GP2 Q3 Week 4 - General Physics

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General Physics 2 – Grade 12 (STEM)
Learning Activity Sheets
Quarter 3 – Week 4: Capacitance and Dielectrics

First Edition, 2021

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WEEKLY LEARNING ACTIVITY SHEETS
General Physics 2, Grade 12, Quarter 3, Week 4

CAPACITANCE AND DIELECTRICS

Learning Objectives

At the end of the lesson, the learners will be able to:

1. deduce the effects of simple capacitors (e.g., parallel-plate, spherical, cylindrical) on the capacitance, charge, and potential difference when the size, potential difference, or charge is changed **(STEM_GP12EM-IIIc-23)**;
2. calculate the equivalent capacitance of a network of capacitors connected in series/parallel **(STEM_GP12EM-IIIc-24)**;
3. determine the total charge, the charge on, and the potential difference across each capacitor in the network given the capacitors connected in series/parallel **(STEM_GP12EM-IIId-25)**;
4. determine the potential energy stored inside the capacitor given the geometry and the potential difference across the capacitor **(STEM_GP12EM-IIId-26)**;
5. describe the effects of inserting dielectric materials on the capacitance, charge, and electric field of a capacitor **(STEM_GP12EM-IIId-29)**; and
6. solve problems involving capacitors and dielectrics in contexts such as, but not limited to, charged plates, batteries, and camera flashlamps **(STEM_GP12EM-IIId-30)**.

Time Allotment: 4 Hours

Key Concepts

- A **capacitor** plays an important role in a circuit. It is a device that serves as the storage reservoir for electrical energy which will subsequently be discharged at a high rate into the consumer circuit producing a quick flow of energy. An example of a commercial capacitor is shown in Fig. 1.
- Basically, any two conductors separated by an insulator (or a vacuum) form a **capacitor** (Fig. 2).
- In circuit diagrams, a capacitor is represented by either of these symbols: ⊣⊢ ⊣⊬
- **Capacitance** is a measure of the ability of a capacitor to store electric charge.
- **Capacitance** can also be defined as a measure of the amount of electrical energy stored or separated for a given electric potential.

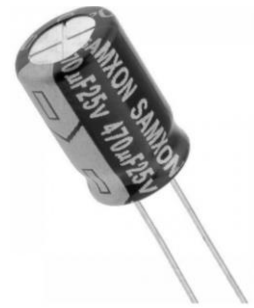

Fig. 1. *An electrolytic capacitor used for power supplies, switched-mode power supplies, and DC-converters.*
Source:https://www.britannica.com/technology/capacitor

- Mathematically, capacitance is a ratio of charge Q to potential difference V_{ab} of the capacitor:

$$C = \frac{Q}{V_{ab}}$$

- The SI unit of capacitance is called **farad** (1 F), in honor of the 19th-century English physicist Michael Faraday.

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One farad is equal to one *coulomb per volt* (1 C/V):

$$\mathbf{1\ F = 1\ farad = 1\frac{C}{V} = 1\frac{coulomb}{volt}}$$

- A simple example of such storage device - capacitor is a parallel-plate capacitor. If positive charges with total charge **+*Q*** are deposited on one of the conductors and an equal amount of negative charge **-*Q*** is deposited on the second conductor, the capacitor is said to have a charge ***Q*** (Fig. 3).
- These parallel conducting plates, with each area ***A*** is separated by a distance ***d*** that is small in comparison with their dimensions (Fig. 3a). When the plates are charged, the electric field is almost completely localized in the region between the plates (Fig. 3b).
- The essentially uniform electric field E between the plates is $\boldsymbol{E = \frac{\sigma}{\epsilon_0}}$, where $\boldsymbol{\sigma}$ is the magnitude of the surface charge density on each plate. This is equal to the magnitude of the total charge ***Q*** on each plate divided by the area A of the plate, or $\boldsymbol{\sigma = \frac{Q}{A}}$, so the field magnitude ***E*** can be expressed as

$$E = \frac{\sigma}{\epsilon_0} = \frac{Q}{\epsilon_0 A}$$

- The field is uniform and the distance between the plates is d, so the potential difference (voltage) between the two plates is

$$\boldsymbol{V_{ab} = Ed = \frac{1}{\epsilon_0}\frac{Qd}{A}}$$

- From this, we see that the capacitance C of a parallel-plate capacitor in vacuum is

$$C = \frac{Q}{V_{ab}} = \epsilon_0 \frac{A}{d}$$

In this equation, if A is in square meters and d in meters, C is in farads. The units of ϵ_0 are $\frac{C^2}{N \cdot m^2}$, so we see that

