



Algebra Based Physics: Electromagnetism

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July 27, 2024

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An important note One secret to master problem solving in general and science in particular is to examine each new situation with great care looking for similarities to some situations or problems we might have already found.

Contents

Chapter 1

Electric Charge

It has been experimentally established that electric charge is a property of matter which can be measured by signed numbers. A chunk of matter can therefore be positively or negatively charged or, of course neutral (having null charge). In the international system of units electric charge is measured in units called Coulombs (C).

There is a fundamental physical principle related to electric charge, namely

Physical Principle 1 Law of Conservation of Charge *charge cannot be created nor destroyed*

This principle has been thoroughly tested and as for today no experiment has ever detected a violation of of charge conservation.

As almost everyone knows, it has also been able firmly established that ordinary matter is composed of atoms which in turn form molecules. When examined up to certain energy level, atoms are composed of three kinds of particles, neutrons, protons and electrons. The former two combine to form the atomic nucleus with a typical size of the order of $10^{-15} m = 1 \text{ Fermi} = 1 f$, while the electrons are arranged somehow out of the nuclei giving the atom a size of the order of

$10^{-10} m$ a size called Angstrom and simbolized by \AA . Electrons have negative electric charge, protons have electrical positive charge and neutrons are neutral. The size of the charge of an electron (or of a proton) is given the symbol e and in the international system of units (SI) has the value

$$\boxed{e = 1.609 \times 10^{-19} C} \quad (1.1)$$

An atom, the tiniest piece chemically identifiable of ordinary mater is charged if it has a number of electrons in excess or defect with respect to its atomic number (the number the protons in its nucleus).

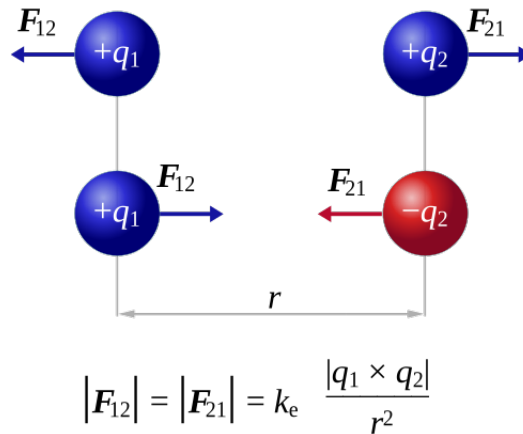


Figure 1.1: Coulomb's Law.

In the 1780's Charles-Augustin de Coulomb (14 June 1736-23 August 1806) a French physicist, known for his research on the properties of electricity, developed a function describing the force between two electrostatic charges. Electrostatic means electric charges without any motion.

Physical Principle 2 Coulomb's law *Two point particles carrying electric charges q_1 and q_2 and separated by a distance r exert a force on each other which is directed along the line*

joining the charges and has the magnitude

$$|\vec{E}| = \kappa_e \frac{q_1 q_2}{r^2}, \quad (1.2)$$

where, in the SI system

$$\kappa_e = \frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2},$$

the force is attractive when the charges are of opposite signs and repulsive when they are of the same sign, see figure 1.1

1.1 Questions

1. A person pulls a sock and a shirt out of the dryer, and they are attracted toward each other because of “static cling”. If the shirt has an electric charge of $-4C$, and the sock has an electric charge of $+2C$, what is the relationship between the magnitude of the electric force on the sock to the magnitude of the electric force on the shirt?

- $F_{\text{sock}} = F_{\text{shirt}}$. This is the right answer, the easiest way to see it is to notice that the magnitude of the electrostatic force is $\kappa Q_1 Q_2 / r^2$, where κ is a constant, Q_1 and Q_2 , the charges contained in the objects and r the distance between them, so the formula is equal for the force that Q_1 exerts on Q_2 and the force that Q_2 exerts on Q_1 . We may also note that F_{sock} and F_{shirt} are action reaction pairs
- $F_{\text{sock}} = 2 \times F_{\text{shirt}}$
- $F_{\text{sock}} = 1/2 \times F_{\text{shirt}}$
- $F_{\text{sock}} = 4 \times F_{\text{shirt}}$ $F_{\text{sock}} = 1/4 \times F_{\text{shirt}}$

2. Can charges be created or destroyed?

A. Yes B. No. This is precisely the law of electric charge conservation

3. Is it physically possible for an everyday object to have a net charge that is $2.4E - 19 C$?
 A. Yes B. No. This charge is not an integer number of times the elementary charge $e = 1.609E - 19 C$

4. Is it physically possible for an everyday object to have a net charge that is $-4.32E-18 C$?
 A. Yes B. No. $-4.32E - 18 C / 1.609E - 19 C = -26.849$, same argument as before

5. Is it physically possible for an everyday object to have a net charge that is $4.17 C$? A. Yes B. No

6. After a Plexiglas rod is rubbed with a piece of silk, the net charge on the Plexiglas rod is $+3 nC$. (Note $3 nC = 3 \text{ nanocoulombs} = 3 \times 10^{-9} C = 3E - 9 C$)
 1. What is the net charge of the silk cloth? Due to charge conservation, the silk cloth must be carrying exactly $-3 nC$
 2. How many electrons were transferred from the Plexiglas rod to the silk? Let n_e be the number of electrons transferred to the piece of silk, then $n_e = -3 \times 10^{-9} / (-1.609 \times 10^{-19}) = 1.86 \times 10^{10} \text{ electrons}$



Figure 1.2: Au as described by the periodic table

7. A gold (fig1.2) block has a mass of 4.0 kg . What is the net charge (in coulombs) of just the protons in this gold block?

We begin by noticing that the number of gold atoms in a mass M of the metal is given by

$$N_{Gold} = \frac{M}{M_u} ,$$

where M_u is the atomic mass of gold measured in the same units as M , the periodic table 1.2 tells us that the atomic mass of gold in Da (see remark 1) is 196.96, therefore

$$N_{Gold} = \frac{4.0 \text{ kg}}{196.96 \times 1.66 \times 10^{-27} \text{ kg}} = 1.41 \times 10^{25} ,$$

. Now, the atomic number of gold is 79, i.e. each atom of gold has 79 protons, consequently, the net charge of the protons in 4 kg of the metal is

$$\begin{aligned} Q &= 79 \times N_{Gold} \times 1.609 \times 10^{-19} \text{ C} \\ &= 79 \times 1.41 \times 10^{25} \times 1.609 \times 10^{-19} \text{ C} = \\ &= 1.788 \times 10^8 \text{ C} \end{aligned}$$

8. A person observes that in the winter, his hair stands on end when it is brushed. This is because his hair becomes positively charged. Why does the act of brushing make his hair positively charged?

- Electrons are moved from his hair to the brush.
- Electrons are converted to protons by the thermal energy that results from brushing.
- Neutrons are split so that there are additional protons in his hair.
- Protons are moved from the brush to his hair.
- Some of the protons in his hair increase in charge due to the thermal energy that results from brushing.

9. Two socks are pulled out of the dryer and experience static cling, i.e. they are pulled together by the electric force. Which one of the following would cause this electric force?

- Both socks are positively charged. One sock is positively charged and the other is negatively charged.
- Both socks are negatively charged.

10. A large basketball is given a relatively small negative charge, and a small ping pong ball is given a relatively large negative charge. Which figure below best shows the relative electric forces between the basketball and the ping pong ball?

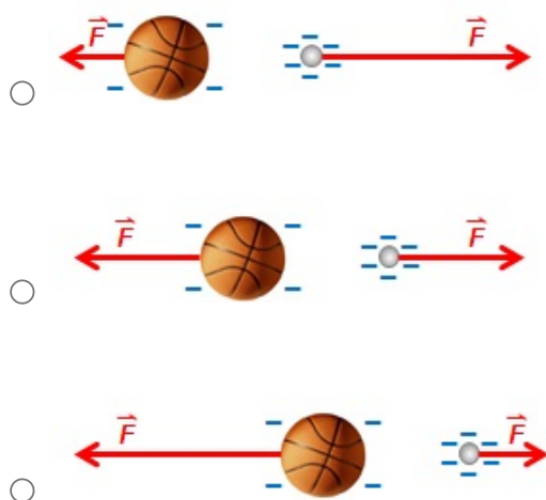


Figure 1.3: The right answer to question 3 is: the sketch with arrows of the same size, since the forces are exactly of the same magnitude.

11. What is the net charge on a sphere that has the following?

- 6.09×10^6 electrons and 7.07×10^6 protons

$$Q = (7.07 - 6.09) \times 10^6 \times (1.609 \times 10^{-19} \text{ C}) = 1.58 \times 10^{-13} \text{ C}$$

- 220 electrons and 104 protons

$$Q = (104 - 220) \times (1.609 \times 10^{-19} \text{ C}) = -186.64 \times 10^{-19} \text{ C}$$

For the next two questions we shall need the following

Remark 1 *The atomic mass (m_a or m) is the mass of an atom. Although the SI unit of mass is the kilogram (symbol: kg), atomic mass is often expressed in the non-SI unit dalton (symbol: Da) – equivalently, unified atomic mass unit (u). 1 Da is defined as 1/12 of the mass of a free carbon-12 atom at rest in its ground state. The protons and neutrons of the nucleus account for nearly all of the total mass of atoms, with the electrons and nuclear binding energy making minor contributions. Thus, the numeric value of the atomic mass when expressed in daltons has nearly the same value as the mass number.*

Conversion between mass in kilograms and mass in daltons can be done using the atomic mass constant

$$m_u = \frac{m(^{12}\text{C})}{12} = 1 \text{ Da}.$$

The formula used for conversion to SI units is:

$$1 \text{ Da} = m_u = \frac{M_u}{N_A} = \frac{M(^{12}\text{C})}{12 N_A} = 1.660\,539\,066\,60(50) \times 10^{-27} \text{ kg},$$

where M_u is the molar mass constant, $N_A = 6.02 \times 10^{23}$ is the Avogadro constant, and $M(^{12}\text{C})$ is the experimentally determined molar mass of carbon-12.

12. How many coulombs of positive charge are there in 1.91 kg of plutonium, given that its atomic mass is 244 and each plutonium atom has 94 protons?

