

Chapter 11 COULOMB'S LAW, ELECTRIC FIELDS, AND ELECTRIC POTENTIAL

In the last chapter we studied the qualitative relationship between charges: that like charges repel and unlike charges attract. Now we will determine the exact way that the electric force behaves, as expressed in Coulomb's law. In this law we meet another INVERSE SQUARE relationship, similar to Newton's law of gravity, with the profound difference that electric forces are both attractive and repulsive while the gravitational forces are only attractive. If by analogy we call mass GRAVITATIONAL CHARGE, then there is only one kind of gravitational charge, where there are two kinds of electrical charge.

Just as we considered any mass (like the earth) to have a gravitational field and a gravitational potential energy associated with it, we will find that any charged object will have an associated electric field and an electric potential energy.

PERFORMANCE OBJECTIVES

After completing this chapter, you should:

1. Recognize that like charges repel and unlike charges attract.
2. a. State Coulomb's law: $F = kq_1q_2/R^2$ where the force is in Newtons, the charges are in Coulombs and the distance between them is in meters, where $k = 9.0 \times 10^9 \text{ N-m}^2/\text{coulomb}^2$.
b. Solve problems using Coulomb's Law
c. To add electric force vectors that are coplanar.
3. a. Define electric force fields
b. Describe (with the aid of a diagram) the electric force field:
(1) about a single charged metal sphere;
(2) between two oppositely charged parallel metal plates.
4. Write the equation which describes the potential energy stored in a system consisting of two point charges as a function of q_1 , q_2 , and R , and solve problems using this equation.
5. Compare $U_E = kq_1q_2/R$ to $U_g = -Gm_1m_2/R$
6. Write the equation which describes electric potential of a system of a point charge as a function of 'q' and 'R' and solve problems using this equation.

1. Experiment 18 THE FORCE BETWEEN TWO CHARGED SPHERES

- a. Have instructor demonstrate experimental apparatus using the overhead projector.
- b. You may wish to now proceed to the next item, view the film and then decide if you wish to accept the fact that the force between two charged objects is inversely proportional to the square of the distance between them or to do Experiment to see for yourself that it is indeed true.

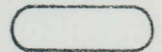
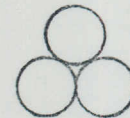
2. Film: COULOMB'S LAW 30 min [Film notes enclosed.]

3. Read: Section 11-1 Force vs Distance page 215

4. Problems: page 216: #1 #2
page 234: #23

5. Read: Section 11-2 Coulomb's Law page 216

6. You have encountered charged sharing between two objects using the idea of symmetry. Do you understand how this works? To be sure, predict the location of 15 negative charges on the two arrangements. To check your prediction, obtain three graphite coated spheres, arrange them as shown, give them a negative charge and compare their charge using an electroscope. When finished, discuss your findings with the instructor.



7. Problems: page 217: #4 #5
page 234: #24 #25

8. Read: Section 11-3 Electric Fields page 218

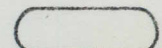
- a. The origin of the equation $\vec{F} = k \cdot q \cdot Q / r^2$ was discussed in Section 11-2. What do the following represent?

q = _____
Q = _____
r = _____

- b. An electric field is represented by the symbol _____, is a (vector - scalar) quantity, points in the direction of _____ and is defined using the electrical force and charge as $\vec{E} = \frac{\vec{F}}{q}$.

- c. Thus for a POINT CHARGE, $\vec{E} = \frac{k \cdot Q}{r^2}$, and has a direction of _____

- d. Summarize your understanding of (1) electric field, (2) electric field lines in written form. Then have it evaluated by your instructor.



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9. Optional...Film ELECTRIC FIELDS 25 min [Film notes provided.]

10. Problems: page 219: #6 #7 #8
page 234: #26

11. Complete enclosed quiz for Sections 1, 2, and 3. Then have it evaluated.

12. Your instructor suggests that you skip over Sections 11-4 and 11-5. The main purpose of these sections is to show:

- a. that the constant field between parallel plates is a direct result of Coulomb's Law.
- b. that the electric field lines and thus the electric field is perpendicular to parallel plates, and
- c. that the magnitude of this electric field is constant.