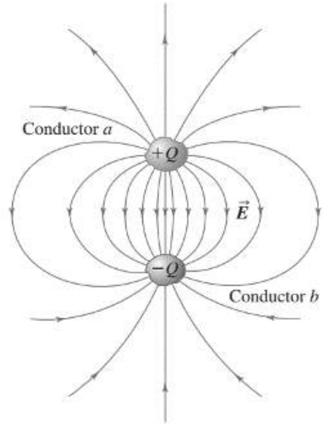

Fig. 2. *Any two conductors a and b insulated from each other form a capacitor.*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

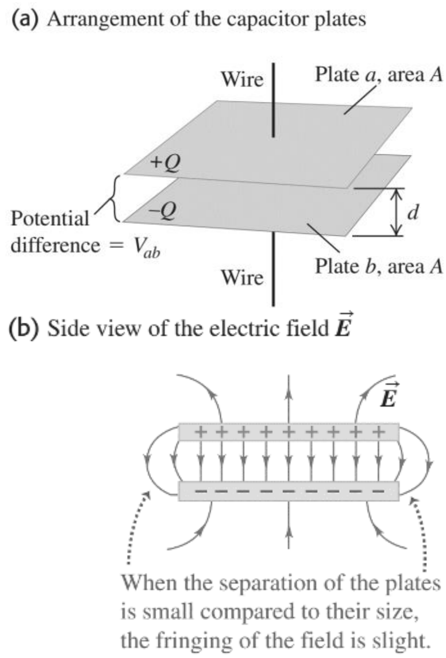

Fig. 3. *A charged parallel-plate capacitor.*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

$$1\ F = 1\frac{C^2}{N \cdot m} = 1\frac{C^2}{J}$$

Because 1 V = 1 J/C (energy per unit charge). Finally the units of ϵ_0 can be expressed as 1 $C^2/N \cdot m^2$ = 1 F/m, so

$$\epsilon_0 = 8.85\ x\ 10^{-12}\ F/m$$

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- In many applications, the most convenient units of capacitance used are *microfarad* ($1\ \mu F = 10^{-6} F$) and the *picofarad* ($1\ pF = 10^{-12}$).
- In **series connection**, capacitors are connected one after the other by conducting wires between points a and b. Figure 4a shows the schematic diagram of a capacitor in series connection.
- When a constant positive potential difference V_{ab} is applied between points a and b, the capacitors become charged.
- ***In this type of connection, the magnitude of charge on all plates is the same.***
- Referring to Fig. 4a, the potential differences between points a and c, c and b, and a and b can be written as

$$\boldsymbol{V_{ac} = V_1 = \frac{Q}{C_1} \qquad V_{cb} = V_2 = \frac{Q}{C_2}}$$

$$\boldsymbol{V_{ab} = V = V_1 + V_2 = Q(\frac{1}{C_1} + \frac{1}{C_2})}$$

And so

$$\boldsymbol{\frac{V}{Q} = \frac{1}{C_1} + \frac{1}{C_2}}$$

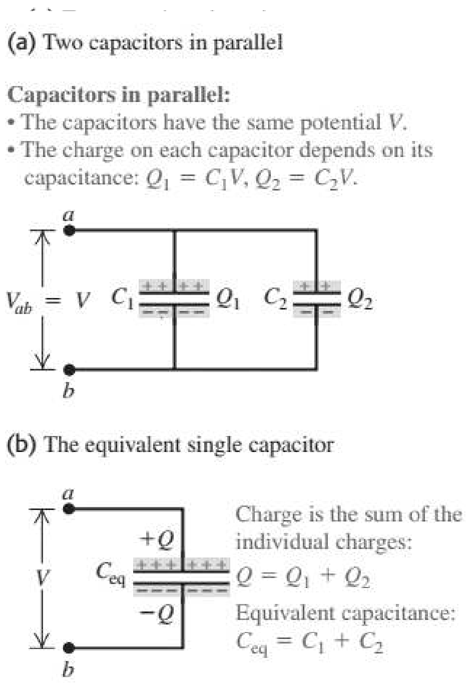

Fig. 5. *Two capacitors in parallel*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