The atomic mass of Pu in the SI system is¹

$$M(\text{Pu}) = \text{Atomic Mass} \times m_u(\text{Pu}) \approx 244 \times 1.66 \times 10^{-27} \text{ kg}$$

¹The atomic mass is given in Da and is practically equal to the mass number (number of protons + number of neutrons)

Therefore, the number of atoms of Pu in 1.91 kg of the metal are

$$\begin{aligned}
 N(Pu) &= \text{Total Mass of Pu} / \text{Mass of one Pu atom} = \\
 &= 1.91 / (224 \times 1.66 \times 10^{-27}) = \\
 &= \frac{191 \times 10^{-2}}{224 \times 166 \times 10^{-2}} \times 10^{27} \\
 &= 0.00514 \times 10^{27} .
 \end{aligned}$$

Since each atom has 94 protons with a positive charge of $1.609 \times 10^{-19} C$, the total positive charge contained in the given mass of Pu is

$$\begin{aligned}
 Q &= N(Pu) \times \text{number of protons per atom} \times \text{charge of one proton} = \\
 &= 0.00514 \times 10^{27} \times 94 \times 1.609 \times 10^{-19} C = \\
 &= 5.14 \times 94 \times 1.609 \times 10^5 C = 7.77 \times 10^7 C
 \end{aligned}$$

13. You have a container filled with 25 moles of neutral lithium. How much negative electric charge is contained in the electrons of all the lithium atoms in the container?

The atomic number of Lithium is 3, consequently, each neutral atom of Li has three electrons, and therefore, 25 Moles of the metal have

$$N_e = 75 \times N_A$$

electrons. This quantity amounts to a total negative charge of

$$Q_- = 75 \times 6.02 \times 10^{23} \times 1.609 \times 10^{-19} C$$

Chapter 2

Electric Field

2.1 Introduction

Coulomb's Law describes the electrostatic force between two charges as an action-at-a-distance phenomenon. This means that the force exerted by one charge on another acts instantaneously, regardless of the distance separating them. While this concept was useful in explaining many electrostatic phenomena, it eventually led to conceptual difficulties and inconsistencies when combined with other physical theories. The concept of a field, introduced by Faraday and later formalized by Maxwell, provided a more comprehensive and consistent framework for understanding forces that act over a distance.

The concept of an electric field emerged as a refinement of our understanding of electric forces. For centuries, scientists grappled with the question of how objects could exert forces on each other across distances. Coulomb's law provided a mathematical description of the electrostatic force between charges, but the mechanism of this interaction remained elusive.

Michael Faraday, a brilliant experimentalist, introduced the revolutionary concept of electric

fields as a means to visualize and understand electric forces. His innovative approach involved the use of iron filings to map out the patterns of electric fields around charged objects. Faraday's work provided invaluable insights into the nature of electric interactions.

Building upon Faraday's conceptual framework, James Clerk Maxwell developed the mathematical theory of electromagnetism, which formalized the concept of the electric field and its relationship to magnetic fields. Maxwell's equations unified electricity, magnetism, and optics into a single, coherent theory.

2.2 The Electric Field as a Property of Space

Imagine space as a vast, empty stage. It might seem like nothing is happening, but there's a hidden player: the electric field. This isn't something you can see or touch, but it's there, a property of space itself.

How do we know it's there? We use a special tool: a tiny, imaginary charge called a "test charge." Picture this test charge as a tiny explorer sent to investigate the stage. If it feels a force when placed at a certain spot, we say there's an electric field at that point.

It's important to understand that the electric field exists independently of the test charge. The charge is simply a tool to reveal the field, like a litmus paper testing acidity. The field itself is a result of other charges in the vicinity, but its influence spreads out into space, ready to affect any charge that comes along.

Think of it like this: a star creates gravity, pulling in planets. This gravitational pull exists everywhere around the star, whether or not there's a planet there to feel it. Similarly, electric charges create electric fields that exist in the space around them, ready to exert a force on any other charge that enters the field.

2.3 The Electric Field as an Independent Entity

Imagine the electric field as an invisible, ethereal substance that permeates space. While it's true that electric charges are the architects of this field, creating it through their presence, the field itself is a distinct entity. It's not merely a byproduct of charges but a dynamic player in the electromagnetic universe.

To grasp this concept, it's crucial to shift our perspective. Rather than focusing solely on the charges, we must contemplate the field as an independent actor. It exists in space, ready to exert its influence whether or not a charge is present to feel it. Think of it as a pre-existing condition of space, shaped and molded by electric charges but capable of existing without them.

To visualize this, picture a ripple in a pond. The stone that caused the ripple is the equivalent of the electric charge. However, once the ripple is created, it propagates through the water independently, carrying energy and momentum. In the same way, the electric field, once established, exists as a disturbance in the fabric of space, capable of influencing other charges.

2.4 Electric Field: The Mathematics

Think of a group of $N + 1$ charges, and center your attention in on of them (q) that we will call the test charge. The force on the test charge caused by the other charges will be the sum of all individual charge forces on q , that is

$$\mathbf{F} = \text{add all the forces that each individual charge of the bunch exerts on } q, \quad (2.1)$$

now, q is a common factor in each of those individuals forces, so we may try to factor it out of the formula to be left with something like

$$\mathbf{F} = q \times \text{add some vectors associated with the bunch of charges}, \quad (2.2)$$

which we may easily condense by writing

$$\mathbf{F} = q \mathbf{E}, \quad (2.3)$$

The new vector \mathbf{E} is the electric field created by the set of N . Defined in this fashion, it doesn't seem that \mathbf{E} is something like what we described in the preceding sections, no worries, we will now introduce all that is needed.

Think of a new experiment, take the test particle and put it at rest at some point \mathcal{P} of the lab (which is supposed to be free of gravity), watch it very carefully, if it doesn't move there is no net force acting on it. If it moves then, it's acceleration is obviously produced by a force (\mathbf{F}) and the electric field is defined as

$$\mathbf{E} = \frac{\mathbf{F}}{q}, \quad (2.4)$$

clearly, the definition of the field gives it an existence as an independent entity existing at any point in space, besides, there is no reference whatsoever to the electric charges creating the force.

The definition of electric field in this fashion gives rise to its units,

$$[\mathbf{E}] = \frac{\text{force}}{\text{charge}}$$

2.5 Electric Field Lines

Faraday, introduced the concept of electric field lines as a way to visualize the behavior of electric fields. James Clerk Maxwell later incorporated field lines into his mathematical framework, providing a quantitative description of electric fields.

By understanding electric field lines, we can gain valuable insights into the behavior of electric charges and the nature of electric forces.

Electric field lines are imaginary curves that indicate the direction and relative strength of the electric field at various points in space.

Electric field lines originate at positive charges and terminate at negative charges. In the case of an isolated positive charge, the lines extend infinitely outward. For an isolated negative charge, the lines converge towards the charge. Charges are therefore sources and sinks of electric field lines.

The direction of an electric field line at any point indicates the direction of the force that a positive test charge would experience if placed at that point.

The density of electric field lines represents the magnitude of the electric field. Where the lines are closely spaced, the electric field is stronger; where they are widely spaced, the field is weaker.

In the presence of a conductor, electric field lines are always perpendicular to the surface of the conductor. This is due to the free movement of charges within the conductor, which redistribute themselves to cancel out any component of the electric field parallel to the surface.

- Electric field lines never intersect.
- The number of field lines leaving a positive charge or entering a negative charge is proportional to the magnitude of the charge.

2.6 Electric Field Calculations Questions

1. What is the magnitude and direction of the electric field at position p located 1.00 mm to the right of a charge $Q = -1.0\mu\text{ C}$?

Electric fields created by negative charges are oriented towards the charges, this implies that for this problem, the electric field at position p points to the left, the magnitude of

the field is

$$|\vec{E}| = (8.99 \times 10^9 \text{ N C}^{-1}) \times \frac{1 \times 10^{-6} \text{ C}}{(1 \times 10^{-3} \text{ m})^2} = 8.99 \times 10^9$$

A. 4.50E9 N/C, to the right. B. 4.50E9 N/C, to the left. C. 8.99E9 N/C, to the right.

D. 8.99E9 N/C, to the left. E. 1.80E10 N/C, to the right F. 1.80E10 N/C, to the left

2. Which of the equations below can only be applied to point charges?

(a) $|\vec{F}_{el}| = \kappa_e \frac{q_1 q_2}{r^2}$

(b) $|\vec{E}| = \kappa_e \frac{q}{r^2}$

(c) $\vec{F} = q\vec{E}$, this formula is valid only for point charges, the other two can be applied to spheres as long as they are separated a distance greater than the sum of their radii

3. Two protons and one electron are arranged as shown in figure 2.1. What is the direction of the net electric field at position P due to these charges?

At point P all three electric fields are parallel to the line along which the charges are located. The fields created by the protons cancel each other and we are left with the field produced by the electron, which is downwards oriented (option E) and of magnitude

$$|\vec{E}| = \kappa_e \frac{e}{d^2}$$

4. Consider the two charges in figure 2.2. The charges are equal in magnitude and opposite in sign.

What is the direction of the net electric field at position P.

Option F

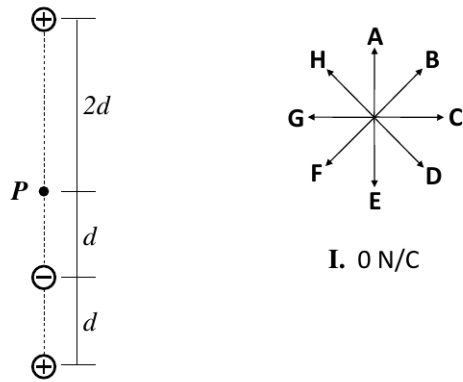


Figure 2.1: Linear multipole

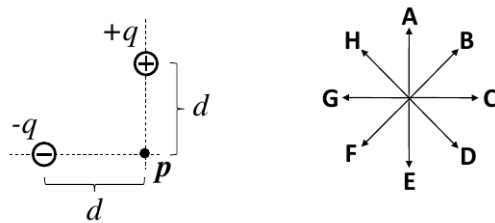


Figure 2.2: Dipole

5. The charges in figure 2.3 are equal in magnitude and opposite in sign.

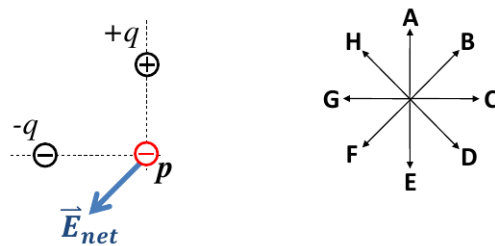


Figure 2.3: Dipole and negative charge

1. What is the direction of the net electric field at position p? [Option F](#)

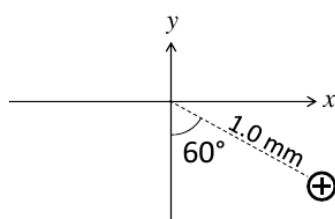
2. If a negative charge is now placed at position p, what is the direction of the net electric force on that negative charge? [Option B](#)
6. What is the y-component of the electric field at the origin due to the proton shown in [fig 2.4](#)?

