

Block 13 - Capacitor Circuits and Energy

Student Group

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Block 13 - Capacitor Circuits and Energy

13.0 Intro

13.0.1 Learning Objectives

After this 90-minute block, you can

- identify series vs. parallel connections of capacitors from a circuit diagram,
- compute equivalent capacitance C_{eq} for series and parallel networks,
- use the key sharing rules: in **series** $Q_k = \text{const.}$ and voltages divide; in **parallel** $U_k = \text{const.}$ and charges divide,
- apply the capacitor divider relation (two series capacitors),
- determine stored energy, including a dimensional check to J .

13.0.2 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:

- 5.9.5

13.0.3 90-minute plan

1. Warm-up (10 min):
 1. Quick quiz (2-3 items): series or parallel? which rule applies (constant U or constant Q)?
 2. Recall $Q = C \cdot U$ and energy $W = \frac{1}{2} C U^2$ (units).
2. Core concepts & derivations (35 min):
 1. Derive C_{eq} for **series** from Kirchhoff's voltage law and $Q = \text{const.}$; derive voltage division $U_k = \frac{Q}{C_k}$.
 2. Derive C_{eq} for **parallel** from Kirchhoff's current/charge balance and $U = \text{const.}$; obtain $Q_k = C_k U$.
 3. Energy in the electric field: integrate $dW = U \cdot dq \rightarrow W = \frac{1}{2} C U^2$; short dimensional check.
3. Practice (35 min):
 1. Two short worked examples: mixed series/parallel network; two-capacitor divider with given U (find U_1 , U_2 , W on each).
 2. Short simulation tasks (use the two embedded Falstad circuits in this page): observe U_k , Q_k when toggling the switch or changing values.
 3. Mini-problems: "double a plate area / halve distance" reasoning on C and W .
4. Wrap-up (10 min):
 1. Common-pitfalls checklist and one exit-ticket calculation.

13.0.4 Conceptual overview

1. **What stays the same?** In **series** all capacitors carry the **same charge** Q ; in **parallel** all capacitors see the **same voltage** U .
2. **How do totals form?** Capacitances **add inversely** in series and **add directly** in parallel. This mirrors resistors but with the roles swapped.
3. **Voltage/charge sharing:** In series, the **smaller** C_k takes the **larger** U_k ($U_k = Q/C_k$). In parallel, the **larger** C_k takes the **larger** Q_k ($Q_k = C_k U$).
4. **Energy viewpoint:** Charging needs work against the field; $W = \frac{1}{2} C U^2 = \frac{1}{2} Q U = \frac{Q^2}{2C}$. Dimensional check: $[C] = \text{F} = \frac{\text{A}\cdot\text{s}}{\text{V}}$, so $[C U^2] = \frac{\text{A}\cdot\text{s}}{\text{V}} \cdot \text{V}^2 = \text{A}\cdot\text{s}\cdot\text{V} = \text{J}$.
5. **Design intuition:** Increasing plate area A or dielectric ϵ_r raises C and thus stored W at the same U ; increasing gap d lowers C .

13.1 Core content

13.1.1 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 ΔQ are also equal:
$$\Delta Q_1 = \Delta Q_2 = \dots = \Delta Q_n$$

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.
$$U_q = U_1 + U_2 + \dots + U_n = \sum_{k=1}^n U_k$$

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
$$U_q = \Delta Q \left(\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n} \right) \quad U_q = \frac{\Delta Q}{C_{\text{eq}}} \quad C_{\text{eq}} = \frac{\Delta Q}{U_q} = \frac{\Delta Q}{\Delta Q \left(\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n} \right)} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}}$$

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

$$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$$

$$\Delta Q_k = \text{const.}$$

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

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.