Fig. 4. *Two capacitors in series*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

- The equivalent capacitance C_{eq} of the series combination is defined as the capacitance of a *single* capacitor for which the charge Q is the same as for the combination when the potential difference V is the same. In other words, the combination can be replaced by an ***equivalent capacitor*** of capacitance ***Ceq*** (Fig. 4b):

$$\boldsymbol{C_{eq} = \frac{Q}{V} \quad or \quad \frac{1}{C_{eq}} = \frac{V}{Q}}$$

- Combining this equation with $\frac{V}{Q} = \frac{1}{C_1} + \frac{1}{C_2}$, we find

$$\boldsymbol{\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}}$$

- We can extend this analysis to any number of capacitors in series. We find the following result for the *reciprocal* of the equivalent capacitance:

$$\boldsymbol{\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots} \text{ (capacitors in series)}$$

The reciprocal of the equivalent capacitance of a series combination equals the sum of the reciprocals of the individual capacitances. In a series connection, the equivalent capacitance is always *less than* any individual capacitance.

- The arrangement of capacitors in **parallel connection** is shown in Fig. 5. As shown in the figure, two capacitors are connected in parallel between points a and b. In this case, the upper plates of the two capacitors are connected by conducting wires to form an equipotential surface, and the lower plates form another.

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- ***In this type of connection, the potential difference for all individual capacitors is the same* and is equal to Vab = V.** So the charges are

$$Q_1 = C_1 V \quad \text{and} \quad Q_2 = C_2 V$$

The total charge *Q* of the combination, and thus the total charge on the equivalent capacitor, is

$$Q = Q_1 + Q_2 = (C_1 + C_2)V$$

so

$$\frac{Q}{V} = C_1 + C_2$$

and

$$C_{eq} = C_1 + C_2$$

In the same way we can show that for any number of capacitors in parallel,

$$C_{eq} = C_1 + C_2 + C_3 + \cdots \text{ (capacitors in parallel)}$$

The equivalent capacitance of a parallel combinations equals the sum of the individual capacitances. In a parallel connection, the equivalent capacitance is always *greater than* any individual capacitance.

- **Dielectrics** are nonconducting materials used to separate the conducting plates in most capacitors. In most cases, these common types of capacitors that we see in our old appliances and other electronic gadgets use long strips of metal foil as the plates, and then separated by strips of plastic sheet such as Mylar. A sandwich of these materials is rolled up, forming a unit that can provide a capacitance of several microfarads in compact package (see Fig. 6). A compact package or the final product as a capacitor is like that of Fig. 1.
- The reasons why a dielectric is placed as a separator of the plates in a capacitor are:

First, it solves the mechanical problem of maintaining two large metal sheets at a very small separation without actual contact.

Second, it increases the maximum possible difference between the capacitor plates. This is because of a phenomenon called **dielectric breakdown** in which any insulating material, when subjected to a sufficiently large electric field, experiences a partial ionization that permits conduction through it.

Third, when there is a dielectric material between the plates than when there is vacuum, the capacitance of a capacitor of given dimensions is greater.

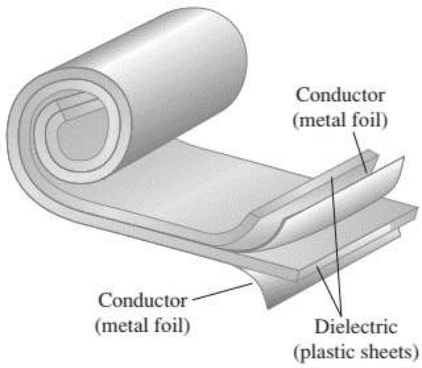

Fig. 6. *A common type of capacitor uses dielectric sheets to separate the conductors.*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