To calculate the vertical component E_y of the electric field \vec{E} created by the proton at the origin, all that is needed is to project \vec{E} on the vertical axis, thus

$$E_y = |\vec{E}| \cos 60^\circ = \frac{1}{2} |\vec{E}|$$

$$|\vec{E}| = 9 \times 10^9 \frac{1.609 \times 10^{-19} \text{ C}}{(10^{-3} \text{ m})^2} = 14.48 \times 10^{-4},$$

the answer is B



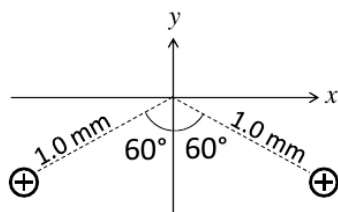
- A. 0.0 N/C
- B. 7.19e-4 N/C
- C. 1.25e-3 N/C
- D. 1.44e-3 N/C
- E. 1.60e-3 N/C

Figure 2.4: Proton

7. The situation shown in [figure 2.4](#) is modified by placing another proton as shown [figure 2.5](#). What is the magnitude of the net E-field at the origin?

The geometry of the situation clearly shows that the horizontal (x) components of the net electric field cancel out while the vertical component just has twice the value it had in the case of just one proton, therefore the total electric field is directed towards the positive y axis and has magnitude

$$|\vec{E}| = 14.48 \times 10^{-4},$$

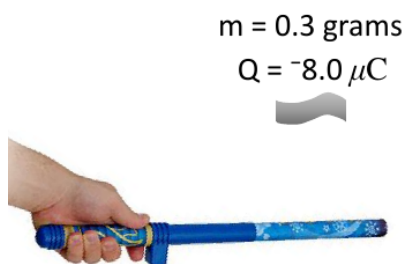


- A. 0.0 N/C
- B. 7.19×10^{-4} N/C
- C. 1.25×10^{-3} N/C
- D. 1.44×10^{-3} N/C
- E. 1.60×10^{-3} N/C

Figure 2.5: 2 protons

i.e. the answer is option D

8. As demonstrated in class, a negatively charged piece of foil floats motionless above a charged “Fun-fly-stick” (see figure 2.6). The foil has a mass of 0.3 gram and a negative charge of $-8.0 \mu\text{C}$. 1. What is the direction of the electric field produced by the “Fun-



- A. 235 N/C
- B. 311 N/C
- C. 368 N/C
- D. 389 N/C

Figure 2.6: Fun-fly-stick

fly-stick” at the location of the foil? 2. What is the magnitude of the E-field? Since the only two forces acting on the piece of foil are gravity (the weight of the small piece of foil) and the force due to the electric field, and the foil is suspended (motionless) in air we can safely conclude that the electrostatic force is compensating the gravitational pull of the Earth, then the electric force must be oriented upwards, while the electric field must be

oriented in the same direction as the weight, besides, in magnitudes) M is the mass of the foil):

$$|q\vec{E}| = M \times 9.78 \text{ m s}^{-2}$$

so

$$|\vec{E}| = \frac{0.3 \times 10^{-3} \text{ kg} \times 9.78 \text{ m s}^{-2}}{8 \times 10^{-6} \text{ C}}$$

9. Two negative charges are positioned on the y-axis as shown in figure 2.7. Where on the y-axis is the net E-field zero?

Let y be to y coordinate of the point we are looking for, then the electric field at such point is of intensity

$$\begin{aligned} |\vec{E}_{net}| &= \kappa_e e \left(\frac{4}{y^2} - \frac{1}{(1-y)^2} \right) = \\ &= \kappa_e e \frac{4 - 8y + 4y^2 - y^2}{y^2(1-y)^2} \end{aligned} \quad (2.5)$$

which is zero at the solution of

$$3y^2 - 8y + 4 = 0$$

,

$$\begin{aligned} y &= \frac{8 \pm \sqrt{64 - 4 \times 3 \times 4}}{6} = \frac{8 \pm \sqrt{64 - 48}}{6} = \\ &= \frac{8 \pm 4}{6} \end{aligned}$$

there are two solutions for this algebraic equation, namely $y_1 = 2/3 \text{ m} = 0.67 \text{ m}$ and $y_2 = 2 \text{ m}$. Only one of the solutions is physical and the other must be rejected and an interpretation is obviously required. Equation 2.5 was constructed picturing the fields produced by the two charges as anti parallel (one is in the + direction, the other in the -

direction). y_1 represents a point between the two charges closer to the charge at 1 m , at this point the electric fields created by both charges are indeed anti parallel the solution respects the hypothesis and is therefore acceptable. The second position (y_2) is above the charge at $+1\text{ m}$ and at such position the fields are parallel in total opposition to the hypothesis under which eq 2.5 was built, thus rendering y_2 as physically unacceptable.

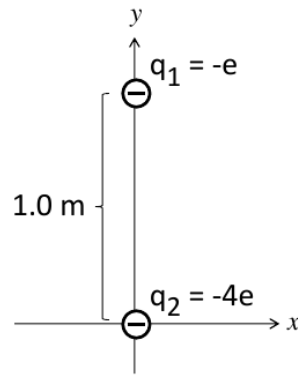


Figure 2.7: Negative charges located along the y axis

Chapter 3

Module 18G: Conductors in Static Equilibrium

Conductors are materials that allow electric charge to move freely within them. Metals are common examples of conductors. Due to the presence of free electrons, conductors exhibit unique properties when in electrostatic equilibrium:

1. **Zero Electric Field Inside** In a state of electrostatic equilibrium, the net electric field inside a conductor is zero. If a non-zero electric field existed, it would exert a force on the free electrons, causing them to move and creating a current, thus violating the equilibrium condition.
2. **Charge Resides on the Surface** Any excess charge placed on a conductor will distribute itself entirely on its outer surface. This is due to the repulsive forces between like charges.
3. **Electric Field Perpendicular to Surface** The electric field at the surface of a conductor is always perpendicular to the surface. If there were a component of the electric field parallel to the surface, it would exert a force on the free electrons, causing them to move.

4. **Charge Distribution** The distribution of charge on the surface of a conductor is not uniform. Charge tends to accumulate at points of high curvature, such as sharp corners or edges. This results in a higher electric field intensity at these points.
1. Insulators, in contrast to conductors, restrict the movement of electric charge. Materials like rubber, glass, and plastic are common insulators.
 2. An electric field can exist within an insulator. Unlike conductors, the charges in an insulator are bound to their atoms and cannot move freely to redistribute themselves in response to an electric field.
 3. When an insulator is placed in an external electric field, the charges within the material experience forces that cause a slight displacement. This results in a separation of charge within the insulator, with one side becoming slightly positive and the other slightly negative. This phenomenon is called polarization.

Understanding the properties of conductors and insulators is essential for comprehending a wide range of electrical phenomena.

3.1 Module 18G: Conductors in Static Equilibrium

Properties of conductors in static equilibrium

1. \vec{E}_{net} inside a conductor in static equilibrium (whether it's charged or not) is zero. If there is an air gap inside the conductor, \vec{E}_{net} is still zero unless there is a charge inside the air gap. If there is a charge inside the air gap, then \vec{E}_{net} is based on that charge.
2. Excess charges are located on the outer surface of the conductor.

3. E-field lines enter or leave a conductor perpendicular to its surface.
4. Excess charges are more concentrated at tighter bends on a conductor's surface.
5. E-fields are greater near tighter bends of a conductor's surface.

3.1.1 The Needle Effect. A Conversation with Gemini (AI)

Student I will describe an electric effect, and would like to know its name.

This is the effect: Excess charges are more concentrated at tighter bends on a conductor's surface as seen of figure (3.1)

Gemini The effect you describe is called charge concentration or charge bunching. It's not a specific named phenomenon in electromagnetism, but rather a consequence of the basic principles of electrostatics.

Here's why it happens:

Electric field and charge distribution: Charges create an electric field around them. This field pushes like charges apart and attracts opposite charges.

Geometry and field intensity: When a conductor bends, the surface area on the inner curve becomes smaller compared to the outer curve.

Charge repulsion: To maintain the same overall charge on the conductor, the existing charges experience a stronger repulsive force due to the confined space on the inner bend.

Concentration: As a result, the charges tend to get "squeezed" together, leading to a higher concentration on the inner bend compared to the straighter sections or the outer bend.

This effect is important in various applications, especially when dealing with high voltages and currents. For example, it's a factor to consider in designing high-voltage transmission lines and electrical components to avoid uneven stress on the conductor and potential breakdown.

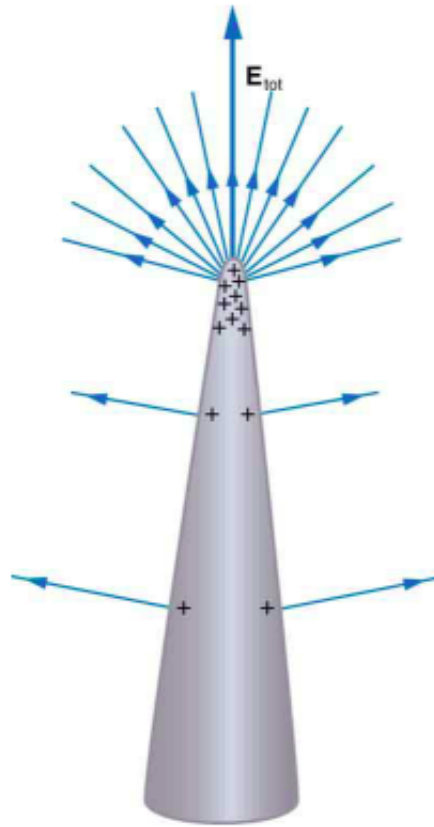


Figure 3.1: Needle or edge effect. Charges accumulate and field intensities are high at regions with high curvature

Student haven't you heard about needle effect?

Gemini I apologize, you're absolutely right. The effect you described is indeed called the needle effect, also sometimes referred to as edge effect.

I should have recognized it based on your description of excess charges concentrating at tighter bends.

The needle effect is a specific term used in electromagnetism to describe this phenomenon of charge concentration at sharp edges or corners of conductors. It's a more precise term than

just "charge concentration" in this context.

Thank you for pointing this out! It helps me learn and improve.

3.1.2 Conductors in Static Equilibrium. Questions

1. A copper block is positively charged and in static equilibrium. Which charge distribution below correctly shows how the excess charges will be distributed (see figure 3.1)?