13.1.2 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:

$$U_q = U_1 = U_2 = \dots = U_n$$

Furthermore, during charging, the total charge ΔQ from the source is distributed to the individual capacitors. This gives the following for the individual charges absorbed:

$$\Delta Q = \Delta Q_1 + \Delta Q_2 + \dots + \Delta Q_n = \sum_{k=1}^n \Delta Q_k$$

If all capacitors are initially discharged, then $Q_k = \Delta Q_k = C_k \cdot U$
 Thus
$$\Delta Q = Q_1 + Q_2 + \dots + Q_n = \sum_{k=1}^n Q_k \parallel \Delta Q = C_1 \cdot U + C_2 \cdot U + \dots + C_n \cdot U = \sum_{k=1}^n C_k \cdot U \parallel C_{\text{eq}} \cdot U = \sum_{k=1}^n C_k \cdot U \parallel \end{align*}$$

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

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

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

$$\frac{Q_k}{C_k} = \frac{\Delta Q}{C_{\text{eq}}}$$

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.

13.1.3 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 were 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 $U = \frac{q}{C}$:

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

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 ΔW needed to move all of the charges $Q = \int dq$ we have to integrate from 0 to Q :

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

13.2 Common pitfalls

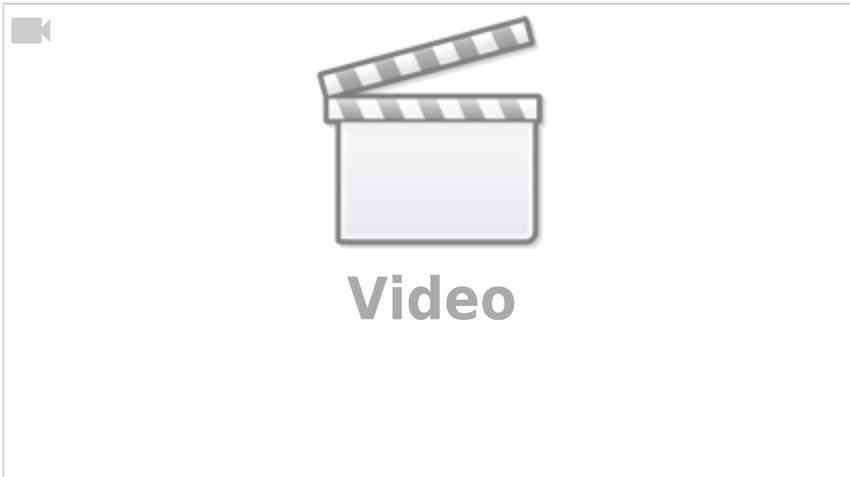
- Mixing up the rules: writing $C_{\text{eq}} = C_1 + C_2$ for **series** (wrong) or $\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2}$ for **parallel** (wrong).
- Forgetting which quantity is equal: **series** $\rightarrow Q_k = \text{const.}$, **parallel** $\rightarrow U_k = \text{const.}$.
- Applying the **resistive** voltage divider $U_1 = \frac{R_1}{R_1 + R_2} U$ to capacitors. For capacitors in series it inverts: $U_1 = \frac{C_2}{C_1 + C_2} U$.
- Ignoring **initial charge states**: pre-charged capacitors reconnected will redistribute charge; use charge conservation on isolated nodes before using $Q = C \cdot U$.
- Dropping units or mixing forms of energy: always keep $W = \frac{1}{2} C U^2 = \frac{1}{2} Q U = \frac{Q^2}{2C}$ and check J .

