Block 02 — Electric Charge, Current, Voltage

Student Group

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2.0 Intro

2.0.1 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 $I = \frac{{\rm d}Q}{{\rm d}t}$.
> - Apply the unit check for $1~\rm A = 1~C/s$ 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.

2.0.2 Preparation at Home

Be aware, that EEE1 has 5 ECTS, i.e. an overall weekly load of about 8..10 hours (incl. our lecture in presence).
So, preparation and follow-up shall take about 5..6 hours (incl. 1.5h tutorial, when you go there).

- Please read through the present chapter and write down anything you did not understand.
- I also gave some clips for more clarification under 'Embedded resources' (check the text above/below, sometimes only part of the clip is interesting).

I would assume, that reading my text first and watching the clips second once clarifying is needed shall work best.

For checking your understanding please do the following exercises:

- 1.5.1

2.0.3 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 $1~\rm A$?”
    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.

2.0.4 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: $1~\rm A$ = $1~C/s$.
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.

2.1 Core Content

2.1.1 Electric Charge

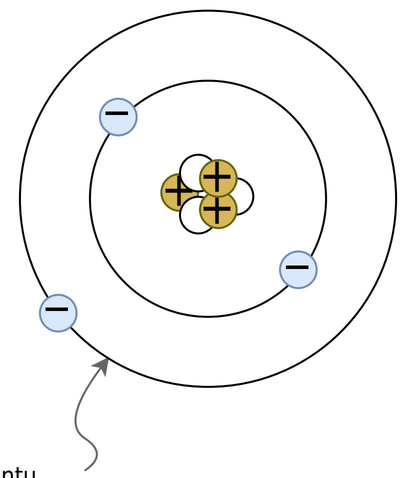


Fig. 1: Atomic model according to Bohr / Sommerfeld

- 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:

$$\begin{align*} e &= 1.602 \cdot 10^{-19}~\rm C \\ Q &= n \cdot e \end{align*}$$

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 repell each other

$$[Q] = 1~\rm C = 1~A \cdot s$$

Example / micro-exercise

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

2.1.2 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

$$i(t) = \frac{{\rm d}Q}{{\rm d}t}$$

Unit check:

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

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

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

2.1.3 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:

- **A**node: Electrode at which the current enters the component.
- Cathode: Electrode at which the current exits the component. (in German ***K****athode*)

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

Fig. 2: Electrodes on the diode

2.1.4 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 $\Delta h_{1,2}$

\begin{align*} \Delta W_{1,2} = m \cdot g \cdot \Delta h_{1,2} \end{align*}

Similarily, 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 φ in the electric case:

\begin{align*} \Delta W_{1,2} = Q \cdot \Delta \varphi_{1,2} \end{align*}

It follows that:
\begin{align*} \boxed{{\Delta W_{1,2} \over {Q}} = \varphi_1 - \varphi_2 = U_{1,2}} \end{align*}

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

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

Typical voltage magnitudes

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

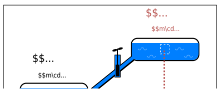
Example / micro-exercise

A charge $Q=2.0~{\rm mC}$ moves through a potential difference of $5.0~{\rm V}$. Energy transferred:
$W=U \cdot Q=5.0~{\rm V} \cdot 2.0~{\rm mC}=10.0~{\rm mJ}$.

2.1.5 Comparison: Mechanics vs Electrics

Fig. 3: Mechanical potential

Fig. 4: Electrical Potential

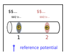


Mechanical System

Potential Energy

Potential energy is always related to a reference level (reference height). The energy required to move m from h_1 to h_2 is independent of the reference level.

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



Electrical System

Potential

The potential φ is always specified relative to a reference point.

Common used are:

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

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

2.2 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.

2.3 Exercises

Exercise E1 Charges on a Ballon

A balloon has a charge of $Q=7~{\rm nC}$ on its surface.
How many additional electrons are on the balloon?

Result

Solution

$$\begin{align*} 43.7*10^{9}~{\rm electrons} \end{align*}$$

$$\begin{align*} Q &= 7~{\rm nC} = 7\cdot 10^{-9}~{\rm C} \\ n_{\rm e} &= {{7*10^{-9}~{\rm C}}\over{1.6022*10^{-19}~{\rm C/electron}}} = 43.7*10^{9}~{\rm electrons} \end{align*}$$

Exercise E2 Charges on a Ballon

A balloon has a charge of $Q=7~{\rm nC}$ on its surface.
How many additional electrons are on the balloon?

Result

$$\begin{align*} 43.7*10^{9}~{\rm electrons} \end{align*}$$

Solution

$$\begin{align*} Q &= 7~{\rm nC} = 7\cdot 10^{-9}~{\rm C} \\ n_{\rm e} &= {{7*10^{-9}~{\rm C}}\over{1.6022*10^{-19}~{\rm C/electron}}} = 43.7*10^{9}~{\rm electrons} \end{align*}$$

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 $1.6022 \cdot 10^{-19}~{\rm C}$, what is the charge on the surface if there are $8 \cdot 10^{22}~{\rm ions}$ added?