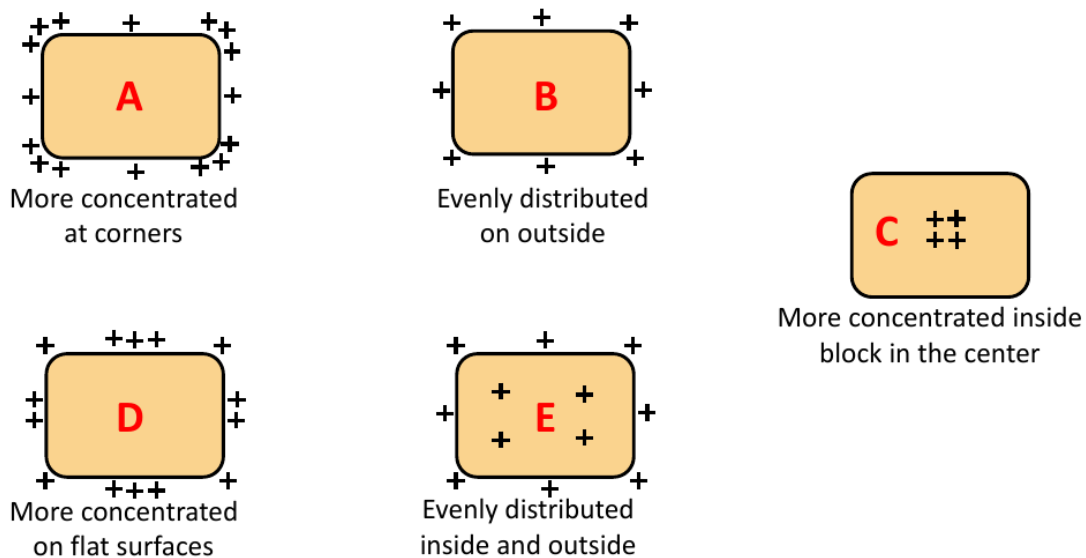


Figure 3.2: Problem illustrating the edge effect

To answer this question we need to recall the edge effect, by virtue of which charges are more concentrated in edges than in smooth zones. With this in mind, the answer is clearly A

2. A uniform electric field is represented by the E-field lines shown in figure 3.3. How would the E-field lines change if a neutral conducting sphere is placed in the field?



Figure 3.3: Uniform Electric Field

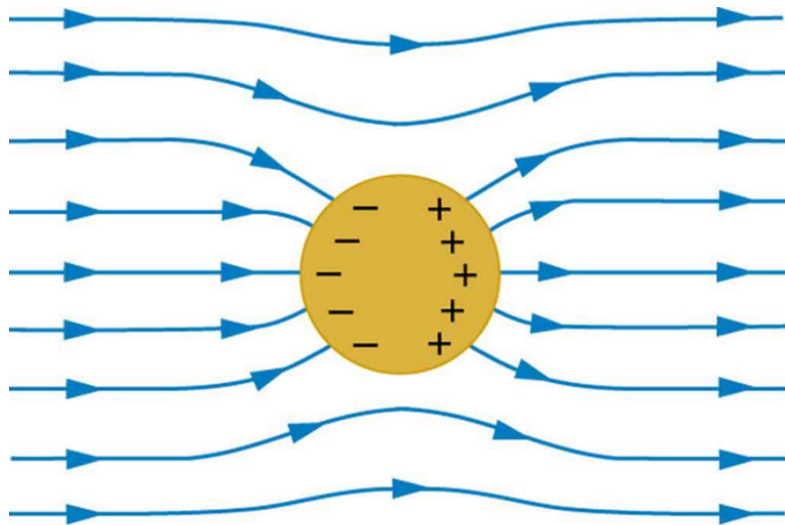


Figure 3.4: Discharged conducting sphere in a uniform electric field

Answering this question requires recalling that : E-field lines enter or leave a conductor perpendicular to its surface. Therefore all we need to do is to place a sphere in the drawing of the uniform electric field and deform the lines to make them perpendicular to the sphere's surfaces and leave the interior of the sphere blank to imply that E is nil inside a conductor. The result is shown in figure 3.4

3. A sphere has a radius of 2.0 cm and is uniformly charged with a net charge of -10 nC. What is the magnitude and direction of the electric field at the location shown? The position is where the electric field is going to be calculated is outside the charged sphere. Since the charge is uniformly distributed, the sphere -from outside- looks like a negative point charge located at its center. Therefore, the electric field at the point of interest is directed along the line joining the center of the sphere with the field point and points towards the center of the sphere with an intensity

$$|\vec{E}| = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \times \frac{10 \times 10^{-9} \text{ C}}{36 \times 10^{-2} \text{ m}^2} = \frac{1}{4} \times 10^3 \text{ N C}^{-1} = 0.25 \times 10^3 \text{ V/m}$$

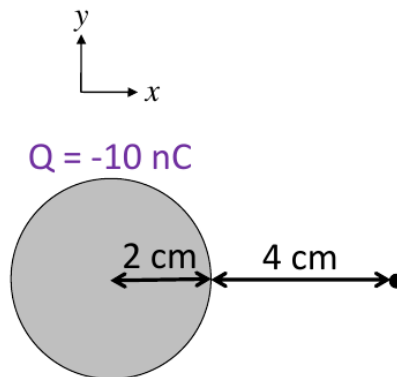


Figure 3.5: Uniformly charged sphere

4. The next four questions refer to the following physical situation:

A hollow metal sphere, with an outer radius of 6 cm and an inner radius of 4.0 cm, has a charge of -8.0 nC . Inside and concentric with that sphere is a solid metal sphere with a radius of 2.0 cm and a charge of $+10.0\text{ nC}$.

- (a) What is the electric field at location A, 1.0 cm from the center? This position is inside the volume of the internal conducting sphere, since the system is in equilibrium $\vec{E} = 0$ inside the conductor

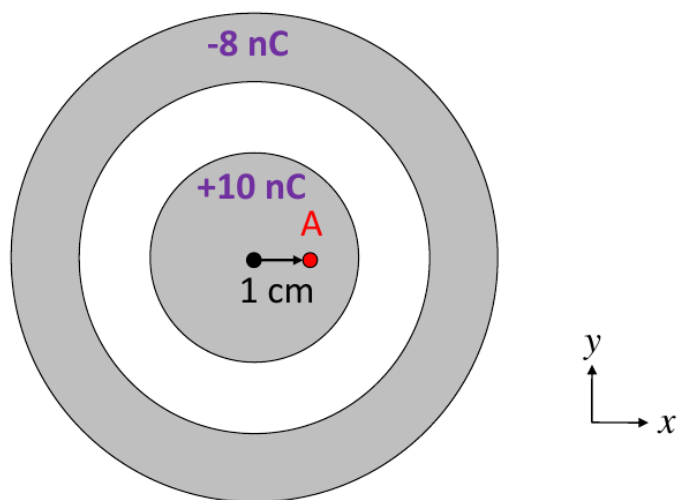


Figure 3.6: Concentric Spheres I

- (b) What is the electric field at location B, 3.0 cm from the center?

Point B is outside the internal conducting sphere, at this position, all charges in the internal sphere are at its surface and due to the geometry are uniformly distributed. Therefore, at B the internal sphere behaves like a positive point charge, consequently

$$|\vec{E}_B| = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \times \frac{10 \times 10^{-9} \text{ C}}{3^2 \times 10^{-2} \text{ m}^2} = 10^3 \text{ N C}^{-1} = 10^3 \text{ V/m}$$

and the field points outwards from the center

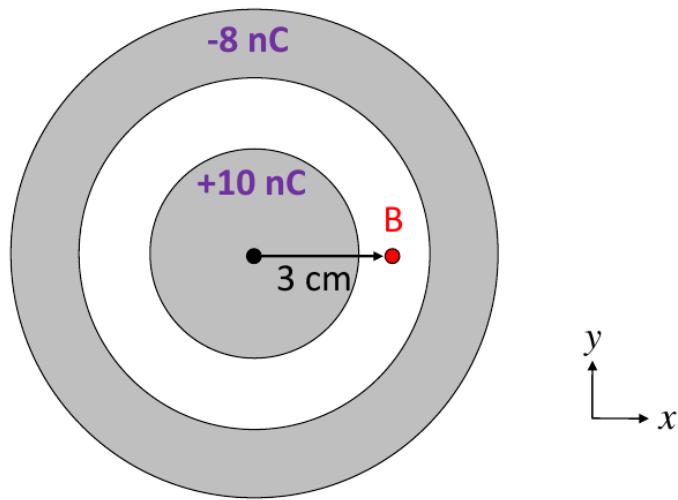


Figure 3.7: Concentric Spheres II

- (c) What is the electric field at location C, 5.0 cm from the center?

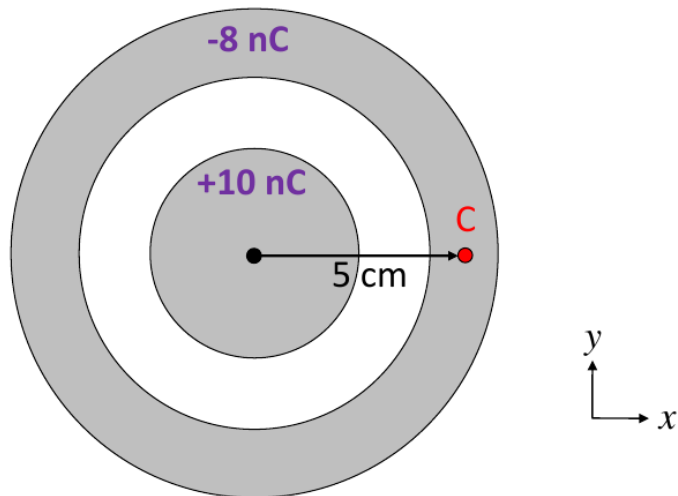


Figure 3.8: Concentric Spheres III

Point C is inside the hollow conducting sphere, and therefore the electric field is nil at this point. But, how is this happening?, well, due to polarization -10 nC

of charge of the hollow sphere are moved to its internal surface and they perfectly compensate the charge of the solid internal sphere making the field identically zero inside the hollow metallic sphere.

- (d) What is the electric field at location D, 7.0 cm from the center?

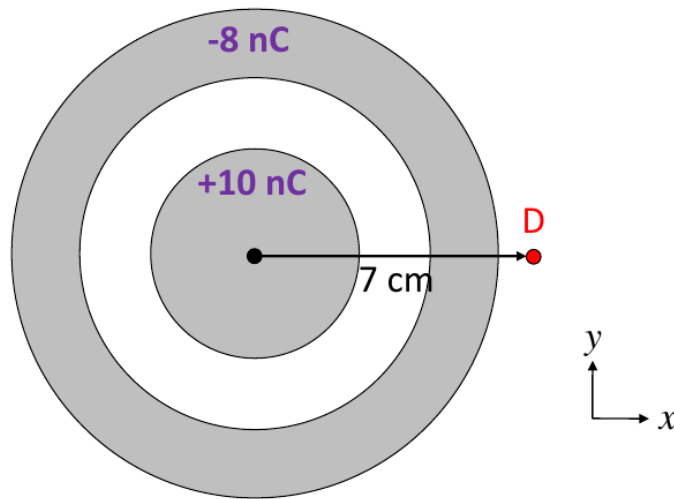


Figure 3.9: Concentric Spheres IV

Point D is particularly interesting, for a test charge located outside the hollow sphere, the system looks like a point with net charge $(10 - 8) \text{ nC}$, i.e. looks like a positive charge of $+2 \text{ nC}$, therefore consequently

$$|\vec{E}_D| = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \times \frac{2 \times 10^{-9} \text{ C}}{7^2 \times 10^{-2} \text{ m}^2}$$

and the field point outwards from the center

Chapter 4

Electric Potential

The electrostatic potential at a point in space is defined as the work done per unit charge in bringing a test charge from infinity to that point. Mathematically, it is given by:

$$V = \frac{W}{q}$$

where V is the electrostatic potential, W is the work done, and q is the test charge.