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- The original capacitance (this is without dielectric) is given by

$$C_0 = \frac{Q}{V_0}$$

- The capacitance of a capacitor with dielectric is given by

$$C = \frac{Q}{V}$$

- The **dielectric constant** is given by

$$K = \frac{C}{C_0}$$

- The capacitance of a parallel-plate capacitor when the dielectric is present is given by

$$C = KC_0 = K\epsilon_0\frac{A}{d} = \epsilon\frac{A}{d}$$

  where A – is the area of the parallel plates, ϵ – is the permittivity of the dielectric which is $\epsilon = K\epsilon_0$, and d – is the distance between the two plates.

Activity 1. How things affect things!

Learning Objectives:

At the end of the lesson, the learners should be able to:

1. deduce the effects of simple capacitors (e.g., parallel-plate, spherical, cylindrical) on the capacitance, charge, and potential difference when the size, potential difference, or charge is changed; and
2. describe the effects of inserting dielectric materials on the capacitance, charge, and electric field of a capacitor.

Materials needed: ballpen, and scientific calculator.

What to do: Answer what is asked in the items below. Show your complete solution (for the items that need solution) and explanation. [Hint: For the first three items, solve first the given equation and compare its result to the results in a and b].

1. $C = \frac{Q}{V_{ab}} = \frac{9\ \mu C}{5\ V} = \frac{9\ x\ 10^{-6}\ C}{5\ V} =$ _______________. What changes do you think you will observe to the capacitance C when:
   a. the charge Q is changed to $Q = 15\ \mu C$? How?
      Answer:

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b. the potential difference V_{ab} is changed to $V_{ab} = 1\,V$? How?
Answer:

2. $Q = CV_{ab} = (50\,pF)(1.5\,V) = (50x10^{-12}\,F)(1.5\,V) =$ _____________. What changes do you think you will observe to the charge Q when:
   a. the capacitance C is changed to $C = 30\,nF$? How?
   Answer:

   b. the potential difference V_{ab} is changed to $V_{ab} = 3.0\,V$? How?
   Answer:

3. $V_{ab} = \frac{Q}{C} = \frac{8.0 \: x \: 10^{-2}\,C}{3.5 \: x \: 10^{-2}\,F} =$ _______________. What changes do you think you will observe to the potential difference V_{ab} when:
   a. the charge Q is changed to $Q = 1.0\,C$? How?
   Answer:

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b. the capacitance C is changed to $C = 4.0 \, x \, 10^{-3} \, F$? How?
Answer:

4. What can you infer from the items above? What do you think are the effects of changing the values of charge and potential difference to the capacitance of a capacitor? Expound your answer in three to four sentences only.
Answer:

5. In this item, a sample problem is given for you to examine. After a deep examination on the given sample, you are to describe what happens to the **capacitance, charge, potential difference,** and **electric field** of a parallel-plate capacitor when a dielectric is inserted between the two plates.

Sample Problem: A capacitor with and without a dielectric.

Suppose the parallel plates in Fig. 7 each have an area of 2000 cm^2 (2.00×10^{-1} m^2) and are 1.00 cm ($1.00 \, x \, 10^{-2}$ m) apart. We connect the capacitor to a power supply, charge it to a potential difference $V_0 = 3.00 \, kV$, and disconnect the power supply. We then insert a sheet of insulating plastic material between the plates, completely filling the space between them. We find that the potential difference decreases to $1.00 \, kV$ while the charge on each capacitor plate remains constant. Find (a) the original capacitance C_0; (b) the magnitude of charge Q on each plate; (c) the capacitance C after the dielectric is inserted; (d) the dielectric constant K of the dielectric; (e) the permittivity ϵ of the dielectric; (f) the magnitude of the induced charge Q_i on each face of the dielectric; (g) the original electric field E_0 between the plates; and (h) the electric field E after the dielectric is inserted.
Solution:

