 3 + V_3 = 0$$

$$V_3 = -3V$$

Electrical Energy

Indication of how much **electrical energy** has been produced/consumed/transferred over an **amount of time**

SI unit is **Joule** (J), but **kilowatt-hour** (kWh) is widely used for practical purposes

Energy consumed translates to **Work done**, they have the same units

If a device (like battery, or generator) has pushed $5A$ of current at $10V$ in an electrical circuit for $10s$, we say the device has pushed $500Wh$ of energy

$$\boldsymbol{E} = 5A \times 10V \times 10s = \mathbf{50W} \times 10s = \mathbf{500J}$$

James Prescott Joule, English physicist discovered the relationship between heat and work in mid 1800s.

Electrical Power

Rate of production/consumption/transmission of electrical energy

SI unit is **Watt** (W) that is Work done per unit time (**J/s**)

If a device (like battery) is pushing $5A$ of current at $10V$ in an electrical circuit, we say the device is producing $50W$ of power

$$\boldsymbol{P = 5A \times 10V = 50W}$$

If a battery is not connected to any circuit, i.e., left open, it may have $5V$ across its terminals, but as **no current is flowing**, **power is zero**. Similarly, say there is $5A$ flowing in an electrical circuit, there is **zero power** in the copper cables as there is **no voltage across them**

James Watt, Scottish engineer invented the Watt steam engine by improving upon an earlier design in late 1700s.

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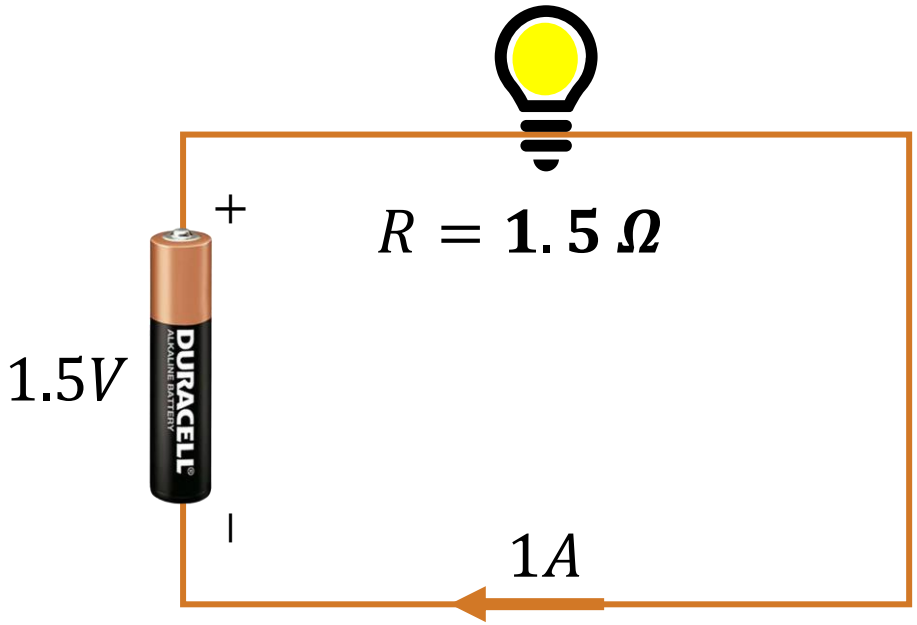
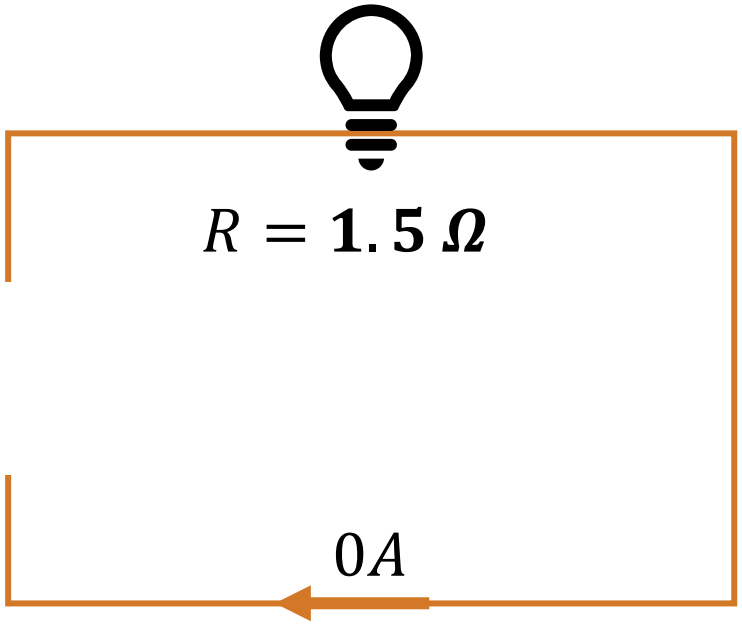
Energy Storing Elements – Reactive Elements

