

# Block 02 — Electric Charge, Current, Voltage

## Student Group

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# Block 02 — Electric charge, current, voltage

## Learning objectives

After this 90-minute block, you can

- Define electric charge  $Q$  and explain its quantization in multiples of the elementary charge  $e$ .
- Distinguish positive and negative charges, their interactions, and typical carriers (electrons, ions).
- Define electric current  $I$  as rate of charge flow; relate  $I$  to moving charge via  $I = \frac{dQ}{dt}$ .
- Apply the unit check for  $1 \text{ A} = 1 \text{ C/s}$  and recall typical current magnitudes (pA ... kA).
- Explain and consistently use the **conventional current direction**.
- Define electric voltage  $U$  as potential difference and relate it to energy per unit charge:  $U = W/Q$ .
- Distinguish potential reference (ground) and explain why only voltage differences are measurable.

## 90-minute plan

1. Warm-up (5-10 min):
  1. Recall of SI units from Block 01; estimate “How many electrons per second flow at  $1 \text{ A}$ ?”
  2. Quick quiz - “What is larger: voltage of a lightning strike or mains outlet?”
2. Core concepts & derivations (60-70 min):
  1. Electric charge: definition, elementary charge, Coulomb’s law (overview only).
  2. Charge carriers in metals vs. electrolytes.
  3. Electric current: definition, instantaneous and average values, unit check.
  4. Typical magnitudes; conventional vs. electron flow.
3. Practice (10-20 min): Quick calculations and sim-based exercises.
4. Wrap-up (5 min): Summary and pitfalls.

## Conceptual overview

1. **Charge  $Q$**  is the fundamental “substance” of electricity, always in multiples of the elementary charge.
2. **Like charges repel, unlike charges attract**; forces are described by Coulomb’s law (detail in Block 09).
3. **Current  $I$**  quantifies \*how fast\* charge moves:  $1 \text{ A} = 1 \text{ C/s}$ .
4. Convention: we follow **conventional current direction** (positive charge motion, from  $+$  to  $-$ ), even though in metals electrons move oppositely.
5. This block connects Block 01 (units) to Block 03 (voltage and resistance), and prepares for Kirchhoff’s laws in Block 04.

## Core content

### Electric charge

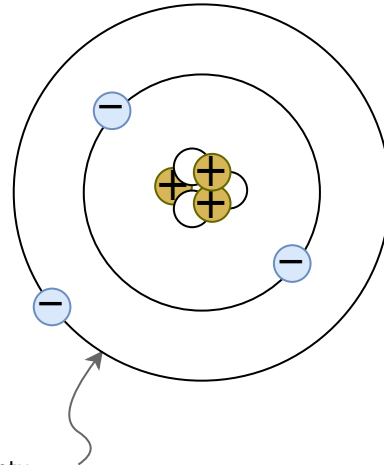


Fig. 1: Atomic model according to Bohr / Sommerfeld <sup>quantized</sup> Text is not SVG - cannot display

- Electric charge  $Q$  is a physical quantity indicating the amount of excess or deficit of electrons or ions.
- the charge is based on the electron shell and the atomic nucleus, see the atomic model of Bohr and Sommerfeld in [figure 1](#)
- Due to the electrons and protons it is **quantized** in multiples of the elementary charge:

$$\begin{aligned} e &= 1.602 \cdot 10^{-19} \text{~}\text{r}\text{m C} \\ Q &= n \cdot e \end{aligned}$$

with  $n \in \mathbb{Z}$ .