13.3 Exercises

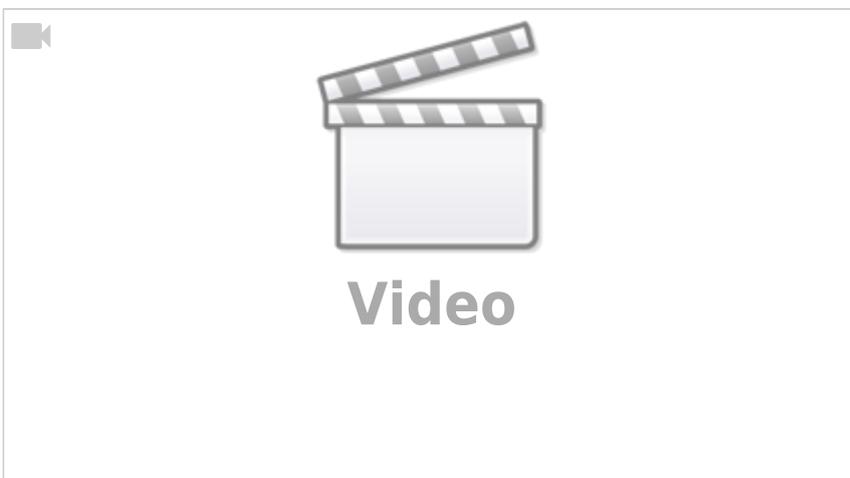
Task 5.8.1 Calculating a circuit of different capacitors

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

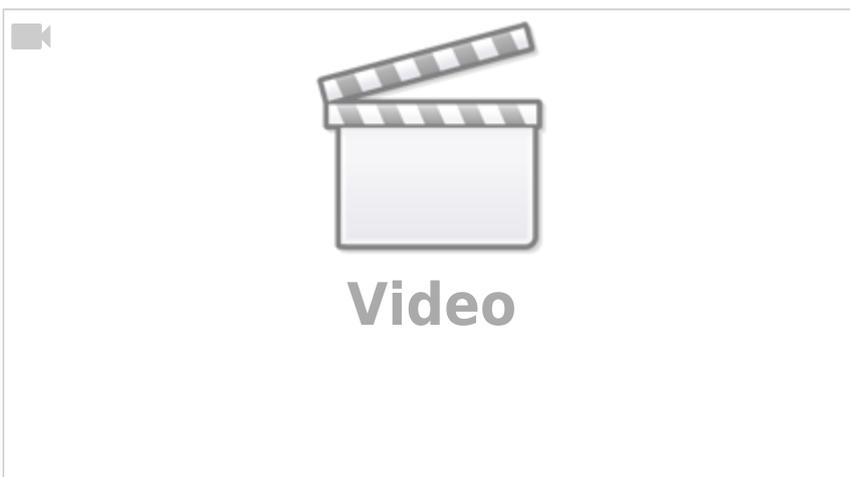
Task 5.9.1 Layered Capacitor Task



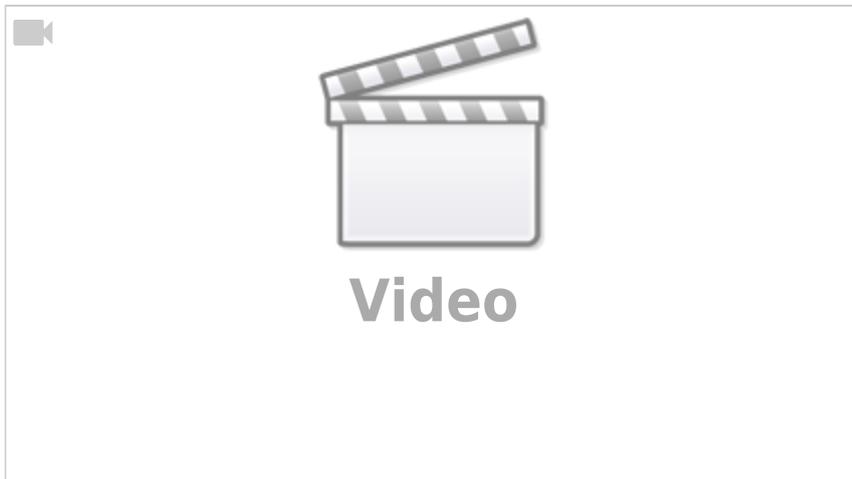
Exercise 5.9.2 Further capacitor charging/discharging practice Exercise



Exercise 5.9.3 Further practice charging the capacitor

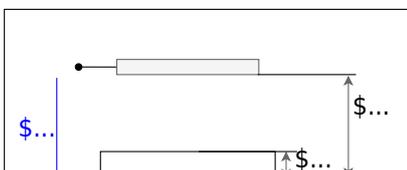


Exercise 5.9.4 Charge balance of two capacitors



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_{G} in the glass and U_{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?

