

# Block 13 - Capacitor Circuits and Energy

## Student Group

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# Block xx - xxx

## Learning objectives

After this 90-minute block, you can

- Recognize a series connection of capacitors and distinguish it from a parallel connection,
- Calculate the resulting total capacitance of a series or parallel circuit,
- Know how the total charge is distributed among the individual capacitors in a parallel circuit,
- Determine the voltage across a single capacitor in a series circuit.

## Preparation at Home

Well, again

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

For checking your understanding please do the following exercises:

- ...

## 90-minute plan

1. Warm-up (x min):
  1. ....
2. Core concepts & derivations (x min):
  1. ...
3. Practice (x min): ...
4. Wrap-up (x min): Summary box; common pitfalls checklist.

## Conceptual overview

1. ...

## Core content

### Series Circuit of Capacitor

If capacitors are connected in series, the charging current  $I$  into the individual capacitors  $C_1 \dots C_n$  is equal. Thus, the charges absorbed  $\Delta Q$  are also equal: 
$$\Delta Q = \Delta Q$$

$$Q_1 = \Delta Q_2 = \dots = \Delta Q_n \end{align*}$$

Furthermore, after charging, a voltage is formed across the series circuit, which corresponds to the source voltage  $U_q$ . This results from the addition of partial voltages across the individual capacitors. 
$$U_q = U_1 + U_2 + \dots + U_n = \sum_{k=1}^n U_k \end{align*}$$

It holds for the voltage  $U_k = \frac{Q_k}{C_k}$ .

If all capacitors are initially discharged, then  $U_k = \frac{\Delta Q}{C_k}$  holds. Thus 
$$U_q = U_1 + U_2 + \dots + U_n = \sum_{k=1}^n U_k \quad U_q = \frac{\Delta Q}{C_1} + \frac{\Delta Q}{C_2} + \dots + \frac{\Delta Q}{C_3} = \sum_{k=1}^n \frac{\Delta Q}{C_k} \cdot \Delta Q \quad \frac{\Delta Q}{C_{\text{eq}}} \cdot \Delta Q = \sum_{k=1}^n \frac{\Delta Q}{C_k} \cdot \Delta Q \end{align*}$$

Thus, for the series connection of capacitors  $C_1 \dots C_n$  :

$$\boxed{\frac{1}{C_{\text{eq}}}} = \sum_{k=1}^n \frac{1}{C_k} \quad \boxed{\Delta Q_k = \text{const.}}$$

For initially uncharged capacitors, (voltage divider for capacitors) holds: 
$$Q = Q_k \quad U_{\text{eq}} \cdot C_{\text{eq}} = U_k \cdot C_k \end{align*}$$

In the simulation below, besides the parallel connected capacitors  $C_1$ ,  $C_2$ ,  $C_3$ , an ideal voltage source  $U_q$ , a resistor  $R$ , a switch  $S$ , and a lamp are installed.

- The switch  $S$  allows the voltage source to charge the capacitors.
- The resistor  $R$  is necessary because the simulation cannot represent instantaneous charging. The resistor limits the charging current to a maximum value.
- The capacitors can be discharged again via the lamp.

## Parallel Circuit of Capacitors

If capacitors are connected in parallel, the voltage  $U$  across the individual capacitors  $C_1 \dots C_n$  is equal. It is therefore valid:

$$U_q = U_1 = U_2 = \dots = U_n \end{align*}$$

Furthermore, during charging, the total charge  $\Delta Q$  from the source is distributed to the individual capacitors. This gives the following for the individual charges absorbed: 
$$\Delta Q = \Delta Q_1 + \Delta Q_2 + \dots + \Delta Q_n = \sum_{k=1}^n \Delta Q_k \end{align*}$$

If all capacitors are initially discharged, then  $Q_k = \Delta Q_k = C_k \cdot U$

Thus 
$$\Delta Q = Q_1 + Q_2 + \dots + Q_n = \sum_{k=1}^n Q_k \quad \Delta Q = C_1 \cdot U + C_2 \cdot U + \dots + C_n \cdot U = \sum_{k=1}^n C_k \cdot U \quad C_{\text{eq}} \cdot U = \sum_{k=1}^n C_k \cdot U \end{align*}$$