- Positive charge: deficiency of electrons generates an excess of positive charges (e.g. ionized atoms).
- Negative charge: excess electrons overcompensates the positive charges.
- charges with different signs attract each other. Charges with similar sign repel each other

$$\begin{aligned} [Q] &= 1 \text{~}\text{r}\text{m C} = 1 \text{~}\text{A} \cdot \text{s} \end{aligned}$$

#### Example / micro-exercise

How many electrons correspond to a charge of  $1 \text{~}\text{r}\text{m C}$ ? 
$$n = \frac{Q}{e} = \frac{1 \text{~}\text{r}\text{m C}}{1.602 \cdot 10^{-19} \text{~}\text{r}\text{m C}} \approx 6.24 \cdot 10^{18}$$

### Electric current

An **electric current** arises when charges move in a preferred direction, e.g. by attraction and repulsion. The current is defined as

$$I = \frac{Q}{t}$$

The instantaneous current is defined as

$$i(t) = \frac{dQ}{dt}$$

Unit check:

$$[i] = \frac{[Q]}{[t]} = \frac{1 \text{ C}}{1 \text{ s}} = 1 \text{ A}$$

Charge transport can take place through

- In metals: flow of electrons.
- In electrolytes: movement of ions.
- In semiconductors: electrons and holes.

### Convention

In this course, we generally use the **conventional current direction**: positive from \$+\$ to \$-\$ . The electron flow is opposite.

### Typical current magnitudes

- \$10 \text{ pA}\$ — control current in a FET gate
- \$10 \text{ }\mu\text{A}\$ — sensitive sensor output
- \$10 \text{ mA}\$ — LED or small sensor supply
- \$10 \text{ A}\$ — heating device
- \$10 \text{ kA}\$ — large generator output

### Electrodes

An electrode is a connection (or pin) of an electrical component.

Looking at a component, the electrode is characterized as the homogenous part of the component, where the charges come in / move out (usually made out of metal).

The name of the electrode is given as follows:

- **Anode**: Electrode at which the current enters the component.
- **Cathode**: Electrode at which the current exits the component. (in German *Kathode*)

As a mnemonic, you can remember the diode's structure, shape, and electrodes (see [figure 2](#)).

Fig. 2: Electrodes on the diode

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## Electric voltage

Every rock on a mountain has a higher energy potential than a rock in the valley. As higher up and as more mass the rock has, as more energy is stored. The energy difference  $\Delta W_{1,2}$  is given by the height difference  $\Delta h_{1,2}$

$$\Delta W_{1,2} = m \cdot g \cdot \Delta h_{1,2}$$

Similarly, charges on the positive pin of a battery has a higher energy potential than charges on the negative pin. Similar to the transport of a mass in the gravitational field, energy is needed/released when charge is moved in an electric field. We will look at the specific electric field starting from [block09](#).

For the energy in an electric field, as higher the object is charged ( $Q$ ), as more energy  $\Delta W_{1,2}$  can be released / is needed for movements. The equivalent to the height  $h$  in the

mechanic picture is the potential  $\varphi$  in the electric case:

$$\Delta W_{1,2} = Q \cdot \Delta \varphi_{1,2}$$

It follows that:

$$\boxed{\frac{\Delta W_{1,2}}{Q} = \varphi_1 - \varphi_2 = U_{1,2}}$$

voltage  $U_{1,2}$  is the energy  $W_{1,2}$  per charge  $Q$  between two points 1 and 2.

- **Units:**  $[U] = [W]/[Q] = 1 \text{ J} / 1 \text{ C} = 1 \text{ V}$ .
- **Reference:** We choose one node as potential zero ("ground"); only differences are meaningful.

## Typical voltage magnitudes

- Thermal noise:  $\sim \mu\text{V}$
- Microcontroller: supply  $1.8 \text{ V}$  to  $5.0 \text{ V}$  (often given as 1V8 and 5V0 or in general as VCC or VDD)
- Mains:  $230 \text{ V}$
- Lightning:  $> 10^6 \text{ V}$

## Example / micro-exercise

A charge  $Q = 2.0 \text{ mC}$  moves through a potential difference of  $5.0 \text{ V}$ . Energy transferred:

$$W = U \cdot Q = 5.0 \text{ V} \cdot 2.0 \text{ mC} = 10.0 \text{ mJ}$$

## Comparison: Mechanics vs Electrics

Fig. 3: Mechanical potential



### Mechanical System

### Potential Energy

Potential energy is always related to a

Fig. 4: Electrical Potential



### Electrical System

### Potential

The potential  $\varphi$  is always specified relative to a reference point.