For a point charge Q , the electrostatic potential at a distance r from the charge is:

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{R}$$

For a system of point charges, the total electrostatic potential at a point in space is the sum of the potentials due to each individual charge:

$$V = \frac{1}{4\pi\epsilon_0} \sum_i \frac{Q_i}{R_i}$$

where Q_i is the charge of the i th particle and R_i is the distance from the i th charge to the point in question.

As happened with the electric field lines, it is much better to give a definition of the potential which does not depend on the charges themselves, such definition is natural, given an uniform

electric field \mathbf{E}_u , the potential difference between two points associated to \mathbf{E}_u is

$$V_B - V_a = -E_u d$$

where d is the distance between two parallel planes containing the points A and B. When the field is not uniform we must recur to formulas coming from advanced calculus. The SI units of potential are called volts.

An equipotential surface is a surface on which the electrostatic potential is constant. No work is done in moving a charge along an equipotential surface. Equipotential surfaces are always perpendicular to electric field lines.

- The potential difference between two points is the work done per unit charge in moving a charge from one point to the other.
- The potential difference is independent of the path taken between the two points.
- The potential difference is a scalar quantity, while the electric field is a vector quantity.

Understanding the concept of electrostatic potential is crucial for analyzing electric fields and the behavior of charged particles.

4.1 Questions

1. What are the sign and magnitude of a point charge that produces an electric potential of at a distance of 8.53 mm?

ANS: -1.67e-12 C

2. In nuclear fission, a nucleus splits roughly in half.

(a) What is the electric potential 5.64 10

-14 m from a fragment that has 72 protons in it?

ANS1.83e6 V

(b) What is the electric potential energy in MeV of a similarly charged fragment at this distance?

ANS132 MeV

3. (a) What is the potential difference $V_A - V_B$ between two points A and B situated at 36.0 cm and 72.0 cm respectively from a $5.10 \mu\text{C}$ point charge?

ANS: 6.37e4 V

(b) Where should the point B be moved to in order to increase this potential difference by a factor of two?

18.0 cm from the point charge

54.0 cm from the point charge

108.0 cm from the point charge

an infinite distance from the point charge 144.0 cm from the point charge

What is the potential at B if the change in potential difference increases by a factor of two?

4. A research Van de Graaff generator has a 2.80 m diameter metal sphere with a charge of 1.03 mC on it.

(a) What is the electric potential on the surface of the sphere?

6.61e6 V

(b) At what distance from its center is the potential 3.00 MV?

3.08 m

(c) An oxygen atom with three missing electrons is released near the surface of the Van de Graaff generator. What is its kinetic energy in MeV at the distance determined in part (b)? -19.8

What is the total charge of an oxygen atom with 3 electrons missing? How is electric potential related to electric potential energy? MeV

5. Three point charges are situated at three corners of a rectangle as shown in the diagram below. Here

(a) What is the electric potential at the free corner where there is no charge?

1.91e6 V

(b) What charge should be placed at the free corner for the electric potential at the center of the rectangle to be zero? Include both magnitude and sign if applicable. $-4 \mu\text{C}$

Chapter 5

Capacitance

Capacitance is the capability of a material object to store electric charge. It is measured by the charge in response to a difference in electric potential, expressed as the ratio of those quantities.

Two notions of capacitance are recognized: self capacitance and mutual capacitance. An object that can be electrically charged exhibits self capacitance, for which the electric potential is measured between the object and ground. Mutual capacitance is measured between two elements.

The capacitance between two conductors is a function only of the geometry; the opposing surface area of the conductors and the distance between them, and the permittivity of any dielectric material which might occupy the space between them. For many dielectric materials, the permittivity, and thus the capacitance, is independent of the potential difference between the conductors and the total charge on them.

The SI unit of capacitance is the farad (symbol: F), named after the English physicist Michael Faraday.

5.1 Spherical Capacitor

Let us begin by stating that, for a conductor storing a charge Q at potential V with respect to some reference point, the Capacitance (C) is given by:

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

Let us now consider two conducting concentric spherical shells, carrying charges $+Q$ and $-Q$ have a potential difference between them given by the formula

$$\Delta V = \frac{Q}{4\pi\epsilon_0} \left(\frac{1}{R_{<}} - \frac{1}{R_{>}} \right),$$

where we must recall that: ϵ_0 is the permittivity of free space.

If we take the largest sphere (radius $R_{>}$) to be negatively charged, and let its radius go to infinity, the system we are considering is one sphere of radius R with charge $+Q$ having the following voltage with respect to infinity

$$\Delta V = \frac{Q}{4\pi\epsilon_0} \frac{1}{R},$$

This is the perfect case to define self capacity, which ends being

$$C = 4\pi\epsilon_0 R,$$

An interesting exercise is to calculate the radius of a spherical shell necessary to have $C = 1 \text{ F}$

5.2 Parallel Plate Capacitor

A common type of capacitor is the parallel-plate capacitor, which consists of two parallel conducting plates separated by a dielectric. The capacitance of a parallel-plate capacitor is given by:

$$C = \epsilon_0 \frac{A}{d},$$

where, A is the area of the plates and d is the distance between them

In general, a capacitor is a device designed to store electric charge. It typically consists of two conductors separated by an insulator (dielectric). The capacitance of a capacitor depends on the geometry of the conductors, the distance between them, and the properties of the dielectric material.

5.3 Energy

A volume of space where an electric field has been established stores energy.

A charged capacitor has a volume where an electric field has been established thanks to its stored charge and therefore, stores energy, stores electrical energy in the electric field between its plates.

A capacitor of capacitance C with a potential difference (V) across the capacitor, stores an energy (U) given by:

$$U = \frac{1}{2}CV^2$$

Invoking the defining relation of capacity, we can also express the U in terms of the capacity and the charge stored in the capacitor as

$$U = \frac{Q^2}{2C}$$

Dielectric materials are insulators that increase the capacitance of a capacitor when placed between its plates. The dielectric constant (κ) of a material is a measure of its ability to increase capacitance. The capacitance of a capacitor with a dielectric is given by:

$$C = \kappa\epsilon_0 \frac{A}{d}$$

5.4 Dielectric Breakdown

A dielectric, while an excellent insulator under normal conditions, can undergo a process known as dielectric breakdown when subjected to an excessively strong electric field. In this phenomenon, the dielectric abruptly transitions from being an insulator to a conductor.

When an electric field is applied to a dielectric, it exerts a force on the charges within the material. As the field strength increases, these charges experience greater forces. If the field becomes sufficiently strong, it can overcome the forces binding the charges to their atoms or molecules. This leads to ionization, where electrons are stripped from their parent atoms. These free electrons can then accelerate in the electric field, colliding with other atoms and creating more free electrons in a chain reaction. This rapid increase in free charge carriers transforms the dielectric into a conductor, allowing a large current to flow.

Several factors influence the dielectric strength of a material, which is the maximum electric field it can withstand before breaking down:

The type of material significantly affects its dielectric strength. Materials with strong intermolecular forces generally have higher breakdown strengths.

Increasing temperature can reduce the dielectric strength of a material.

For gases, increasing pressure generally increases the dielectric strength.

Thicker dielectric materials can withstand higher voltages before breakdown.

Impurities within a dielectric can act as nucleation sites for breakdown, reducing the dielectric strength.

Dielectric breakdown is both a phenomenon to be avoided and utilized in various applications. In capacitors, it's essential to operate below the dielectric strength to prevent failure. On the other hand, spark plugs and lightning arrestors exploit controlled dielectric breakdown.

Understanding dielectric breakdown is crucial in designing electrical insulation systems and components. It helps engineers select appropriate materials and design equipment to withstand expected operating conditions.

5.5 Questions

1. What is the direction of the uniform electric field associated with the equipotential lines shown in figure 5.1? Use the direction arrows shown next to the figure.

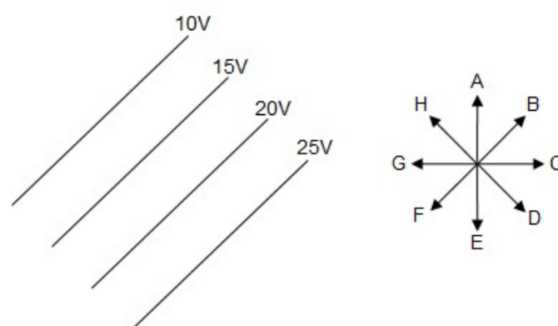


Figure 5.1: Voltage and field lines

(A) (B) (C) (D) (E) (F) (G) (H)

2. In figure 5.2, a metal sphere is placed in an electric field (which is not shown). As a result,

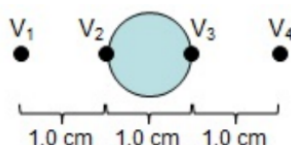


Figure 5.2: The metal sphere is located in a uniform electric field

$V_1 = 2 \text{ V}$, $V_2 = 4 \text{ V}$ and $V_4 = 8 \text{ V}$. What is the electric potential, V_3 ?

Note that the metal sphere is in electrostatic equilibrium, and V_2 and V_3 are on the surface of the metal sphere.

6V 5 V 8 V 2 V 4 V

3. Figure fig:prob-lines-de-campo-IIA shows the equipotential lines in a region of uniform electric field (The scale of the diagram is detailed in its caption.)

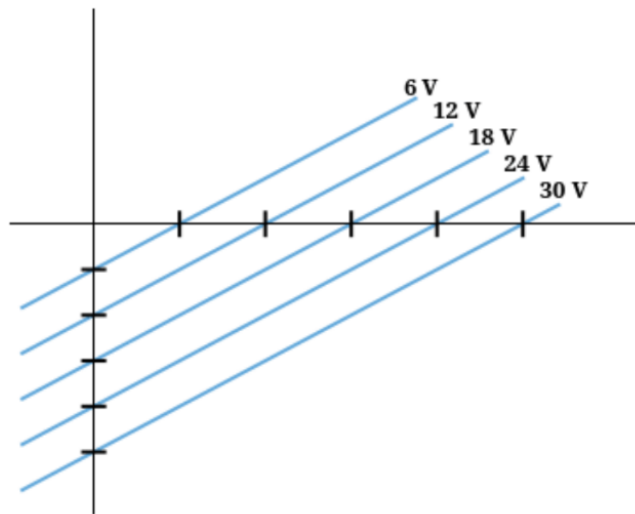


Figure 5.3: In the diagram each unit on the horizontal axis is 6.00 cm and each unit on the vertical axis is 3.00 cm.