So far, we have looked at a resistor. A **resistor responds instantaneously** to the **application of voltage** across it, by **allowing current to flow** (as per Ohm's Law)

If you **remove the voltage**, the **current flow immediately stops**.





Energy Storing Elements – Reactive Elements

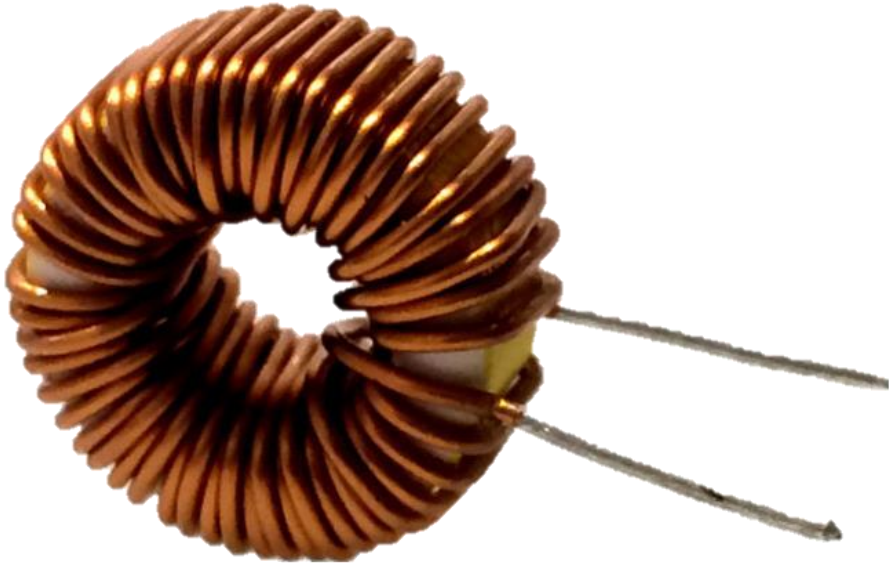
There is another type of element, called **reactive element**, or **energy storing element**, that responds/behaves according to the **present AND the past!**

When you **apply voltage** to a reactive element, the reactive element **starts storing energy** (in various forms – discussed next) while allowing current to flow

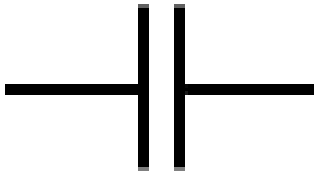
When you **remove the voltage**, the stored energy in it **still pushes current** until all the **stored energy is dissipated**