Common used are:

- Earth potential (ground, earth, ground).
- infinitely distant point

reference level (reference height). The energy required to move  $m$  from  $h_1$  to  $h_2$  is independent of the reference level.

$$\Delta W_{1,2} = W_1 - W_2 = m \cdot g \cdot h_1 - m \cdot g \cdot h_2 = m \cdot g \cdot (h_1 - h_2)$$

To shift the charge, the potential difference must be overcome. The potential difference is independent of the reference potential.  $\Delta W_{1,2} = W_1 - W_2 = Q \cdot \varphi_1 - Q \cdot \varphi_2 = Q \cdot (\varphi_1 - \varphi_2)$

## Common pitfalls

- Mixing electron flow vs. conventional current.
- Misinterpreting current as “speed” rather than rate of charge flow.
- Given the definition, rechargeable batteries not have a fixed cathode / anode. Here, usually discharging the battery is considered.

## Exercises

### Exercise E1 Charges on a Ballon

A balloon has a charge of  $Q = 7 \text{ nC}$  on its surface.

**Result** How many additional electrons are on the balloon?

**Solution**

$$43.7 \cdot 10^9 \text{ electrons}$$

$$Q = 7 \text{ nC} = 7 \cdot 10^{-9} \text{ C} \quad n_e = \frac{7 \cdot 10^{-9} \text{ C}}{1.6022 \cdot 10^{-19} \text{ C/electron}} = 43.7 \cdot 10^9 \text{ electrons}$$

### Exercise E2 Charges on a Ballon

A balloon has a charge of  $Q = 7 \text{ nC}$  on its surface.

**Result** How many additional electrons are on the balloon?

**Solution**

$$43.7 \cdot 10^9 \text{ electrons}$$

$$\begin{aligned} Q &= 7 \text{ nC} = 7 \cdot 10^{-9} \text{ C} \\ n_e &= \frac{7 \cdot 10^{-9} \text{ C}}{1.6022 \cdot 10^{-19} \text{ C/electron}} = 43.7 \cdot 10^9 \text{ electrons} \end{aligned}$$

### Exercise E3 Charges in Electroplating

To get a different metal coating onto a surface, often [Electroplating](#) is used. In this process, the surface is located in a liquid, which contains metal ions of the coating.

In the following, a copper coating (e.g. for corrosion resistance) shall be looked on. The charge of one copper ion is around  $1.6022 \cdot 10^{-19} \text{ C}$ , what is the charge on the surface if there are  $8 \cdot 10^{22} \text{ ions}$  added?

$$12'818 \text{ C}$$

Solution

$$8 \cdot 10^{22} \cdot 1.6022 \cdot 10^{-19} \text{ C} = 12'817.6 \text{ C}$$

### Exercise E4 Charges in Electroplating

To get a different metal coating onto a surface, often [Electroplating](#) is used. In this process, the surface is located in a liquid, which contains metal ions of the coating.

In the following, a copper coating (e.g. for corrosion resistance) shall be looked on. The charge of one copper ion is around  $1.6022 \cdot 10^{-19} \text{ C}$ , what is the charge on the surface if there are  $8 \cdot 10^{22} \text{ ions}$  added?

$$12'818 \text{ C}$$

Solution

$$8 \cdot 10^{22} \cdot 1.6022 \cdot 10^{-19} \text{ C} = 12'817.6 \text{ C}$$

### Exercise E1.5.1 Direction of the voltage

Fig. 5: Example of conventional voltage specification  
Result

- + is the higher potential. Terminal 1 has the higher potential.  $\varphi_1 > \varphi_2$
- For  $U_{\text{Batt}}$ : The arrow starts at terminal 1 and ends at terminal 2. So  $U_{\text{Batt}} = U_{12} > 0$
- $U_{21} < 0$

Explain whether the voltages  $U_{\text{Batt}}$ ,  $U_{12}$  and  $U_{21}$  in [figure 5](#) are positive or negative according to the voltage definition.