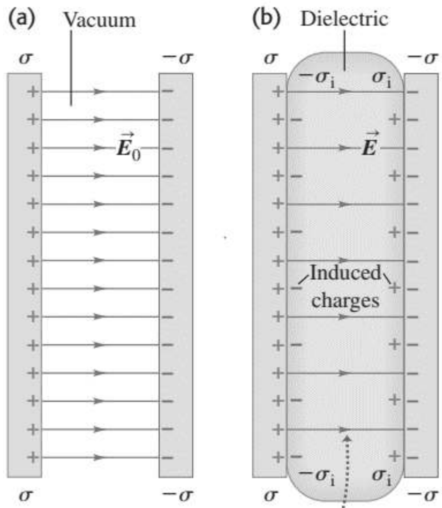

Fig. 7. Parallel-plate capacitors (a) without and (b) with dielectric.
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

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(a) With a vacuum between the plates, with K=1 we have:

$$C_0 = \epsilon_0 \frac{A}{d}$$

$$C_0 = (8.85\ x\ 10^{-12}\ F/m)\frac{2.00\ x\ 10^{-1}\ m^2}{1.00\ x\ 10^{-2}\ m}$$

$$C_0 = 1.77\ x\ 10^{-10}\ F = 177\ pF$$

(b) From the definition of capacitance,

$$Q = C_0 V_0$$

$$Q = (1.77\ x\ 10^{-10}\ F)(3.00\ x\ 10^3\ V)$$

$$Q = 5.31\ x\ 10^{-7} = 0.531\ \mu C$$

(c) When the dielectric is inserted, Q is unchanged but the potential difference decreases to $V = 1.00\ kV$. Hence the new capacitance is

$$C = \frac{Q}{V} = \frac{5.31\ x\ 10^{-7}\ C}{1.00\ x\ 10^3\ V}$$

$$C = 5.31\ x\ 10^{-10}\ F$$

$$C = 531\ pF$$

(d) The dielectric constant is

$$K = \frac{C}{C_0} = \frac{5.31\ x\ 10^{-10}\ F}{1.77\ x\ 10^{-10}\ f} = \frac{531\ pF}{177\ pF}$$

$$K = 3.00$$

(e) The permittivity constant is

$$\epsilon = K\epsilon_0$$

$$= (3.00)\left(8.85\ x\ 10^{-12}\ \frac{C^2}{N \cdot m^2}\right)$$

$$\epsilon = 2.66\ x\ 10^{-11}\ \frac{C^2}{N \cdot m^2}$$

(f) The induced charge Q_i is

$$Q_i = Q\left(1 - \frac{1}{K}\right)$$

$$Q_i = (5.31\ x\ 10^{-7}\ C)\left(1 - \frac{1}{3.00}\right)$$

$$Q_i = 3.54\ x\ 10^{-7}\ C$$

(g) Since the electric field between the plates is uniform, its magnitude is the potential difference divided by the plate separation:

$$E_0 = \frac{V_0}{d} = \frac{3000\ V}{1.00\ x\ 10^{-2}\ m}$$

$$E_0 = 3.00\ x\ 10^5\ V/m$$

(h) After the dielectric is inserted,

$$E = \frac{V}{d} = \frac{1000\ V}{1.00\ x\ 10^{-2}\ m}$$

$$E = 1.00\ x\ 10^5\ V/m$$

Answer:

RUBRICS			
3	**2**	**1**	**0**
The answer is scientifically explained consistent to the concepts, and has no misconceptions.	The answer is scientifically explained consistent to the concepts, but with minimal misconceptions.	The answer is explained consistent to the concepts but with misconceptions.	No answer.

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Activity 2. There's always a solution to every problem!

Learning Objectives:

At the end of the lesson, the learners should be able to:

1. calculate the equivalent capacitance of a network of capacitors connected in series/parallel;
2. determine the potential energy stored inside the capacitor given the geometry and the potential difference across the capacitor; and
3. solve problems involving capacitors and dielectrics in contexts such as, but not limited to, charged plates, batteries, and camera flashlamps.

Materials needed: ballpen, and scientific calculator.

What to do: Read and analyze the problem given. Show your solutions on the space provided neatly.

Example: For the system of capacitors shown in Fig. 8, $V_{ab} = 28.0\,V$. Calculate:

(a) the total capacitance across a to d;
(b) the equivalent capacitance across a to b; and
(c) the value of the charge and potential difference across each capacitor.