13. Read Section 11-6 Electric Potential page 227

- a. Electric Potential Energy is represented by the symbol _____, is expressed with units _____ and is a (vector - scalar).
- b. For a POINT CHARGE "q", the potential energy is calculated using the formula _____ where "Q" represents _____.
- c. What information must be known to determine if the potential energy increases or decreases as the objects move apart or closer together?
- d. At what separation is the potential energy identified as zero for:
 - (1) two like charges
 - (2) two unlike charges

14. Electric potential (electric potential energy per unit charge) is introduced to help us understand how batteries and power sources are identified by the potential difference they provide.

- a. Electric potential is represented by symbol _____ has units of _____ per _____ which is known as a _____. It is a (vector - scalar).
- b. For a point charge, the electric potential is calculated using the formula $V = \frac{kQ}{r}$.
- c. Thus electric potential represents the _____ per unit of _____ at distance _____ from the source of the electric field (Q).

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15. As previously stated, potential difference is how energy sources are identified.
- a. Potential difference V is calculated by finding the difference in potential between 2 different locations (for point charges).
 - b. Thus $\Delta V = V_f - V_i$. Knowing that $\Delta V = U_E/q$, we can say that $\Delta V = U_E/q - U_E/q = \Delta U_E/q$.
 - c. Therefore potential difference equals change in electric potential energy per unit charge.
 - d. We can now say that if the potential difference is 12 volts for a car battery then _____joules of energy is supplied to 1 coulomb of charge that enters the circuit.

16. Problems: page 229: #16 #17 #18

17. Read: Section 11-7 The Constant In Coulomb's Law page 229

18. Film COULOMB'S FORCE CONSTANT 34 min [Film notes provided.]

a. Professor Rogers reasons and then demonstrates that:

- (1) the force on a charged sphere placed midway between the plates is independent of the area of the plates.
- (2) the force on a charged sphere is inversely proportional to the plate separation, and
- (3) the force on a charged sphere is directly proportional to the number of batteries supplying the charges to the parallel plates.

Note...Do not fall asleep (mentally). The ideas are critical.

(4) Next the number of charges on a sphere is determined and finally,

(5). the constant 'k' is calculated.

b. As a final exercise, Professor Rogers contrasts the gravitational attraction and the electrical attraction for two objects.

19. Problems: page 233: #19 #20 #21 #22
page 235: #29 #30

20. Complete enclosed 1-page written exercise. Then have it evaluated.

Chapter 11 Answers

4. (1) 1.0×10^{-5} N
 (2) (a) 1.2×10^{-5} N (b) 9×10^{-6} N to the left
 (23) (a) 1.8×10^{-6} N, to right (b) 4.4×10^{-6} N (the direction is ___?)
7. (4) (a) 0.91 kqQ/r^2 (b) all will move toward the center
 (5) (a) 1.5×10^{-5} N to the left (b) 2.0×10^{-5} N to the left
 (24) (a) S.A.B. (b) S.A.B. (c) increases by a factor of 8
 (25) (a) increases by a factor of 2.7 (b) S.A.B.
8. (a) q = charge on test object placed in the electric field
 Q = charge on fixed object that gives rise to electric field (usually)
 r = distance between the charged object 'q' and 'Q' (center to center)
 (b) \vec{E} , vector, the force on the '+' test charge, \vec{F}/q
 (c) $E = kQ/r^2$, of the force on a '+' test charge 'q'
10. (6) S.A.B.
 (7) no
 (8) (a) no (b) yes, at the extreme right
 (26) S.A.B.
13. (a) U_e , joules, scalar
 (b) kqQ/r Q is the charge on the object that causes the electric field
 (c) the sign of the charge on both 'q' and 'Q'
 (d) for both situation, it is zero at infinity
14. (a) V, joules/coulomb, volt, scalar
 (b) kQ/r
 (c) energy, charge, r
15. (d) 12
16. (16) and (17) S.A.B.
 (18) 2:1
19. (19) (a) 2×10^{-4} N (b) 6×10^{-4} N
 (20) S.A.B.
 (21) 2.3×10^{-16} N
 (22) 9×10^{-18} N/elem chg pointing toward the object, -5×10^{-18} joule/elem chg
 (29) (a) 3.3×10^{-6} N (b) 1.2×10^{-15} N/elem chg (c) 2.8×10^9 elem charges
 (30) 5.6×10^{11} elementary charges