Hints

- Which terminal has the higher potential?
- From where to where does the arrow point?

## Task 2.1: Counting charges in a current

A flashlight bulb is supplied with  $I=0.25\text{~}\text{A}$ . How many electrons pass through the filament in one second?

Strategy

Use  $n=\frac{I \cdot t}{e}$  with  $t=1\text{~}\text{s}$ .

Solution

$$n = \frac{0.25\text{~}\text{C}}{1.602 \cdot 10^{-19}\text{~}\text{C}} \approx 1.6 \cdot 10^{18}$$

## Exercise E5 Electron flow

How many electrons pass through a control cross-section of a metallic conductor when the current of  $40\text{~}\text{mA}$  flows for  $4.5\text{~}\text{s}$ ?

Solution

$$1.1 \cdot 10^{18}\text{~}\text{electrons}$$

$$Q = I \cdot t = 0.04\text{~}\text{A} \cdot 4.5\text{~}\text{s} = 0.18\text{~}\text{As} = 0.18\text{~}\text{C} = \{0.18\text{~}\text{C}\} \cdot \left\{ \frac{1}{1.6022 \cdot 10^{-19}\text{~}\text{C/electron}} \right\} = 1.1 \cdot 10^{18}\text{~}\text{electrons}$$

## Exercise E6 Determining the Current from Charge per Time

Two objects are connected by a wire and the charge in [figure 6](#) on an object changes non-linearly in the charge per time.

Result

A non-linear charge increase leads to a non-constant current.  
 For a non-constant current, one has to use the time derivative of the charge  $Q$  to get the current  $I$ .  
 So, the formula  $I = \frac{dQ}{dt}$  has to be used instead of  $I = \frac{\Delta Q}{\Delta t}$ .

Fig. 6: Time course of the charge ...

1. Determine the currents  $I_1$  and  $I_2$  for the two objects from the  $Q$ - $t$ -diagram [figure 6](#) and plot the currents into a new diagram.

Solution

- Have a look how much increase  $\Delta Q$  per time duration  $\Delta t$  is there for each object.
- For this choose a distinct time period, e.g. between  $0\text{ s}$  and  $20\text{ s}$ .
- The current is then given as the change in charge per time:  $I = \frac{\Delta Q}{\Delta t}$

### Exercise E7 Electron flow

How many electrons pass through a control cross-section of a metallic conductor when the current of  $40\text{ mA}$  flows for  $4.5\text{ s}$ ?

Result

## Solution

$$\begin{aligned} & 1.1 \cdot 10^{18} \text{ electrons} \end{aligned}$$

$$\begin{aligned} Q &= I \cdot t = 0.04 \text{ A} \cdot 4.5 \text{ s} = 0.18 \text{ As} \\ &= 0.18 \text{ C} = 0.18 \text{ C} \cdot \frac{1}{1.6022 \cdot 10^{-19} \text{ C/electron}} = 1.1 \cdot 10^{18} \text{ electrons} \end{aligned}$$

**Exercise E8 Determining the Current from Charge per Time**

Two objects experience a charge increase over time, as per the graph in figure 6. One object has a non-linear increase in the charge per time.

**Result**

## Result

A non-linear charge increase leads to a non-constant current.

For a non-constant current, one has to use the time derivative of the charge  $Q$  to get the current  $I$ .

So, the formula  $I = \frac{dQ}{dt}$  has to be used instead of  $I = \frac{\Delta Q}{\Delta t}$ .