Energy Storing Elements – Reactive Elements

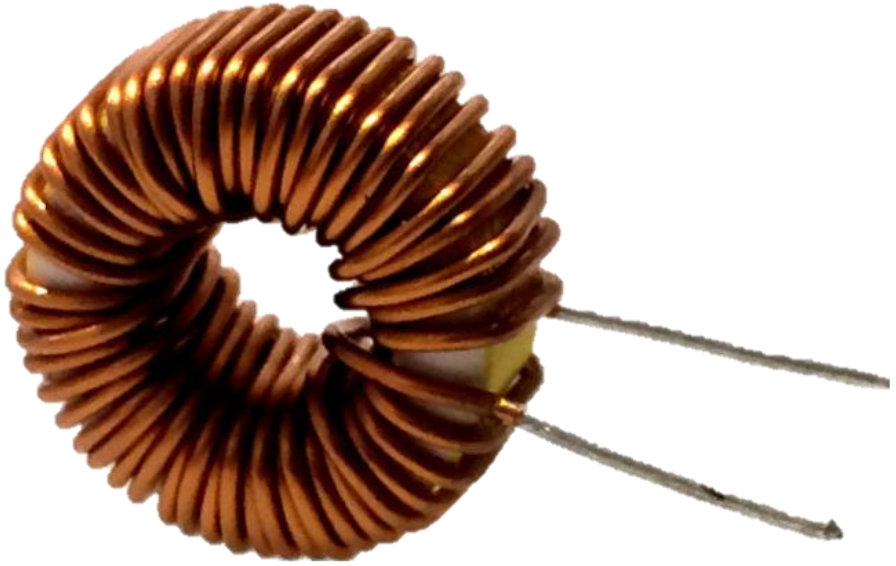
Inductors



Capacitors



Inductor



Electrical symbol

A coil of wire wound around a magnetic core like iron

They have a property called **Inductance** (SI unit: **Henry**, symbol **H**)

Voltage applied is proportional to **rate of change of Current** (unlike Ohm's law)

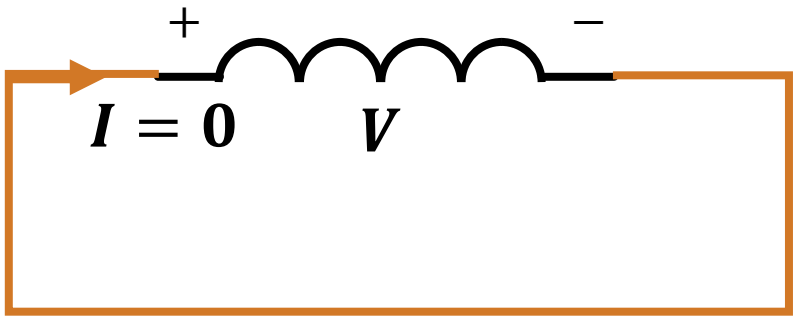
$$V \propto \frac{dI}{dt}$$

$$V = L\frac{dI}{dt}$$

Current in the coil (aided by the magnetic core) creates a magnetic field and hence magnetic flux

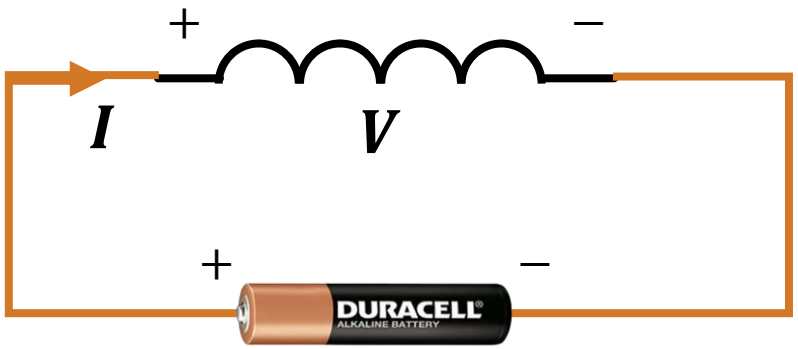
Changing the magnetic flux in the coil induces a voltage that prevents the flux change