More questions from "The Flying Circus of Physical Phenomena" by Jearl Walker

1. My grandmother has a lightning rod on her house. She thinks that the purpose of the rod is to attract lightning, so she sticks it up a bit higher than the top of the house. She also thinks that when the lightning hits, the electrical current will travel down the rod. She doesn't understand why the top of the rod is pointed. What do you think?
2. When I was little my mother told me that thunder had something to do with lightning. How is thunder made? Why does the thunder last for such a relatively long time? I've read that if you stand within 100 yards of the lightning flash you first hear a click, then a crack (as a whip cracks), and finally the rumbling. What causes the click and crack? If you're a little further away, you'll hear not the sharp click but a swish.
3. Why is there static on the radio? Why is there less on F.M. radio? Does intensity and frequency of static change with the time of day? With the season? Can you eliminate all static?

TEACHER'S GUIDE TO THE PSSC FILM

Coulomb's Law - (2)

COULOMB'S LAW

(30 min.)

Eric Rogers, Princeton University

Experiments are performed which demonstrate that the force between two charges is proportional to the product of the charges and varies inversely as the square of the distance between them.

Summary:

The qualitative characteristics of electric forces between charges are demonstrated. The student is reminded that he is already familiar with the inverse-square law of light and of gravitation, and it is suggested that the electric force also obeys the same inverse-square law.

To measure the dependence of electric force on distance, a charged sphere is mounted on a beam balance. The force of repulsion by a second similarly charged sphere is measured by a calibrated spring. The distance between the charged spheres is doubled, then tripled, and the force is seen to decrease to one-fourth, then to one-ninth, of the original value. The charge on each sphere is then halved by charge-sharing, and the resultant force decreases to one-fourth the initial value. Thus

Coulomb's law $F \sim \frac{q_1 q_2}{r^2}$ is established.

Professor Rogers argues that if this inverse-square relationship is correct, then the geometry of a charged metallic hollow sphere is such that the sum of the forces due to all the charges on this sphere add up to give no net force on a test charge at any point inside this sphere. This effect is demonstrated.

A further experiment with a huge wire cage shows that this effect is independent of the shape of the conducting enclosure.

Points for Discussion and Amplification:

(a) You will recognize the 'ancient charging device' used by Professor Rogers as an electrophorus plate which can be very strongly charged by induction. If you should have an electrophorus plate available, this is a good place to review charging by induction as discussed in Section 27-5 of the PSSC text.

(b) The students should realize that during the series of experiments that demonstrated the inverse r^2 relationship, the initial charge on the spheres had to be maintained throughout the three experiments. It was not possible to recharge the spheres during the experiments, since the same charge cannot be obtained each time the electrophorus plate is used. Because there is always some charge leakage, it was necessary to do this series as quickly as possible after charging the spheres.

(c) The null experiment used in this film is an example of a technique frequently used in experimentation to obtain greater sensitivity. Professor Rogers performed his precise test for the $\frac{1}{r^2}$ dependence of Coulomb's law by choosing an experiment which gave a null result; i.e., all the forces canceled. This was much easier than the alternative of accurately measuring the force between two charged spheres, which would require a very sensitive balance.

The inverse r^2 dependence of Coulomb's law is known to one part in 10^9 (i.e., the exponent 2 is known to be accurate to one part in 10^9).

(d) Symmetry is used in arguing that the charge on one of the spheres is divided equally with another identical sphere brought in contact with it. It should be pointed out that this argument is independent of the character of the force law between charges. Symmetry arguments are used to explain many physical phenomena.