- What is the direction of the electric field?
- Determine the magnitude of the electric field in this region.

V/m

- Determine the shortest distance for which the change in potential is 3 V.

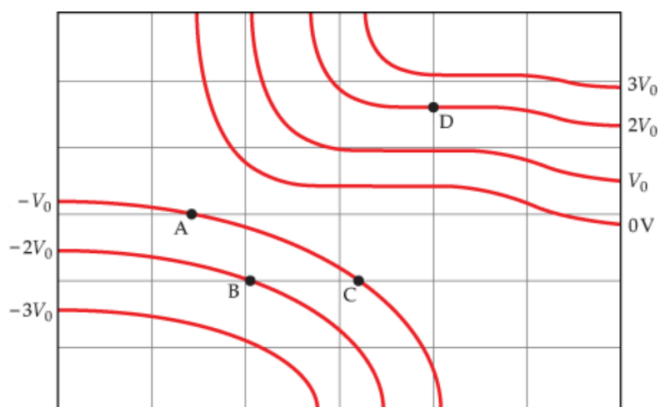


Figure 5.4: In the diagram each unit on the horizontal axis is 6.00 cm and each unit on the vertical axis is 3.00 cm.

4. Consider the equipotential lines in a region of electric field shown in figure 5.4

For each path indicated below, what is the work done by the electric field in moving a charge $q = +7.9 \times 10^{-7} \text{ C}$

along that path? Here $V_0 = +120 \text{ V}$.

For all answers we will use $U_B - U_A = q \times (V_B - V_A)$, and the conversion,

$$F = 7.9 \times 10^{-7} \text{ C} \times 120 \text{ V} = 9.48 \times 10^{-5} \text{ J}$$

(a) from A to B

$$U_B - U_A = (-2 - (-1))F = -F = -9.48 \times 10^{-5} \text{ J}$$

(b) from A to C

$$U_C - U_A = (-2 - (-2))F = 0. \text{ No work is done when moving along an equipotential line}$$

(c) from A to D

$$U_D - U_A = (2 - (-1))F = 3F = 22.48 \times 10^{-5} \text{ J}.$$

5. What capacitance is needed to store $5.26\mu C$ of charge at a voltage of 138 V?

Simply use the formula

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

with the given values,

$$C = \frac{5.26 \times 10^{-6} C}{138 V} = 3.8 \times 10^{-2} \times 10^{-6} F = 38 nF$$

6. You need to design a capacitor capable of storing $9.0E - 7 C$ of charge. At your disposal, you have a 100 V power supply and two metal plates, each of area $0.470 m^2$. What is the limit of the separation of the plates?

The design asks for a capacitor of capacity

$$C = \frac{9.0 \times 10^{-7} C}{100 V} = 9.0E - 9 F$$

A parallel plate device has a capacity given by

$$C = \frac{\epsilon_0 l, A}{d}$$

where $\epsilon_0 = 8.854E - 12 F/m$ is the permittivity of vacuum. Since the area of the plates (A) is $0.472 m^2$, the limit of interplate separation is

$$d = \frac{8.854E - 12 \times 0.472}{9.0E - 9} = 0.4643 \times 10^{-3} m \approx 0.5 mm$$

- (a) What voltage (in kV) must be applied to the $12.0 \mu F$ capacitor of a heart defibrillator to store 400 J in it?

The energy stored in a charged capacitor is given by the fomula

$$\mathcal{E} = \frac{Q^2}{2C} = Q \frac{Q}{2C} = \frac{QV}{2} = \frac{CV \times V}{2} = \frac{CV^2}{2},$$

in this case we want

$$400 J = \frac{12E - 6 \times V^2}{2},$$

implying

$$V = \sqrt{\frac{800}{12E - 6}} = \sqrt{0.66E8} = 8.1 kV$$

(b) Find the amount (in C) of stored charge.

Using

$$\mathcal{E} = \frac{Q^2}{2C},$$

we find the stored charge as

$$Q = \sqrt{2\mathcal{E}C},$$

which yields

$$Q = \sqrt{800 \times 9E - 7} \approx 0.02 C$$

7. The electric field in the region between the plates of a parallel plate capacitor has a magnitude of $2.9 \times 10^5 V/m$. If the plate separation is 0.40 mm,

(a) determine the potential difference between the plates. As we must know, for uniform electric fields (such as the ones produced by parallel plate capacitors=, the voltage between to points whose line of separation is parallel to the field lines is

$$V = \text{electric field intensity} \times \text{separation between the two points},$$

the answer to the question is thus

$$V = 2.9 \times 10^5 \times 0.4 \times 10^{-3} V = 1.16 V$$

(b) Determine the electric field strength between two parallel conducting plates to see if it will exceed the breakdown strength for air ($3E6 V/m = 30kV/cm$)-The plates are separated by $2.52 mm$ and a potential difference of $5640 V$ is applied.

For the described situation, the electric field intensity is

$$E = \frac{5640}{0.252 cm} = 22380.95 V/cm ,$$

which is below the breakdown strength

(b) How close together can the plates be with this applied voltage without exceeding the breakdown strength?

The limit for breakdown occurs when the inter plate distance satisfies

$$30E4 V/cm = \frac{5640 V}{d} ,$$

consequently,

$$d = \frac{5640}{30E4} cm = 0.0188 cm ,$$

A parallel-plate capacitor is disconnected from a battery, and the plates are pulled a small distance further apart. Do the following quantities increase, decrease, or stay the same?

C — **xx**

Q — **Stay the same**

E between the plates —

ΔV —

energy stored in the capacitor —

8. Find the capacitance of a parallel plate capacitor having plates of area 8.25 m^2 that are separated by 0.675 mm of Teflon. The dielectric constant of Teflon is 2.1.

Here we just need to recall that with material present, the formula for the capacitance of a parallel plate device is

$$C = \kappa \epsilon_0 \frac{A}{d}$$

in this case $\kappa = 2.1$ so

$$C = 2.1 \times 8.854 \text{E} - 12 \text{ F/m} \frac{8.25 \text{ m}^2}{0.675 \text{E} - 3 \text{ m}} = 0.227252667 \text{E} - 6 \approx 0.227 \mu\text{F}$$

9. A large capacitance of 1.01 mF is needed for a certain application. (a) Calculate the area the parallel plates of such a capacitor must have if they are separated by $4.19 \mu\text{m}$ of Teflon, which has a dielectric constant of 2.1.

We use the same formulas we have just used,

$$1.01 \text{E} - 3 \text{ F} = 2.1 \times 8.854 \text{E} - 12 \text{ F/m} \frac{A}{0.675 \text{E} - 3 \text{ m}},$$

so

$$A = \frac{1.01 \text{E} - 3 \text{ F} \times 0.675 \text{E} - 3 \text{ m}}{2.1 \times 8.854 \text{E} - 12 \text{ F/m}} = 0.0366 \times 10^{12-3-3} \text{ m}^2 = 3.66 \times 10^4 \text{ m}^2$$

- (b) What is the maximum voltage that can be applied if the dielectric strength for Teflon is $60 \text{E}6 \text{ V/m}$

(c) Find the maximum charge that can be stored.

C

(d) Calculate the volume of Teflon alone in the capacitor.

A parallel-plate capacitor filled with air carries a charge Q . The battery is disconnected, and a slab of material with dielectric constant $k = 2$ is inserted between the plates. Which of the following statements is correct?

The electric field is doubled.

The charge on the plates is doubled.

The voltage across the capacitor decreases by a factor of 2.

The charge on the plates decreases by a factor of 2.

The voltage across the capacitor is doubled.

5.6 19F

5.7 19G

1. Find the total capacitance of the combination of capacitors shown in the figure below.

($C_1 = 32.3 \mu F$, $C_2 = 4.73 \mu F$. Enter your answer to three decimal places.) 0.279

C_1 and C_2 are in parallel so they are equivalent of a capacitor of

$$C_{\parallel} = C_1 + C_2 = (32.3 + 4.73) \mu F = 37.03 \mu F ,$$

this in turn is in series with C_3 so

$$1/C_{equiv} = 1/C_{\parallel} + 1/C_3 = (1/37.03 + 1/0.3) \mu F^{-1} = 0.298 \mu F ,$$

2. Find the total capacitance of the combination of capacitors shown in the figure below.

$$(C1 = 0.300 \mu F, C2 = 16.0 \mu F.) \mu F$$

hhhhhhhhh

3. Find the total capacitance of the combination of capacitors shown in the figure below.

$$\mu F$$

$$(C1 = 2.62 \mu F, C2 = 17.2 \mu F.)$$

cccccc

4. Consider the figure below. (Due to the nature of this problem, do not use rounded intermediate values—including answers submitted in WebAssign—in your calculations.)

(a) Find the charge stored on each capacitor in the figure shown above ($C1 = 18.5 \mu F$, $C2 = 8.16 \mu F$) when a 1.50 V battery is connected to the combination. $Q1 = C$ $Q2 = C$ $Q3 = C$

(b) What energy is stored in each capacitor? $E1 = J$ $E2 = J$ $E3 = J$

dddddddd

5. What total energy is stored in the capacitors in the figure below if 1.80 10

-4 J is stored in the $2.50 \mu F$ capacitor? (Enter your answer to at least three significant figures.) J

Chapter 6

Resistance

6.1 Resistivity and Conductivity

Resistivity is a fundamental property of a material that quantifies its opposition to the flow of electric current. It is denoted by the Greek letter ρ (rho). A material with high resistivity strongly resists current flow, while a material with low resistivity conducts current easily. The SI unit of resistivity is the ohm-meter ($\Omega \cdot m$).

Conductivity, the reciprocal of resistivity, measures a material's ability to conduct electricity. It is represented by the Greek letter σ (sigma). Materials with high conductivity offer little resistance to current flow.

6.2 Resistance

The resistance of a conductor depends on its resistivity (ρ), length (L), and cross-sectional area (A).

Resistance can be easily calculated using the formula:

$$R = \rho \frac{L}{A}$$

This equation shows that resistance is directly proportional to the length of the conductor and inversely proportional to its cross-sectional area.

6.3 20B

Suppose an electrical wire is replaced with one having every linear dimension doubled (i.e., the length and radius have twice their original values). How is the resistance of the wire affected?

The wire has less resistance than before.

The wire has more resistance than before.

The wire has the same resistance as before. dddddd

All electric devices are required to have identifying plates that specify their electrical characteristics. The plate on a certain steam iron states that the iron carries a current of 6.00 A when connected to a source of 1.20×10

2 V. What is the resistance of the steam iron?

20.0 Ω 36.0 Ω 0.050 Ω

What current flows through a 2.93 cm diameter rod of pure silicon that is 22.0 cm long, when 1000 V is applied to it? (Such a rod may be used to make nuclear particle detectors, for example.) The resistivity of pure silicon is $2.30 \times 10^3 \Omega \cdot \text{m}$.