Thus, for the parallel connection of capacitors  $C_1 \dots C_n$  :

$$\boxed{C_{\text{eq}}} = \sum_{k=1}^n C_k \quad \boxed{U_k}$$

$= \{\text{const.}\} \end{align*}$

For initially uncharged capacitors, (charge divider for capacitors) holds:  $\begin{align*} \boxed{\Delta Q = \sum_{k=1}^n Q_k} \end{align*}$

$\begin{align*} \boxed{\left\{ \frac{Q_k}{C_k} = \frac{\Delta Q}{C_{\text{eq}}} \right\}} \end{align*}$

In the simulation below, again, besides the parallel connected capacitors  $C_1$ ,  $C_2$ ,  $C_3$ , an ideal voltage source  $U_q$ , a resistor  $R$ , a switch  $S$ , and a lamp are installed.

## Energy in the electric Field

Now we want to see how much energy is stored in a capacitor during charging. When we want to charge a capacitor charges have to be separated (see [figure 1](#)). This gets more and more difficult as more charges are moved, since these already moved charges create an electric field.

Fig. 1: summary of electrostatics



We already had a first look onto the energy in the electric field in [block09](#).

There, we got:

$$\begin{aligned} \Delta W &= \int \vec{F} \cdot d\vec{r} \quad \&= q \int \vec{E} \cdot d\vec{r} \quad \&= q \int U \quad dW \\ &= dq \int U \end{aligned}$$

Now, For a capacitor we include the formula for the capacitor  $C = \frac{q}{U}$ , or better its rearranged version  $U = \frac{q}{C}$ :

$$\begin{aligned} dW &= dq \cdot \frac{q}{C} \quad \int dW = \int \frac{q}{C} dq \end{aligned}$$

Here we again see, that the needed energy portion  $dW$  to move a portion  $dq$  is also related to the already moved charges  $q$ .

To get the energy  $\Delta W$  needed to move all of the charges  $Q = \int dq$  we have to integrate from  $0$  to  $Q$ :

$$\begin{aligned} \Delta W &= \int_0^Q dW \quad \&= \int_0^Q \frac{q}{C} dq \quad \&= \\ &= \frac{1}{2} \frac{Q^2}{C} \quad \boxed{\Delta W =} \\ &= \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} QU = \frac{1}{2} CQ^2 \end{aligned}$$

## Common pitfalls

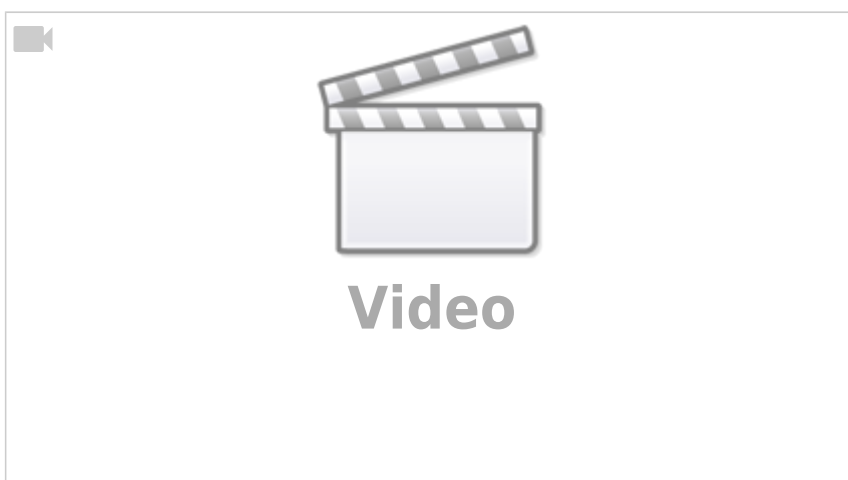
- ...