(e) Professor Rogers asks, "What would gravity be like inside a hollow earth?" The argument would be exactly the same as he used for the hollow charged sphere, since gravity also obeys an inverse-square law. The gravitational force would be zero at any point inside an earth which is a hollow spherical shell. However, there is one important difference that should be emphasized. For gravity the null result requires spherical symmetry, whereas for electric forces the null result will occur inside a conductor of any shape. This is because the charges are free to move and will distribute themselves appropriately on the surface of a conductor until the force on a charge inside the conductor is zero.

(f) When one uses charged metallic spheres instead of an ideal point charge, the charges are free to move on the metallic sphere. Hence, the force between charged spheres is only approximately described by the $\frac{1}{r^2}$ relation. For example, if only one sphere were charged, it would induce an electric dipole on the other, producing an attractive force. Fortunately, the forces due to induced charges are important only at distances closer than those used by Professor Rogers. (See also PSSC Teacher's Guide, Lab. IV-3.)

(g) Students may wonder why the young assistant in the film charged and discharged herself with a rod of wood, which is normally thought of as an insulator. The wood has a very high resistance, so the discharge occurs slowly. She is not injured, since her resistance is much lower than that of the wood; the potential difference across the wood is much higher than across her. Of course the resistance can't be too high or the charge will not flow off in a reasonable time.

(OVER)

TEACHER'S GUIDE TO THE PSSC FILM

ELECTRIC FIELDS

(25 min.)

Francis Bitter, M.I.T., and
John Waymouth, Sylvania Electric Products, Inc.

In this film the characteristics of the electric field in the space around a charge are discussed, and qualitative methods of detecting the magnitude and direction of the field are demonstrated.

Summary:

The concept of a field is introduced as a property of space used to describe various physical problems including electrostatics, magnetism, and gravitation. The discussion then centers on electric fields with the emphasis placed on the forces between point charges. The electric field (\vec{E}) around a charge is defined, at a given point, in terms of the net force (\vec{F}) acting on a test charge (q) at that point: $\vec{E} = \vec{F}/q$.

A field direction indicator (an electric compass consisting of two conducting pith balls on a conducting arm, free to rotate and align itself along the direction of the field) is used to map out the field patterns of several configurations of charges. The absence of an electric field inside a metallic enclosure is also illustrated.

Then, in another demonstration, a long tube with walls containing a conducting liquid is used to show that the interior of the tube is shielded from the field due to fixed external charges, just as occurred in the previous demonstration. When this conductor is connected to a circuit (e.g. a battery), charge flows in the conductor and there is an electric field inside which points in the direction of the current flow. The field of the fixed charges is still shielded by the conducting walls, and the field observed inside is due entirely to the charges continually introduced by the battery.

Finally, oscillating electric fields (radio waves) are shown to induce an alternating current in an antenna which causes a small lamp to glow.

Points for Discussion and Amplification:

(a) In the film the statement was made that when a positive test charge is used, "lines of force originate on a plus charge and terminate on a minus charge." If a negative test charge were used instead, the lines of force would point in the opposite direction. But in either case the direction of the electric field, $\vec{E} = \vec{F}/q$ is the same.

(b) It is interesting to compare the zero field produced in this film with the zero field shown by Professor Rogers in the film *Coulomb's Law*. Professor Rogers used a charged metallic sphere with no field due to external fixed charges. In this film, Professor Bitter used an uncharged metallic enclosure in a field due to fixed external charges. In both cases there was a zero field inside the metallic enclosure and in each case the field was the result of the inverse-square law of force (Coulomb's law). Professor Rogers diagrammed how the zero field occurred inside the charged

Electric Fields - (2)

sphere; in that case the discussion was simplified by the fact that the charge was uniformly distributed on the sphere. The charge distribution was not so simple in the demonstrations shown in this film, but the contribution to the electric field by each charge is still described simply by Coulomb's law. A sample configuration is shown in Fig. 1.