Fig. 6: Time course of the charge ...

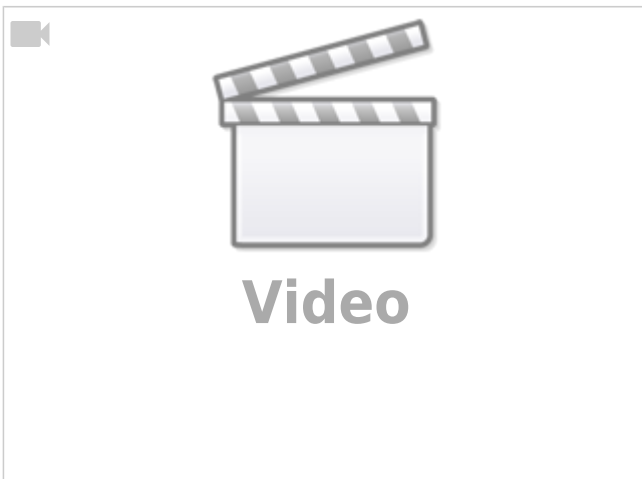
1. Determine the currents  $I_1$  and  $I_2$  for the two objects from the  $Q$ - $t$ -diagram figure 6 and plot the currents into a new diagram.

## Solution

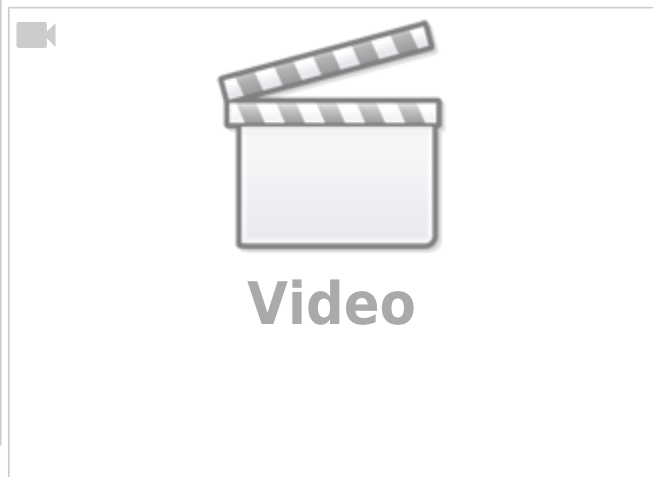
- Have a look how much increase  $\Delta Q$  per time duration  $\Delta t$  is there for each object.
- For this choose a distinct time period, e.g. between  $0 \text{ s}$  and  $20 \text{ s}$ .
- The current is then given as the change in charge per time:  $I = \frac{\Delta Q}{\Delta t}$

## Embedded resources

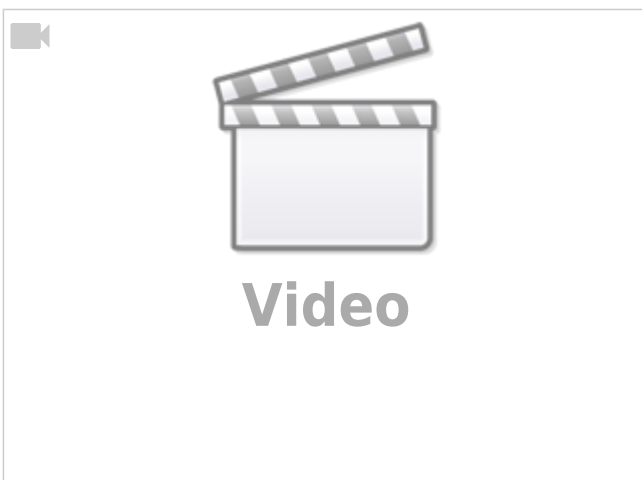
Charge in Matter



What is Electric Charge and How Electricity Works



Electric - Hydraulic Analogy: Charge, Voltage, and Current



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