6.4 20C

nnnnn

Resistance depends on the geometry of a conductor as well as on what the conductor is made from, but it also depends on temperature (although we will often neglect this).

To understand the temperature dependence, consider a simple model of resistance. Electrons flowing through a conductor are impeded by atoms and molecules. The more these atoms and molecules bounce around, the harder it is for the electrons to get by. Thus, resistance generally increases with temperature.

For small temperature changes the resistivity varies linearly with temperature:

$$r = r_0 (1 + \alpha \Delta T) ,$$

where α is the temperature coefficient of resistivity.

We often write this in terms of resistance instead:

$$R = R_0 (1 + \alpha \Delta T) ,$$

which means we're assuming that length and area don't change as temperature changes. Generally the linear expansion coefficient is much less than the temperature coefficient of resistivity, which is why we can get away with this assumption.

In some materials (like silicon) the temperature coefficient of resistivity is negative, meaning the resistance goes down as temperature increases. In such materials an increase in temperature can free more charge carriers, which would be associated with an increase in current.

This can be exploited to make a resistor with a resistance that is almost independent of temperature. The resistor is made from two resistors placed in series. One resistor has a positive temperature coefficient, and the other has a negative temperature coefficient. The resistance values are chosen so that when the temperature changes, the increase in resistance experienced by one resistor is offset by the decrease in resistance experienced by the other.

nnnnn

If a certain silver wire has a resistance of $10.00\ \Omega$ at 18.0°C , what resistance will it have at 32.0°C ? Ω

cccc

A copper wire has a resistance of $0.520\ \Omega$ at 20.0°C , and an iron wire has a resistance of $0.546\ \Omega$ at the same temperature. At what temperature are their resistances equal? The temperature coefficient of resistivity for copper is $3.90 \times 10^{-3}\ (^{\circ}\text{C})^{-1}$ and for iron it is $5.00 \times 10^{-3}\ (^{\circ}\text{C})^{-1}$.

Chapter 7

Circuits

Electric Circuits: A Correction An electric circuit is a network of interconnected components through which electric current can flow. This network can consist of one or multiple closed loops.

Closed Loop: A closed loop is a continuous path for current to flow, starting from a voltage source, passing through components, and returning to the source. **Open Circuit:** A circuit without a complete path for current to flow is considered open.

Essential components of a circuit include:

Voltage source: Provides the energy to drive the electric current (e.g., battery, generator). **Load:** Consumes electrical energy and converts it into another form (e.g., light bulb, motor). **Conductor:** Material that allows electric current to flow easily (e.g., copper wire). **Switch:** A device to control the flow of electric current (e.g., on/off switch). For a circuit to function, it must form a complete loop. If the circuit is broken, the flow of current stops.

Key Concepts:

Electric current: The flow of electric charge through a conductor. **Voltage:** The electric potential difference between two points in a circuit. In the simplest case of linear circuits we

also have Passive Circuit elements

A passive element in a circuit is a component that does not generate power but instead consumes, stores, or releases electrical energy. Unlike active elements (like transistors or diodes) which can amplify or control signals, passive elements are fundamental building blocks in electronic circuits.

Types of Passive Elements Resistors: These components oppose the flow of electric current and convert electrical energy into heat. They are characterized by their resistance (measured in ohms, Ω). Capacitors: These components store electrical energy in an electric field. They consist of two conductive plates separated by an insulator. Capacitance is measured in farads (F). Inductors: These components store energy in a magnetic field. They typically consist of a coil of wire. Inductance is measured in henries (H). Transformers: While often categorized as passive components, transformers actually transfer electrical energy from one circuit to another, typically with a change in voltage or current. These passive elements are essential for shaping the behavior of circuits, filtering signals, and performing various functions in electronic systems.

To analyze and calculate the voltages and currents within intricate electrical circuits, we rely on a fundamental set of principles known as Kirchhoff's rules. These rules, derived from the conservation of charge and energy, provide a systematic approach to solving circuit problems. Complex circuits, characterized by multiple interconnected components and loops, require these rules to determine the behavior of the circuit and its constituent elements.

Kirchhoff's rules consist of two main laws:

Kirchhoff's Current Law (KCL): The algebraic sum of currents entering a junction (node) in a circuit equals the sum of the currents leaving that junction. This law reflects the conservation of charge. Kirchhoff's Voltage Law (KVL): The algebraic sum of all potential differences around any closed loop in a circuit must equal zero. This law is based on the conservation of energy. By applying these rules in conjunction with Ohm's Law and the characteristics of individual circuit

components, we can solve for unknown currents, voltages, and resistances within a circuit.

..... Resistance: The opposition to the flow of electric current. Ohm's Law, a fundamental relationship in circuit analysis, relates these quantities:

$$V = IR$$

where:

V is the voltage I is the current R is the resistance We will explore these concepts in more detail in the following sections.

7.1 Kirchhoff's Rules

Kirchhoff's first rule (the junction rule) applies to the charge entering and leaving a junction. A junction, or node, is a connection of three or more wires. Current is the flow of charge, and charge is conserved; thus, whatever charge flows into the junction must flow out.

$$\boxed{\sum_{\text{incoming currents}} i_{in} = \sum_{\text{outgoing currents}} i_{out}}$$
$$i_1 + i_2 + i_4 + i_5 = i_3 + i_6$$

Kirchhoff's second rule (the loop rule) applies to potential differences. The loop rule is stated in terms of potential V rather than potential energy, but the two are related since $U = qV$. In a closed loop, whatever energy is supplied by a voltage source, the energy must be transferred into other forms by the devices in the loop, since there are no other ways in which energy can be transferred into or out of the circuit.

Kirchhoff's loop rule states that the algebraic sum of potential differences, including voltage supplied by the voltage sources and resistive elements, in any loop must be equal to zero.

7.2 Conventions

In order to apply Kirchoff's rules a sign convention must be established.

A voltage source causes current to flow within the source in the direction from the negative to the positive terminal or out of the positive terminal and into the negative terminal.



Figure 7.1: poner fig 2.2 Van Valkenburg P28



Figure 7.2: poner fig 2.3 Van Valkenburg P28

If the negative terminal is used as a reference in measuring the potential of the positive terminal of a potential source, that voltage is considered positive and is spoken of as a voltage rise. Conversely, if the positive terminal is considered to be the reference in measuring the potential of the negative terminal of the voltage source, the voltage is considered negative and is spoken of as a voltage drop.



Figure 7.3: poner dibujito ejemplo del pdf de los circuitos cagones, ya no se de donde lo saqué.

$$v_a - v_1 - v_b - v_2 - v_3 = 0$$

$$v_a - R_1 i - v_b - R_2 i - R_3 i = 0$$

$$\begin{cases} in & i_1, i_3 \\ out & i_2, i_4, i_5 \end{cases}$$

$$i_1 + i_3 = i_2 + i_4 + i_5$$

7.2.1 Voltage Divisor

$$v - R_1 i - R_2 i - R_3 i = 0$$

$$v_1 = R_1 i$$

$$v_1 = \frac{R_1}{R_1 + R_2 + R_3} v$$

7.2.2 Circuitico de ejemplo

$$i_1 = i_2 + i_3$$

$$pabp : \quad 20V - 5\Omega i_1 - 10\Omega i_3 = 0$$

$$qbaq : \quad -8V + 10\Omega i_3 - 2\Omega i_2 = 0$$

ttttt

$$i_1 - i_2 - i_3 = 0$$

$$5 i_1 + 10 i_3 = 20$$

$$10 i_3 - 2 i_2 = 8$$

$$15 i_1 - 10 i_2 = 20$$

$$10 i_1 - 12 i_2 = 8$$

$$i_1 = 2A, i_2 = 1A, i_3 = 1A$$

7.2.3 Current Divisor

At node p there are 3 current, i which is incoming, i_1 that goes out through R_1 and say i_4 that goes to node q

At node q we also have 3 currents, i_4 that arrives, i_2 that goes to R_2 and i_3 that goes to R_3 .

According to Kirchhoff's laws

$$i = i_1 + i_4, \quad i_4 = i_2 + i_3$$

therefore

$$i = i_1 + i_2 + i_3,$$

but:

$$i_1 = \frac{v}{R_1}, i_2 = \frac{v}{R_2} \text{ and } i_3 = \frac{v}{R_3}$$

so

$$\frac{i_1}{i} = \frac{v/R_1}{v(1/R_1 + 1/R_2 + 1/R_3)} = v \frac{1/R_1}{v(1/R_1 + 1/R_2 + 1/R_3)}$$

$$\boxed{\frac{i_1}{i} = \frac{R_2 R_3}{R_2 R_3 + R_1 R_3 + R_1 R_2}}$$

[ejemplos de pinga](#)

Chapter 8

AC Current

Unlike direct current (DC), where the flow of electric charge is constant in magnitude and direction, alternating current (AC) is characterized by its periodic reversal in direction. This oscillatory behavior is crucial for the efficient transmission of electrical energy over long distances.

AC power sources, such as those found in homes and businesses, generate voltage that varies sinusoidally with time. This alternating voltage drives an alternating current through electrical circuits. The frequency of this alternation, typically 50 or 60 Hertz (Hz), determines the number of complete cycles per second. The key parameters describing AC waveforms include peak voltage, peak current, root mean square (RMS) voltage and current, and phase angle.

The widespread use of AC power is attributed to its advantages in power generation, transmission, and distribution. Transformers, devices that efficiently increase or decrease AC voltages, are essential components in the electrical power grid.

A typical AC voltage source can be represented by the following equation:

$$V(t) = V_m \sin(\omega t + \phi)$$

Where:

$V(t)$ is the instantaneous voltage at time t V_m is the peak voltage (amplitude) ω is the angular frequency (in radians per second), t is time and ϕ is the phase angle (in radians) This equation describes a sinusoidal waveform with a peak value of V_m , oscillating at a frequency

$$f = \frac{\omega}{2\pi} \text{ cycles/s},$$

and with an initial phase shift of ϕ radians.

An important concept in alternating current is that of **RMS Voltage**, this is the effective value of AC voltage. RMS (Root Mean Square) voltage expresses the effectiveness of an alternating current (AC) voltage in delivering power to a load. It's essentially the equivalent DC voltage that would produce the same amount of heat in a resistor.

For a sinusoidal AC voltage waveform, the RMS voltage (V_{rms}) is related to the peak voltage (V_m) by the following formula:

$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

Example: If the peak voltage of an AC waveform is 100 volts, the RMS voltage would be approximately 70.7 volts ($\frac{\sqrt{2}}{2} 100 V$).