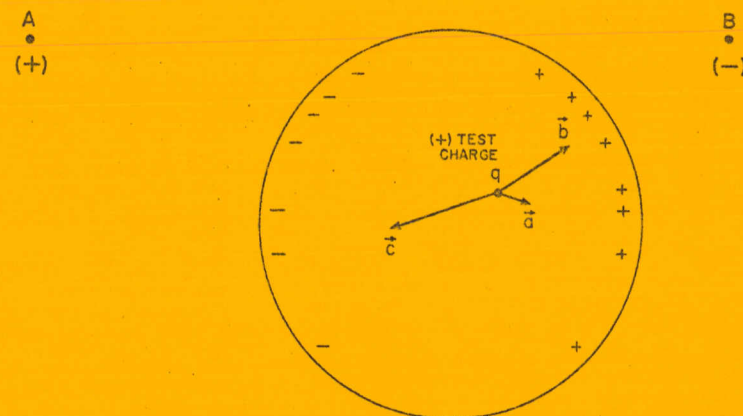


Fig. 1. A metallic cylinder is placed between two equal but opposite charges A and B. Consider all the forces acting on a positive test charge, q , placed inside the cylinder. Vectors \vec{a} and \vec{b} represent the forces on q due to charges A and B. Vector \vec{c} is the resultant force on q due to the distribution of induced charges on the metallic cylinder. $\vec{a} + \vec{b} + \vec{c} = 0$ for any position of q inside the cylinder.

(c) The student may find it easier to understand why there is a field in a conductor when current flows in it by first understanding that there is no field in a conductor when there is no current. You might remind him that the shielding effect of a metallic enclosure occurs because the electrons are free to move about in the conductor and orient themselves so that their distribution will produce an electric field which is just sufficient to cancel the field due to the external charges (see Fig. 1). The resultant distribution of charge on the conductor and the distribution of charge external to the conductor create a net electric field of zero inside the conductor.

When an electric field is imposed by connecting a battery directly across the conducting enclosure, the free electrons will move and tend to be redistributed so as to cancel the imposed field. However, the battery maintains this field in the conductor by continually supplying additional charges. This consistent electric field in the conducting enclosure produces a continual movement of charge - a current. In this film, when the conducting tube was connected to a circuit and current flowed, the field indicators aligned themselves in the direction of the field imposed by the circuit. Any field due to fixed external charges is still shielded by the conducting walls.

(OVER)

1. Three identical metal spheres have equal charges. When they are spaced 10 cm apart along a straight line, the electric forces on the left-hand one is 10^{-5} Newtons.

(a) in which direction?
(b) What is the net electrical force on the center object?
(c) What is the electric force on the right-hand one?

a. _____

b. _____

c. _____

Now, two of the spheres are moved very close together and placed 10 cm from the third. What is the electric force on the third sphere?

d. _____

2. Two equal point charges A and B, are spaced 1 cm apart. They repel each other with a force of 10^{-7} Newtons. A third equal charge, C moves along the perpendicular bisector of the line joining A and B. Find the net force on the third charge C when:

a. C is directly between A and B

b. C is 1 cm from both A and B

c. C is 10 cm from both A and B

a. _____

b. _____

c. _____

3. Two identical metal spheres carry equal positive charges so that they repel each other with a force of 10^{-5} Newtons when they are placed a certain distance apart. A third identical but uncharged sphere is touched first to the one on the left and then to the one on the right and finally is placed midway between the first two. What is the electrical force on the third sphere?

TEACHER'S GUIDE TO THE PSSC FILM

COULOMB FORCE CONSTANT

(34 min.)

Eric Rogers, Princeton University

Professor Rogers determines the value of the Coulomb force constant using a large-scale Millikan apparatus.

Summary:

To determine the constant in Coulomb's force law, ($F = K q_1 q_2 / d^2$), Professor Rogers performs a series of experiments in which he measures the force F repelling two identically charged metal spheres, the distance d between them, and the charge q on each of them.