Inductor



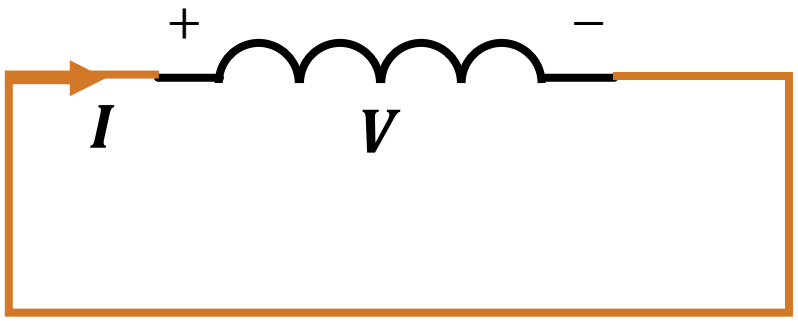
Inductor is discharged

Mass is stationary



Voltage applied, Inductor current starts increasing

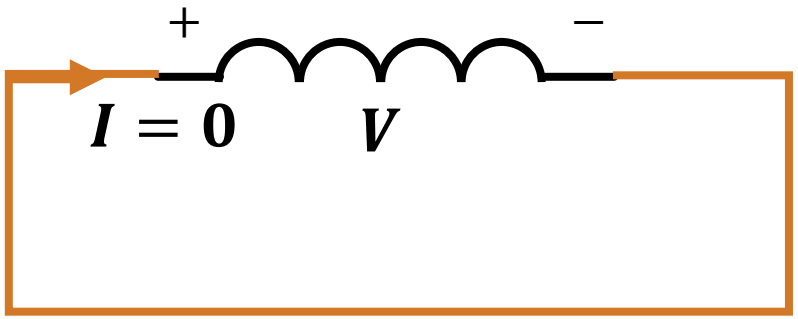
Force applied, mass starts gaining velocity



Voltage removed, current starts declining and eventually stops due to magnetic leakage and tiny (but finite) resistance in copper wires

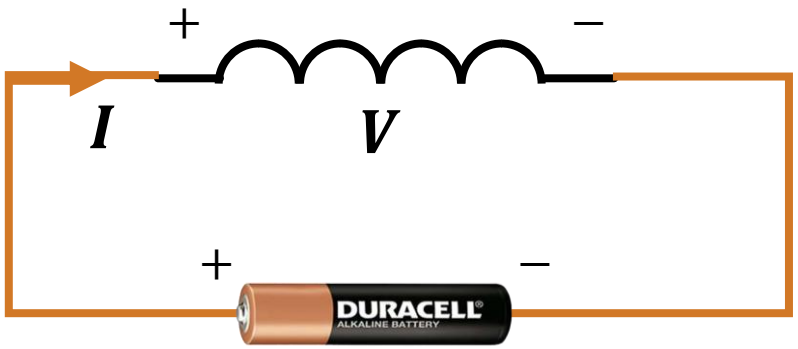
Force removed, mass slows down and stops eventually due to friction