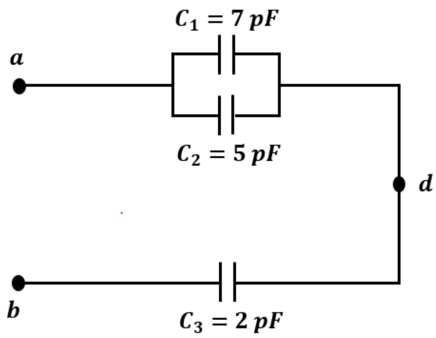

Fig. 8. *A system of capacitors.*

Solution:

Generally, in the figure, capacitors C_1 and C_2 are in parallel connection to each other. Therefore, capacitor C_3 is obviously in series with the parallel connection of C_1 and C_2. For an easy solution, we must solve first the equivalent capacitance for the parallel connection before series connection.

(a) Capacitors in series connection is given by $C_{eq} = C_1 + C_2 + C_3 + \cdots$. So for the total capacitance across a to d:

$$C_{12} = C_{eq} = C_1 + C_2$$
$$C_{12} = C_1 + C_2$$
$$C_{12} = 7\,pF + 5\,pF$$
$$C_{12} = 7.0\,x\,10^{-12}\,F + 5.0\,x\,10^{-12}\,F$$
$$\boldsymbol{C_{12} = 12.0\,x\,10^{-12}\,F}$$

(b) This time, capacitors C_1 and C_2 have now became one which is $C_{12} = 12.0\,x\,10^{-12}F$. Seeing the figure, C_{12} is now clearly seen as one capacitor in series connection with C_3. Now the capacitors in series connection is given by $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$. So for the equivalent capacitance across a to b:

$$\frac{1}{C_{123}} = \frac{1}{C_{eq}} = \frac{1}{C_{12}} + \frac{1}{C_3}$$
$$\frac{1}{C_{123}} = \frac{1}{12.0\,x\,10^{-12}\,F} + \frac{1}{2.0\,x\,10^{-12}\,F}$$
$$\boldsymbol{C_{123} = 1.7\,x\,10^{-12}F}$$
$$\boldsymbol{C_{eq} = 1.7\,x\,10^{-12}F}$$

(c) Basically, when the capacitors are in series connection, the charges in the series are of the same values. In this case, since C_{12} is in series connection with C_3, they would have the same value of charges Q_{12} and C_3:
To reiterate, the charge of every capacitor in series is equal to the

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equivalent capacitance times the total voltage of the circuit.

$Q = Q_{12} = Q_3$

$Q = C_{eq}(V_{ab})$

$Q = (1.7\ x\ 10^{-12} F)(28.0\ V)$

$\boldsymbol{Q = 4.76\ x\ 10^{-11} C}$

Hence,

$\boldsymbol{Q_{12} = 4.76\ x\ 10^{-11}\ C}$

$\boldsymbol{Q_3 = 4.76\ x\ 10^{-11}\ C}$

However, Q_{12} is the charge of a parallel connection of C_1 and C_2. To solve for Q_1, and Q_2, you have to know first $V_{12} = V_1 = V_2$ (since parallel) and V_3. Take note that when connection is parallel, the voltages are the same. But when connection is series, the voltage divides.

<u>For $V_{12} = V_1 = V_2$:</u>

$$V_{12} = V_1 = V_2 = \frac{Q_{12}}{C_{12}}$$

$$V_{12} = \frac{4.76\ x\ 10^{-11} C}{12.0\ x\ 10^{-12} F}$$

$\boldsymbol{V_{12} = 4.0\ V}$

Hence, since parallel

$\boldsymbol{V_1 = 4.0\ V}$

$\boldsymbol{V_2 = 4.0\ V}$

<u>For V_3:</u>

$$V_3 = \frac{Q_3}{C_3} = \frac{4.76\ x\ 10^{-11} C}{2.0\ x\ 10^{-12} F}$$

$\boldsymbol{V_3 = 24\ V}$

<u>To check:</u>

$$V_{ab} = V_{12} + V_3 = 4.0\ V + 24.0\ V = 28.0\ V$$

<u>Now going back to Q_1 *and* Q_2:</u>

$Q_1 = C_1 V_1$

$Q_1 = (7.0\ x\ 10^{-12} F)(4.0\ V)$

$\boldsymbol{Q_1 = 2.8\ x\ 10^{-11} C}$

$Q_2 = C_2 V_2$

$Q_2 = (5.0\ x\ 10^{-12} F)(4.0\ V)$

$\boldsymbol{Q_2 = 2.0\ x\ 10^{-11} C}$

1. **Size of 1 1-F capacitor**
   The parallel plates of 1.0-F capacitor are 1.0 mm apart. What is this area?