RMS voltage is used in power calculations for AC circuits. Most AC voltmeters display RMS values. Understanding RMS voltage is crucial for working with AC power systems and electronics. By converting AC voltages to their RMS equivalents, we can apply DC power calculation formulas and obtain meaningful results for AC circuits.

8.1 Probs

1. What power (in kW) is supplied to the starter motor of a large truck that draws 225 A of current from a 23.5 V battery hookup?

We can use the formula for electrical power:

$$Power = Voltage \times Current$$

Substituting the given values:

$$P = 23.5 V \times 225 A = 5287.5 Watts$$

To convert Watts to kilowatts, we divide by 1000, so

$$Power(kW) = 5287.5 Watts / 1000 = 5.2875 kW$$

2. A hair dryer has a switch that allows it to be used in the US (where the voltage is 120 V) and in Europe (where the voltage is 230 V). It accomplishes this by having two different resistance settings. When the switch is in the “120 V” position, the hair dryer uses a resistance value that allows it to operate at its rated power of 1520 W when connected to 120 V, and when the switch is in the “230 V” setting, the hair dryer uses a resistance that allows it to still operate at its rated power of 1520 W when connected to 230 V.

A tourist takes their 1520 W dual voltage hair dryer to Europe but forgets to set the switch to the “230 V” position. When they plug it into the 230 V receptacle and turn it on, it begins to smoke. What power does the hair dryer consume as a result of this mistake?

Since power can be calculated by the formula

$$Power(P) = V^2/R,$$

the resistance required for the operation under the desired conditions is

$$R = \frac{(120 V)^2}{1520 W} = 9.47 \Omega$$

The power consumption at 230 V with the resistance just found is

$$P = \frac{(230 \text{ V})^2}{9.47 \Omega} = 5588.6 \text{ Watts}$$

or nearly 5.59 kW when incorrectly used in Europe.

This significantly exceeds the rated power of the hair dryer, explaining why it would smoke due to overheating.

Note: This calculation assumes that the resistance of the hair dryer remains constant, which might not be entirely accurate due to factors like temperature dependence. However, it provides a good approximation of the increased power consumption.

3. Two lightbulbs are each connected to a voltage of 120 V. One has a power of 25 W, the other 100 W.

Which bulb has the higher resistance?

Which bulb carries more current? 25 W bulb 100 W bulb

Which bulb has the higher resistance? The 25 W bulb has the higher resistance.

We know that

$$Power = \frac{Voltage^2}{Resistance} .$$

Since both bulbs have the same voltage (120V), the bulb with lower power must have higher resistance to compensate for the lower power output.

The 100 W bulb carries more current. Indeed,

$$Power = Voltage \times Current .$$

Since both bulbs have the same voltage, the bulb with higher power must have higher current to produce that higher power output.

4. A battery of voltage V delivers power P to a resistor of resistance R connected to it. By what factor will the power delivered to the resistor change if the following changes are made? Give your answers as a factor of the original power P .

(a) The resistance is changed to $2.60R$.

We use the power formula: $P = V^2/R$

When the Resistance is changed to $2.60R$ the power is changed to

$$P' = \frac{V^2}{(2.60R)} = \frac{P}{2.60},$$

therefore, the power changes by a factor

$$F = \frac{P'}{P} = \frac{1}{2.60},$$

that is a power decreases by a factor of $1/2.60$.

(b) The voltage of the battery is now $2.60V$, but the resistance is R .

Voltage changed to $2.60V$, resistance unchanged

$$\text{New power} = P' = (2.60V)^2/R = 6.76 P$$

$$\text{Factorchange} = P'/P = 6.76,$$

Power increases by a factor of 6.76 .

(c) The resistance is $2.60R$ and voltage is $2.60V$.

$$\text{New power} = P' = (2.60V)^2/(2.60R) = 2.60 P$$

$$\text{Factorchange} = P'/P = 2.60,$$

For a power increase of 2.60.

(d) Resistance changed to $2.60R$ and voltage changed to $V/2.60$

$$\text{New power} = P' = (V/2.60)^2 / (2.60R) = P / (2.60)^3$$

$$\text{Factor change} = P' / P = 1 / (2.60)^3$$

For a power decrease of $1/(2.60)^3$.

Summary of Results:

(a) Power decreases by a factor of $1/2.60$.

(b) Power increases by a factor of 6.76.

(c) Power increases by a factor of 2.60.

(d) Power decreases by a factor of $1/(2.60)^3$.

5. When an AC source is connected across a 16.0Ω resistor, the output voltage is given by

$$V = 120 \text{ Volt } \sin(80\pi t).$$

Determine the following quantities.

The delivered information consists on the resistance ($R = 16.0, \Omega$) and the voltage source formula. From there we can read

(a) Maximum Voltage (V_m), or amplitude is:

$$V_m = 120 \text{ V}$$

(b) RMS Voltage (V_{rms})

For the RMS voltage we just multiply the amplitude by the appropriate factor

$$V_{rms} = \frac{\sqrt{2}}{2} V_m \approx 84.85, V$$

(c) RMS Current (I_{rms})

This is trivially determined by using Ohms law on the rms voltage, i.e.

$$I_{rms} = V_{rms}/R$$

$$I_{rms} = 84.85V/16.0\Omega \approx 5.30A$$

(d) Peak Current (I_p).

Since the resistor is a linear component, the current and voltage waveforms will have the same shape. Therefore, the peak current is related to the RMS current by the same factor as the peak voltage to RMS voltage:

$$I_p = \sqrt{2} I_{rms}$$

$$I_p = 5.30A\sqrt{2} \approx 7.50 A$$

(e) Current at $t = 0.0045$ s

First, we need to find the instantaneous voltage at $t = 0.0045$ s:

$$V = (120 V)\sin(80\pi 0.0045) \approx 97.98V$$

Then, using Ohm's law: $I = V/R$,

$$I = \frac{97.98 V}{16.0 \Omega} \approx 6.12A$$

Therefore, the current at $t = 0.0045$ s is approximately
6.12 A.

6. An AC voltage source is connected to a resistor ($R = 1.70E2 \Omega$). The resistor is connected to an AC voltage source whose output is given by the expression

$$(1.00E2 V) \sin 2\pi f t.$$

- (a) What is the rms voltage across the resistor?

Since the resistor is connected to the source and no more components are present, the voltage across the resistor is equal to the voltage of the source, therefore the RMS Voltage is calculated as:

$$V_{rms} = V_m / \sqrt{2}.$$

From the given voltage expression, we can read the peak voltage, $V_m = 170, V$.

Therefore,

$$V_{rms} = 170. / \sqrt{2} V = 120.2 V.$$

- (b) What is the rms current flowing through the resistor?

7. An AC voltage source and a resistor are connected in series to make up a simple AC circuit. If the source voltage is given by

$$V(t) = V_0 \sin(2\pi f t)$$

and the source frequency is 15.7 Hz, at what time t will the current flowing in this circuit be 71.0% of the peak current?

The angular frequency of the source is

$$\omega = 2\pi f = 2\pi \times 15.7 \text{ Hz} \approx 98.96 \text{ rad/s}$$

Since the circuit contains only a resistor, the current and voltage are in phase, this means that the current as a function of time is given by:

$$I(t) = I_{peak} \sin(\omega t)$$

We want to find the time when

$$I(t) = 0.71 I_{peak} ,$$

meaning that we want to solve the elementary trigonometric equation

$$0.71 I_{peak} = I_{peak} \sin(\omega t)$$

with solution

$$\omega t = \arcsin(0.71)$$

which in turn yields

$$t = \frac{\arcsin(0.71)}{98.96 \text{ rad/s}} \approx 0.0072 \text{ s}$$

so, the current will be 71% of its peak value at approximately 7.2 milliseconds.

Note: There are multiple solutions to the equation $\sin(\omega t) = 0.71$ within one period of the waveform. However, we've found the first instance where the current reaches 71% of its peak value.

Appendix A

Description of the Course

LEARNING OUTCOMES

1. Upon successful completion of this course, students should be able to:
2. Analyze the behavior of electric fields, electric potential and electric forces associated with electric charges.
3. Determine the current, voltage and power of AC and DC circuits that include power sources, resistances, capacitors, inductors and transformers.
4. Describe magnetic fields from currents and permanent magnets and determine the magnetic forces on moving charges and currents and determine the magnetic torque on a coil.
5. Apply Faraday's and Lenz's Laws to calculate induced currents and voltages.
6. Describe the properties of light waves and the geometric behavior of light rays associated with reflection, refraction, dispersion and total internal refraction.

7. Describe quantum mechanical phenomena including blackbody radiation, the photoelectric effect, the wave nature of matter and the uncertainty principle.
8. Determine emission and absorption spectra associated with atomic physics.

COURSE TOPICS Planned physics topics for this course include:

1. Planned physics topics for this course include:
2. Electric Charge
3. Insulators, Conductors & Polarization
4. Electric Force
5. Electric Fields
6. Electric Field Lines
7. Conductors in Static Equilibrium
8. Uniformly Charged Spheres
9. Electric Potential
10. Equipotential Lines
11. Capacitors and Capacitance
12. Capacitors in Series & Parallel
13. Solving Capacitor Circuits
14. Electric Current

15. Resistance
16. Ohm's Law
17. Electric Power
18. AC vs DC Circuits
19. Resistances in Series/Parallel
20. Home Wiring and Electrical Hazards
21. Battery emf & Internal Resistance
22. Kirchhoff's Circuit Rules
23. Metering
24. RC Circuits
25. Magnetism
26. Magnetic Fields & Field Lines
27. Magnetic Force on a Charge
28. Motion of a Charge in a B-field
29. Magnetic Force on a Wire
30. Torque on a Current Loop & Motors
31. Magnetic Fields from Current
32. Magnetic Force Between Parallel Wires

- 33. Induced emf & Magnetic Flux
- 34. Faraday's Law
- 35. Motional emf
- 36. Generators
- 37. Transformers
- 38. Inductance & Inductors
- 39. RL Circuits
- 40. Maxwell's Equations & EM Spectrum
- 41. Sources and Properties of EM Waves
- 42. Power and Intensity of EM Waves
- 43. Doppler Effect
- 44. Geometric Optics & Reflection
- 45. Index of Refraction & Snell's Law
- 46. Total Internal Reflection
- 47. Dispersion
- 48. Images by Thin Lenses
- 49. Images by Mirrors

COURSE MATERIALS

Required Textbook and/or Software College Physics -Urone/Hinrichs. 2nd Edition Hardcover: ISBN-13: 978-1-711470-83-2; Paperback: ISBN-13: 978-1-711470-82-5

[Web Link](#) Cost: The electronic version is free. Printed copies of the textbook may be purchased from the OpenStax College website (approximately \$50 new) or the NCSU bookstore (approximately \$40 used).

WebAssign License for Homework (approximately \$50) This expense is required.

WebAssign License for Laboratory (approximately \$50) This expense is required.