Inductor



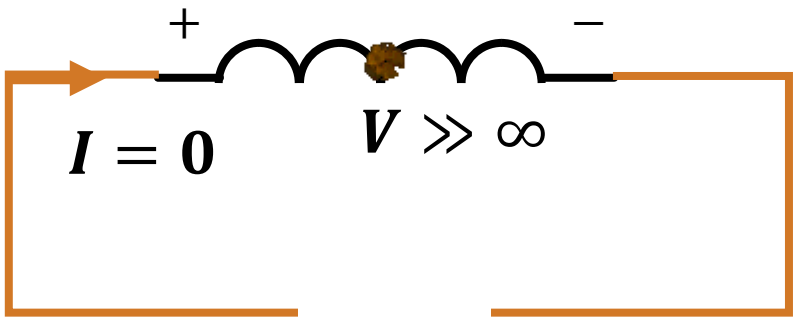
Inductor is discharged

Mass is stationary

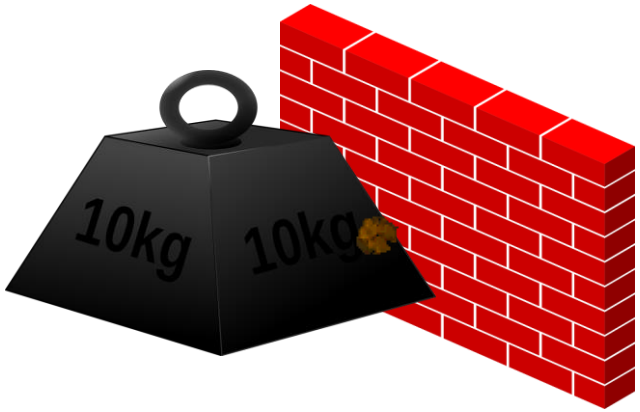


Voltage applied, Inductor current starts increasing

Force applied, mass starts gaining velocity



Voltage removed and current path broken, i.e., open-circuit, near infinite voltage induced across coil to force current flow – **explosion** if high-enough energy was stored!