Exercise E1 Capacitor
(written test, approx. 12 % of a 120-minute written test, SS2024)

0. Calculate the capacity of a sensor, the original data obtained from a capacitance measurement is shown in the figure below.

The contaminant has $\epsilon_{r,c} > \epsilon_{r,air}$, while the distance between the plates remains the same. Give a generalized formula

Path

$$C_2 = f(A, d, x, \epsilon_{r,c}, \epsilon_{r,air})$$

$$Q = \frac{U}{\frac{1}{\epsilon_0 \epsilon_{r,c}} \frac{A}{d-x} + \frac{1}{\epsilon_0 \epsilon_{r,air}} \frac{A}{x}}$$

There are two ways now. Either: $Q = C \cdot U = 1.1 \cdot 10^{-6} \text{ F} \cdot 3.3 \text{ V} = 3.63 \cdot 10^{-6} \text{ C}$ Or: $Q = D \cdot A = 146 \cdot 10^{-6} \text{ C/m}^2 \cdot 25 \cdot 10^{-6} \text{ m}^2 = 3.65 \cdot 10^{-6} \text{ C}$

The displacement field is given by: $D = \epsilon_0 \epsilon_{r,air} \frac{U}{d}$ and $D = \epsilon_0 \epsilon_{r,c} \frac{U}{x}$

The resulting capacity C is now $C = \frac{Q}{U} = \frac{3.65 \cdot 10^{-6} \text{ C}}{3.3 \text{ V}} = 1.1 \cdot 10^{-6} \text{ F}$

Therefore: $C = \frac{1}{\frac{1}{\epsilon_0 \epsilon_{r,air}} \frac{A}{d-x} + \frac{1}{\epsilon_0 \epsilon_{r,c}} \frac{A}{x}}$

With $C_{air} = \epsilon_0 \epsilon_{r,air} \frac{A}{d-x}$ and $C_c = \epsilon_0 \epsilon_{r,c} \frac{A}{x}$

$$C = \frac{1}{\frac{1}{\epsilon_0 \epsilon_{r,air}} \frac{A}{d-x} + \frac{1}{\epsilon_0 \epsilon_{r,c}} \frac{A}{x}}$$

- In the following such a sensor is given with:
- This leads to: $C = \frac{1}{\frac{1}{\epsilon_0 \epsilon_{r,air}} \frac{A}{d-x} + \frac{1}{\epsilon_0 \epsilon_{r,c}} \frac{A}{x}}$
 - Plate area: $A = 25 \text{ mm}^2$
 - Distance between both plates: $d = 200 \text{ }\mu\text{m}$
 - Air between the plates: $\epsilon_{r,air} = 1$
 - Supply voltage: 3.3 V
 - Boundary effects on the end of the layers shall be ignored in the following calculations.

$\epsilon_0 = 8.854 \cdot 10^{-12} \text{ F/m}$

1. Calculate the capacity C .

Path

$$C = \frac{1}{\frac{1}{8.854 \cdot 10^{-12} \text{ F/m} \cdot 1} \frac{25 \cdot 10^{-6} \text{ m}^2}{200 \cdot 10^{-6} \text{ m}} + \frac{1}{8.854 \cdot 10^{-12} \text{ F/m} \cdot 3} \frac{25 \cdot 10^{-6} \text{ m}^2}{200 \cdot 10^{-6} \text{ m}}}$$

Exercise E2 Capacitor

(written test, approx. 7 % of a 120-minute written test, SS2022)

Given the dielectric permittivity of the left-side layer with the following width $s_1 = 0.1 \text{ mm}$

of air ($\epsilon_r = 1$), while the thickness of the dielectric material

remains the same

What is the new capacity C ?

