

# Block 02 — Electric Charge, Current, Voltage

## Student Group

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## Table of Contents

<b>Block 02 — Electric charge, current, voltage</b> .....	3
<b>Learning objectives</b> .....	3
<b>90-minute plan</b> .....	3
<b>Conceptual overview</b> .....	3
<b>Core content</b> .....	4
Electric charge .....	4
Example / micro-exercise .....	4
Electric current .....	4
Convention .....	5
Typical current magnitudes .....	5
Electrodes .....	5
Electric voltage .....	6
Typical voltage magnitudes .....	7
Example / micro-exercise .....	7
Comparison: Mechanics vs Electrics .....	7
Mechanical System .....	7
Electrical System .....	7
<b>Common pitfalls</b> .....	8
<b>Exercises</b> .....	8
Exercise E13 Charges on a Ballon .....	8
Exercise E14 Charges on a Ballon .....	8
Exercise E15 Charges in Electroplating .....	9
Exercise E16 Charges in Electroplating .....	9
Exercise E1.5.1 Direction of the voltage .....	10
Task 2.1: Counting charges in a current .....	11
Exercise E17 Electron flow .....	11
Exercise E18 Determining the Current from Charge per Time .....	11
Exercise E19 Electron flow .....	12
Exercise E20 Determining the Current from Charge per Time .....	13

**Embedded resources** ..... 14

# 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

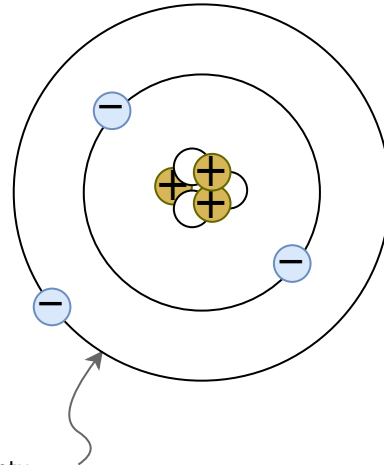


Fig. 1: Atomic model according to Bohr / Sommerfeld <sup>quantum</sup> Text is not SVG - cannot display

- 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:

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

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{~}\text{pA}\$ — control current in a FET gate
- \$10\text{~}\text{\mu A}\$ — sensitive sensor output
- \$10\text{~}\text{mA}\$ — LED or small sensor supply
- \$10\text{~}\text{A}\$ — heating device
- \$10\text{~}\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 E13 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 E14 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 E15 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  $8 \cdot 10^{22}$  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 E16 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  $8 \cdot 10^{22}$  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 E17 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 E18 Determining the Current from Charge per Time

Two objects are connected by a wire and a charge  $Q$  flows from one object to the other. The charge per time  $Q/t$  is not constant. How can the current be determined when the charge flows 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 E19 Electron flow

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

## 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 E20 Determining the Current from Charge per Time**

Two objects experience a charge increase over time, as shown 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 ...

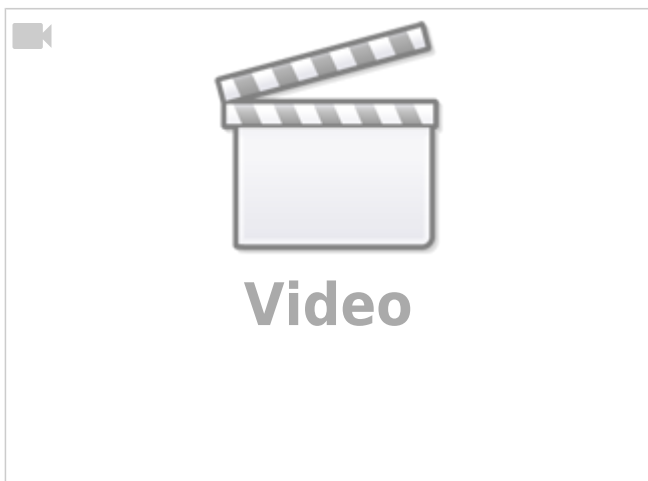
1. Determine the currents  $I_1$  and  $I_2$  for the two objects from the  $Q$ - $t$ -diagram figure 6 and plot the currents into a new diagram.

## Solution

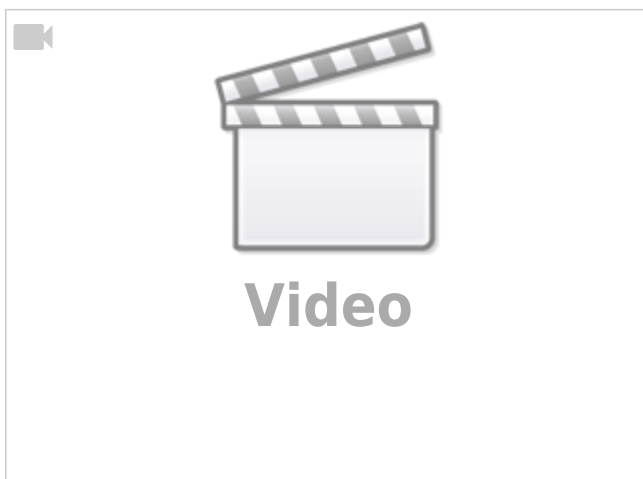
- Have a look how much increase  $\Delta Q$  per time duration  $\Delta t$  is there for each object.
- For this choose a distinct time period, e.g. between  $0 \sim \text{ms}$  and  $20 \sim \text{ms}$ .
- The current is then given as the change in charge per time:  $I = \frac{\Delta Q}{\Delta t}$

## Embedded resources

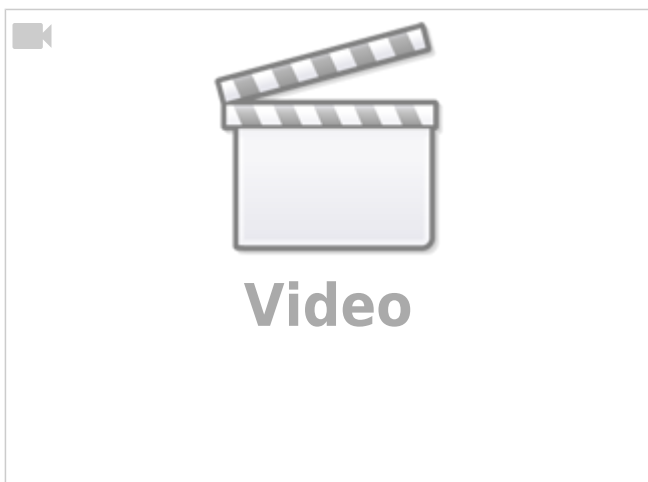
Charge in Matter



What is Electric Charge and How Electricity Works



Electric - Hydraulic Analogy: Charge, Voltage, and Current



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