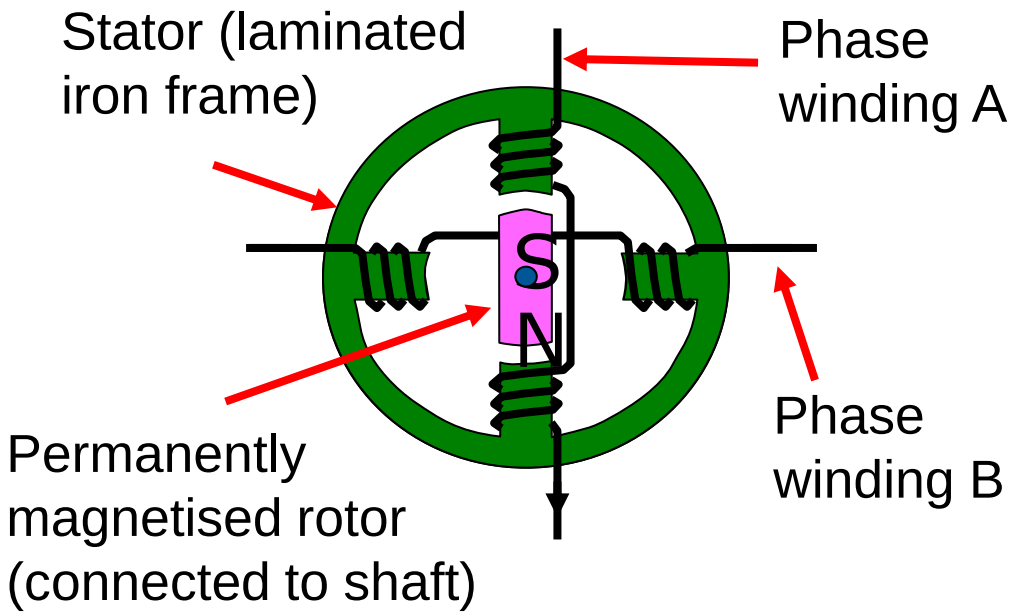


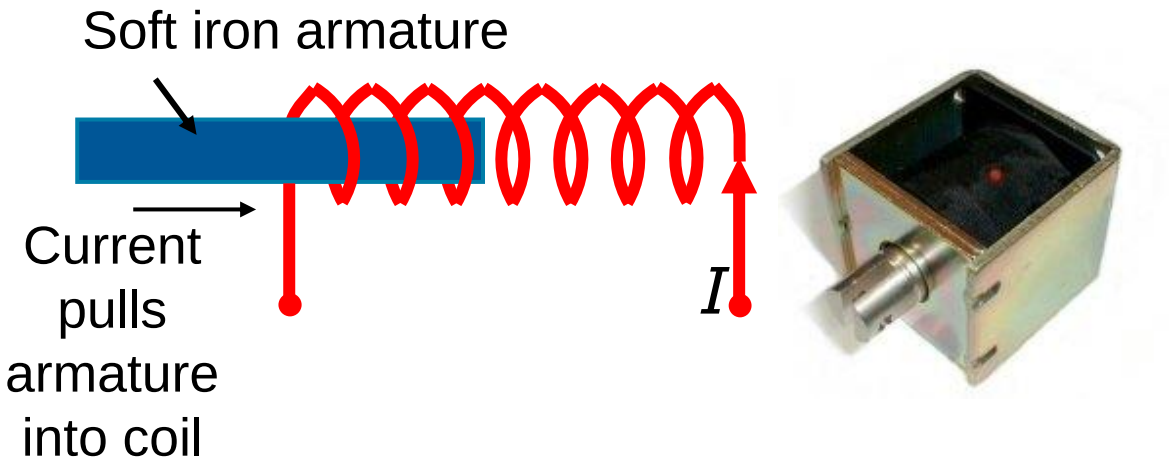
Unmovable brick wall

Inductor

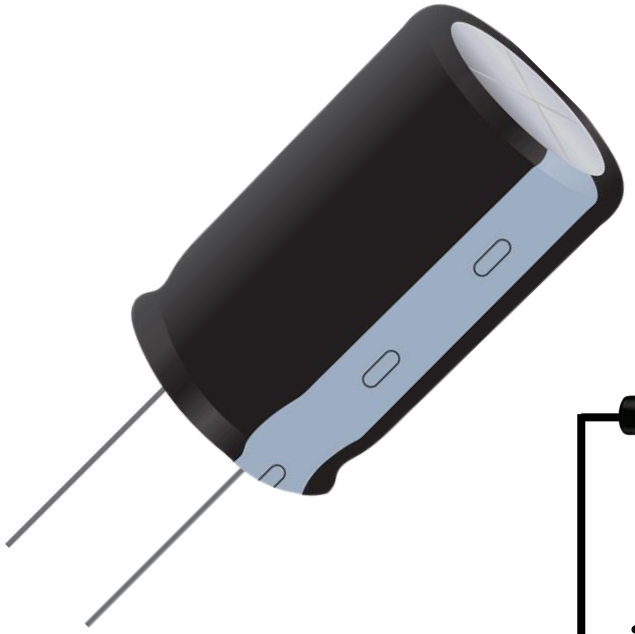
Examples in real life

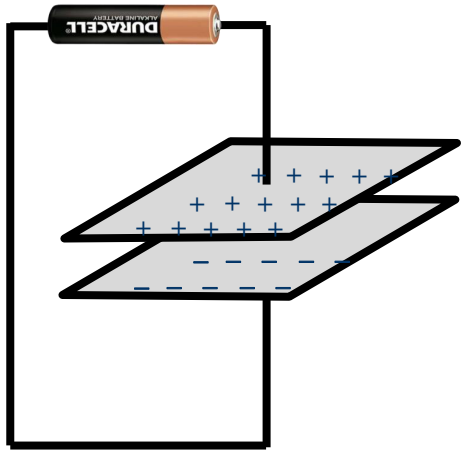
Filtering out rapidly-changing (high frequency signals) e.g., to stop unwanted noise going down power leads

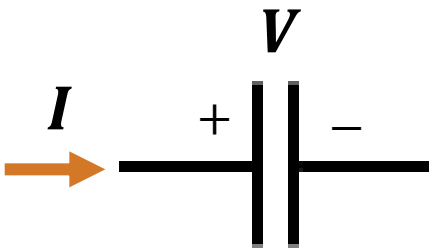




Capacitor







Electrical symbol

Two parallel plates with insulation (dielectric) in between

They have a property called **Capacitance** (SI unit: **Farad**, symbol **F**)