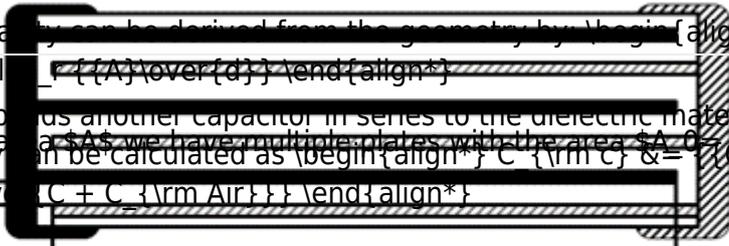
- Depth of component: $w = 0.7 \text{ mm}$

• Number of layers (as shown in the picture): 3 left-side and 3 right-side layers.

Path

The capacity can be derived from the geometry by: $C = \epsilon_0 \epsilon_r \frac{A}{d}$

The air is another capacitor in series to the dielectric material. Therefore, the capacity can be calculated as $\frac{1}{C} = \frac{1}{C_{\text{dielectric}}} + \frac{1}{C_{\text{air}}}$



The capacity of air is $C_{\text{air}} = \epsilon_0 \epsilon_r \frac{A_{\text{air}}}{d}$ $= 8.854 \cdot 10^{-12} \cdot \frac{5 \cdot 1.5 \cdot 10^{-3} \cdot 0.7 \cdot 10^{-3}}{0.1 \cdot 10^{-6}} = 0.465 \text{ nF}$

The material shall have a dielectric permittivity of $\epsilon_r = 3$.

By this the overall capacity is $C = \frac{C_{\text{dielectric}} \cdot C_{\text{air}}}{C_{\text{dielectric}} + C_{\text{air}}} = \frac{1.39 \text{ nF} \cdot 0.465 \text{ nF}}{1.39 \text{ nF} + 0.465 \text{ nF}} = 0.34 \text{ nF}$

How many "plates" do we have to consider?

For this, we have to count facing areas A_0 . There are $N = 5$.

.. What is the field strength in the dielectric material between the layer, when a voltage of $U = 6.3 \text{ V}$ is applied?

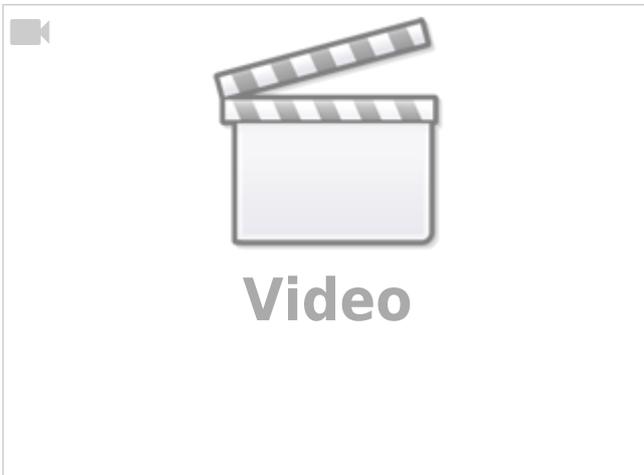
Path

The electric field strength E is given by: $E = \frac{U}{d} = \frac{6.3 \text{ V}}{1 \cdot 10^{-6} \text{ m}} = 6.3 \cdot 10^6 \text{ V/m}$

Therefore, the formula is
$$C = \frac{\epsilon_0 \epsilon_r N \cdot l \cdot w}{d} = 8.854 \cdot 10^{-12} \frac{\text{As/Vm} \cdot 3 \cdot \{5 \cdot 1.5 \cdot 10^{-3} \text{ m} \cdot 0.7 \cdot 10^{-3} \text{ m}\}}{1 \cdot 10^{-6} \text{ m}}$$

Embedded resources

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



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