   Solution:

2. **Properties of a parallel-plate capacitor**
   The plates of a parallel-plate capacitor in vacuum are 5.00 mm apart and 2.00 m^2 in area. A 10.0-KV potential difference is applied across the capacitor. Compute:

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(a) the capacitance;
Solution:

(b) the charge on each plate; and
solution:

(c) the magnitude of the electric field between the plates.
Solution:

3. Capacitors in series and in parallel

In Fig.4, and Fig.5, let $C_1 = 6.0\,\mu F$, $C_2 = 3.0\,\mu F$, and $V_{ab} = 18\,V$. Find the equivalent capacitance and the charge and potential difference for each capacitor when the capacitors are connected:

(a) in series (see Fig.4)
Solution:

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(b) in parallel (see Fig.5)
Solution:

4. For the system of capacitors shown in Fig. 9, find the equivalent capacitance

(a) between *b* and *c*
Solution:

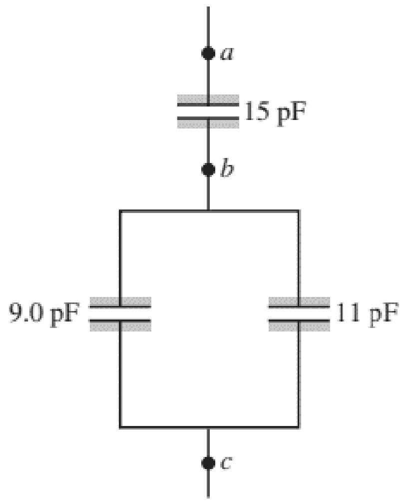

Fig. 9. *A system of capacitors*
Source: "Sears and Zemansky's University Physics with Modern Physics", 13th edition.

(b) between a and c
Solution:

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Reflection

For years, capacitors and dielectrics have been playing great role in the electronic industry and economic progress. What do you think would happen if capacitors and dielectrics were not discovered? How would our electronic industries be? Write your five-sentence answer in a separate sheet of paper.

RUBRICS				
5	**4**	**3**	**2**	**0**
Practical application is scientifically explained consistent to the concepts, and has no misconceptions.	Practical application is scientifically explained consistent to the concepts, but with minimal misconceptions.	Practical application is explained consistent to the concepts but with one or two misconceptions.	Practical applications are explained consistent to the concepts but with more than two misconceptions.	No discussion at all.

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Answers Key

Activity 1

1. $1.8 \times 10^{-6}\ F$
   a. $3 \times 10^{-6} F$
   b. $9 \times 10^{-6} F$
2. $7.5 \times 10^{-11}\ C$
   a. $4.5 \times 10^{-8}\ C$
   b. $1.5 \times 10^{-10}\ C$
3. $2.29\ V$
   a. $28.57\ V$
   b. $20.0\ V$
4. Answers may vary.
5. Answers may vary.

Activity 2

1. A = $1.1 \times 10^8\ m^2$
2. a. C = 3.54×10^{-9} F = 0.00354 μF
   b. Q = 3.54×10^{-5} C = 35.4 μC
   c. E = 2.00×10^6 N/C
3. a. $C_{eq} = 2.0\ \mu F$
   $Q = 36\ \mu C$
   $V_{ac} = 6.0\ V$
   $V_{cb} = 12.0\ V$
   b. $C_{eq} = 9.0\ \mu F$
   $Q_1 = 108\ \mu C$
   $Q_2 = 54\ \mu C$
   V= 18 V
   (same across each capacitor)
4. a. $C_{eq} = 20\ pF$
   b. $C_{123} = 8.6\ pF$

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