Result

$$\begin{align*} 12'818~{\rm C} \end{align*}$$

Solution

$$\begin{align*} 8 * 10^{22} \cdot 1.6022 *10^{-19}~{\rm C} = 12'817.6~{\rm C} \end{align*}$$

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 $1.6022 \cdot 10^{-19}~{\rm C}$, what is the charge on the surface if there are $8 \cdot 10^{22}~{\rm ions}$ added?

Result

$$12'818~{\rm C}$$

Solution

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

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 $U_{\rm Batt}$: The arrow starts at terminal 1 and ends at terminal 2. So $U_{\rm Batt}=U_{12}>0$
- $U_{21}<0$

Explain whether the voltages $U_{\rm Batt}$, 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 $I=0.25~\rm A$. How many electrons pass through the filament in one second?

Strategy

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

Solution

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

Exercise E5 Electron flow

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

Result

Solution

$$1.1*10^{18}~{\rm electrons}$$

$$\begin{align*} Q &= I \cdot t \\ &= 0.04~{\rm A} \cdot 4.5~{\rm s} \\ &= 0.18~{\rm As} \\ &= 0.18~{\rm C} \\ &={0.18~{\rm C}}\cdot {1\over{1.6022*10^{-19}{\rm C/electron}}} = 1.1 \cdot10^{18}~{\rm electrons} \end{align*}$$

Exercise E6 Determining the Current from Charge per Time

Two objects experience a charge increase per time. In the figure 6 one can see these non-linear increases in the charge per time.

2. How can the current be determined, when the charge in current on an object changes linearly?

Result 2

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 $I= {{{\rm d} Q}\over{{\rm d} t}}$ has to be used instead of $I= {{\Delta Q}\over{\Delta t}}$.

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 ΔQ per time duration Δt is there for each object.
- For this choose a distinct time period, e.g. between $0~\rm s$ and $20~\rm s$.
- The current is then given as the change in charge per time: $I= {{\Delta Q}\over{\Delta t}}$

Exercise E7 Electron flow

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

Result

Solution

\begin{align*} 1.1*10^{18}~{\rm electrons} \end{align*}

\begin{align*} Q &= I \cdot t \\ &= 0.04~{\rm A} \cdot 4.5~{\rm s} \\ &= 0.18~{\rm As} \\ &= 0.18~{\rm C} \\ &={0.18~{\rm C}}\cdot {1\over{1.6022*10^{-19}{\rm C/electron}}} = 1.1 \cdot10^{18}~{\rm electrons} \end{align*}

Exercise E8 Determining the Current from Charge per Time

Two objects experience a charge increase per time. In the figure 6 one can see these increases in the charge per time.

2. How can the current be determined, when the charge increase on an object changes non-linearly?

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 $I= {{{\rm d} Q}\over{{\rm d} t}}$ has to be used instead of $I= {{\Delta Q}\over{\Delta t}}$.

Fig. 6: Time course of the charge

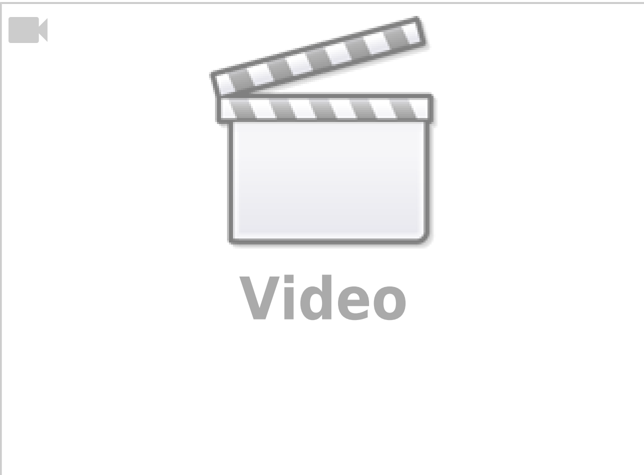
1. Determine the currents I_1 and I_2 for the two objects from the Q-t-diagram figure 6 and plot the currents into a new diagram.

Solution

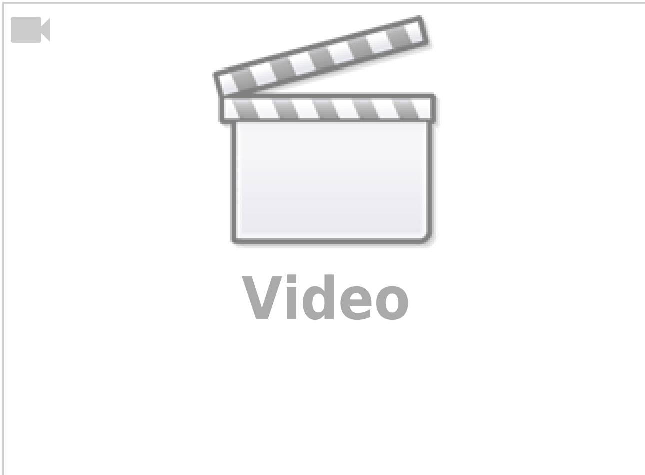
- Have a look how much increase ΔQ per time duration Δt is there for each object.
- For this choose a distinct time period, e.g. between $0~\rm s$ and $20~\rm s$.
- The current is then given as the change in charge per time: $I= {{\Delta Q}\over{\Delta t}}$

Embedded resources

Charge in Matter



What is Electric Charge and How Electricity Works



Electric - Hydraulic Analogy: Charge, Voltage, and Current