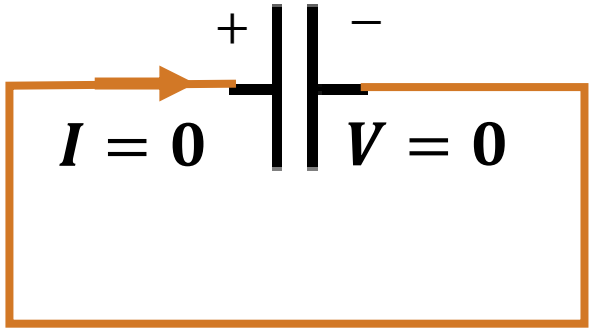
Current applied is proportional to **rate of change of Voltage** (unlike Ohm's law)

$$I \propto \frac{dV}{dt}$$

$$I = C\frac{dV}{dt}$$

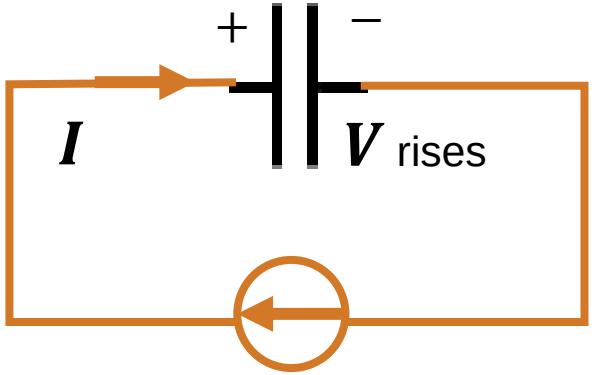
Energy stored using electrostatic attraction: + and – charges in adjacent plates attract each other

Capacitor



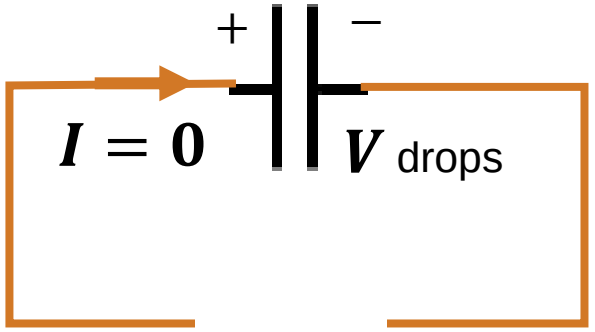
Capacitor is discharged

Mass is stationary



Current applied, Capacitor voltage starts increasing

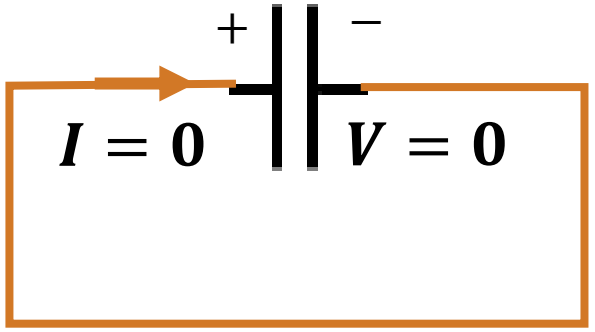
Force applied, mass starts gaining velocity



Current removed, voltage starts declining and eventually goes to zero due to charge leakage

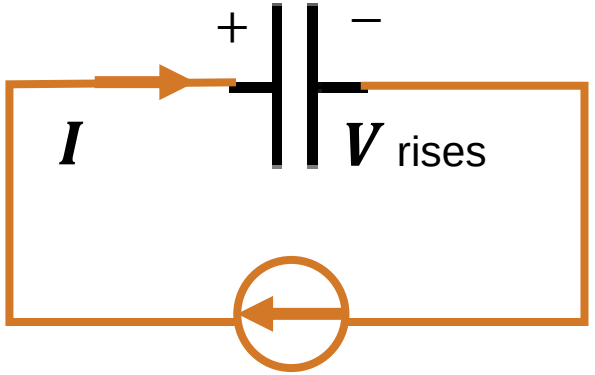
Force removed, mass slows down and stops eventually due to friction