## Exercises

### Task 5.8.1 Calculating a circuit of different capacitors

See <https://www.youtube.com/watch?v=vSeSHampd4Y>

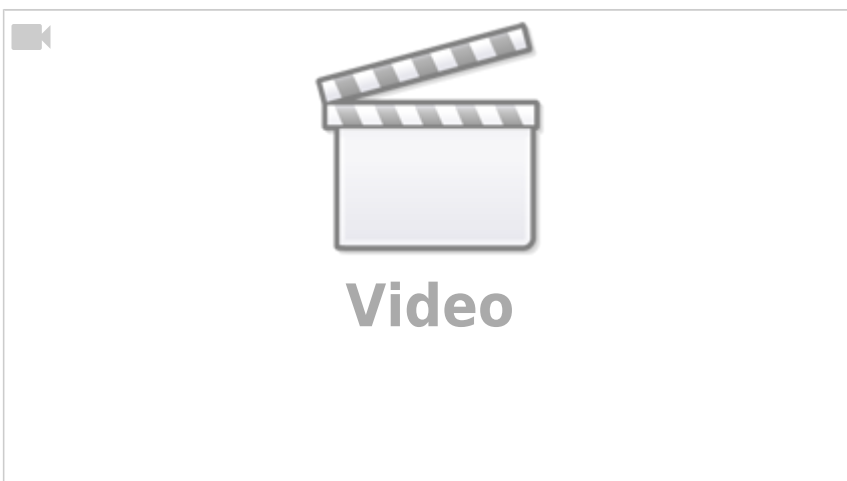
### Task 5.9.1 Layered Capacitor Task



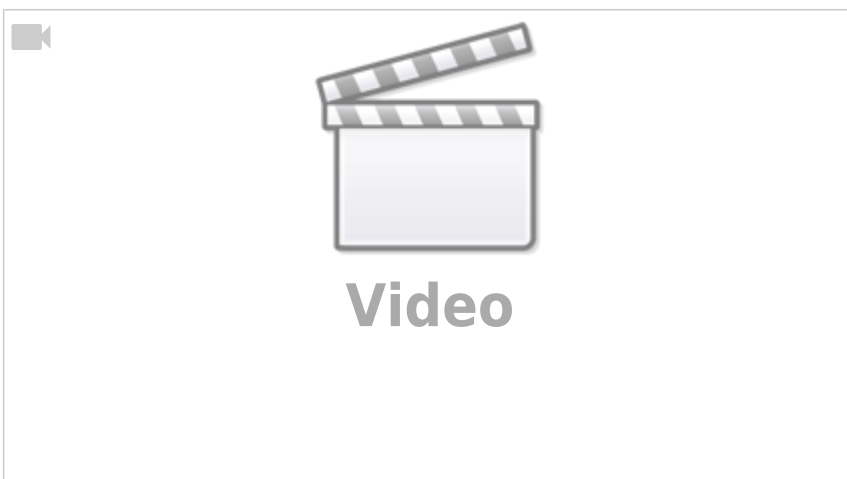
### Exercise 5.9.2 Further capacitor charging/discharging practice Exercise



### Exercise 5.9.3 Further practice charging the capacitor

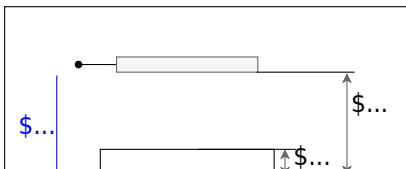


### Exercise 5.9.4 Charge balance of two capacitors



### Exercise 5.9.5 Capacitor with glass plate

Fig. 2: Structure of a capacitor with glass plate



Two parallel capacitor plates face each other with a distance  $d_{\text{K}} = 10 \text{ mm}$ . A voltage of  $U = 3'000 \text{ V}$  is applied to the capacitor. Parallel to the capacitor plates, there is a glass plate ( $\varepsilon_{\text{r, G}} = 8$ ) with a thickness  $d_{\text{G}} = 3 \text{ mm}$  in the capacitor.

1. Calculate the partial voltages  $U_{\text{G}}$  in the glass and  $U_{\text{A}}$  in the air gap.
2. What is the maximum thickness of the glass pane if the electric field  $E_{\text{0, G}} = 12 \text{ kV/cm}$  must not exceed?

## Embedded resources

The equivalent capacitor for series of parallel configuration is well explained here



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Last update: **2025/10/31 22:28**