The student is reminded that the charge q on a small sphere can be determined with a Millikan apparatus. In order to measure the number of elementary charges on the larger spheres used in the experiment, Professor Rogers used an enlarged version of the Millikan apparatus. First he establishes in a series of experiments how to relate the force per elementary charge in the larger apparatus to the force per elementary charge established in the film Millikan Experiment. He demonstrates that (1) the force (measured with a beam balance) on a charged sphere placed midway between the plates does not change when the area of the plates is increased; (2) the force is halved when the plate separation is doubled; (3) the force is doubled when the number of batteries supplying the charge is doubled.

In the film Millikan Experiment three batteries supplied the charge to parallel plates spaced just 3.1 mm apart. In his apparatus Professor Rogers uses a plate separation of 31 cm, giving a force/(elem. ch.) 1/100 of that in Millikan Experiment. Using 300 batteries to supply the charge to the larger plates, the force/(elem. ch.) is then increased by a factor of 100. Thus, in this larger apparatus the force/(elem. ch.) is the same as in Millikan Experiment - 1.4×10^{-14} newtons.

The force of repulsion F between two identically charged spheres separated by a given distance d is measured with the beam balance. To determine the number of elementary charges on the spheres, one of these spheres (still charged) is placed midway between the plates of the scaled-up Millikan apparatus and the electric force on it is measured.

Using these data the constant K in Coulomb's law is calculated.

Points for Discussion and Amplification:

(a) This film should be used after the student has seen the preceding film Millikan Experiment, and has discussed Sections 28-4 and 28-5 of the text.

Coulomb Force Constant - (2)

(b) The principal intent of this film is to determine the value of K , the Coulomb force constant. In this series of experiments Professor Rogers shows that the force per elementary charge varies directly with the number of batteries connected and inversely with the spacing between the plates of the apparatus. This dependence of the electric force need not be greatly emphasized at this point, but the student should at least be aware of it since in succeeding sections of the text and in later films reference will be made to this experimental evidence.

(c) Film data:

Force/(elem. ch.) between plates = 1.4×10^{-14} nt
 Plate separation = 31 cm
 Plate voltage = 27,000 volts (300 90-volt batteries)
 Force on sphere between plates = 35.5×10^{-6} nt
 Separation of spheres = 15 cm

From these data the charge on the sphere is calculated to be 25.4×10^{10} elem. ch., and the force constant K is computed to be 2.34×10^{-28} nt-m²/(elem. ch.)². (In this film Professor Rogers estimates these numbers as 25×10^{10} and 2.4×10^{-28} .)

(d) When a charge is brought near a conductor, it is attracted to the conductor because of the induced charges on the latter. Since the charge on the spheres in these experiments is large (10^{10} elem. ch.), the sphere is attracted by a relatively large force. Professor Rogers was careful to place the charged sphere midway between the plates. In this position the forces due to induced charges canceled because of symmetry.

This was not a cause for concern in the original Millikan experiment because the induction effects of the few units of charge on that sphere had negligible effect on the charge distribution on the plates.

(e) The charging mill used in this film is similar to that described in the PSSC Teacher's Guide, page D-1.

(f) An electrophorus plate was used in this film to charge the spheres, just as in the film Coulomb's Law.

Chapter 11 Written Exercise

1. (a) How does the force between two charged particles change if each charge is halved and their distance is now three times greater?
 (b) What if the charge of each is doubled and the distance apart is doubled?

a. _____

b. _____

2. Two small spheres are supposed to be given a charge of +1 coulomb each: their centers are 1 meter apart.

a. Compute the electrostatic force on either sphere.

b. Is this a feasible experiment? Why or why not?

a. _____

b. _____

3. A small ball of mass 4.6×10^{-5} kg and bearing a charge of +4 elementary charges is at a distance 'r' from a small fixed object having a charge of -6 elementary charges. Assume that the resulting electrostatic force is the only appreciable force acting on the ball, compute the acceleration of the ball at the moment when:
 (a) $r = 0.08$ m (b) $r = 0.04$ m

a. _____

b. _____

4. Three fixed pithballs $q_1 = 4$ elementary charges, $q_2 = 3$ elementary charges, and $q_3 = -2$ elementary charges form the vertexes of a right triangle as shown. Find the net electrical force on q_1 .