Capacitor



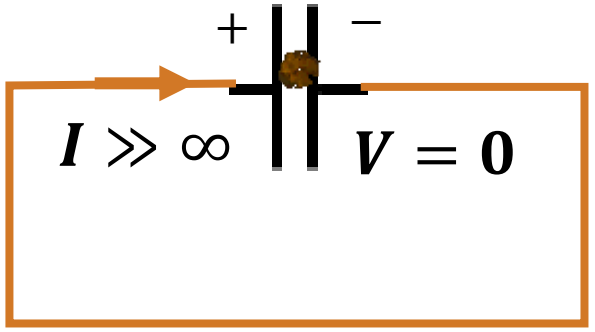
Capacitor is discharged

Mass is stationary

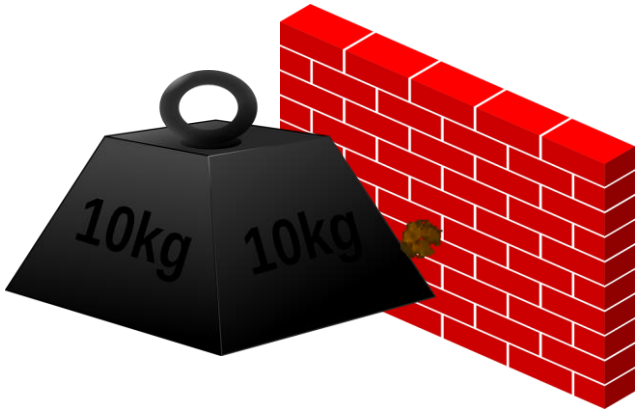


Current applied, Capacitor voltage starts increasing

Force applied, mass starts gaining velocity



Current removed and current path closed, i.e., short-circuit, near infinite current generated through capacitor to force non-zero voltage – **explosion** if high-enough energy was stored!



Unmovable brick wall

Capacitor

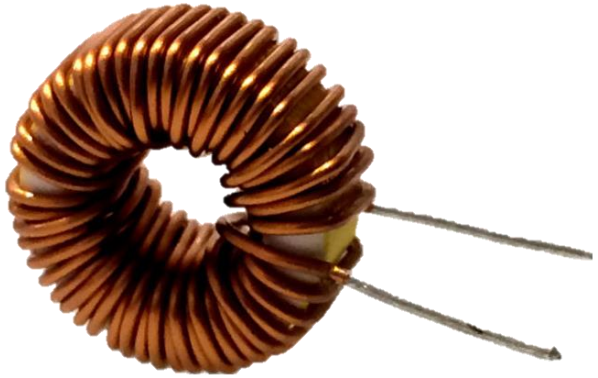
Examples in real life

Stores charge to cause xenon spark for photographic flash

Practically all Electronics have small PCB-mount capacitors for voltage stabilization

All Electric Motors that are PWM-controlled (practically all in today's world)

Voltage/Current Duality



Inductor **opposes sudden changes** in **current**

By **inducing** as much **voltage** is theoretically needed to **keep the current steady**

Capacitor **opposes sudden changes** in **voltage**

By **generating** as much **current** is theoretically needed to **keep the voltage steady**

Summary

- What is **Engineering**?
  - **Mechanical**
  - **Electrical** – sub-branch **Electronic engineering**
  - **Electromechanical**
  - **Computer/Software**
- Fundamentals of **Electrical Engineering**
  - **Charge**, **Current**, **Voltage** – concept of **Across** & **Through** variables
  - Resistance & **Ohm's Law**
  - Kirchhoff's Current Law (**KCL**) & Kirchhoff's Voltage Law (**KVL**)
  - **Power** & **Energy**
- Electrical **energy storing elements** – **Reactive** elements
  - **Capacitor**
  - **Inductor**

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Attendance