Summary

The **electric potential** V at any point in space is defined as the electric potential energy per unit charge:

$$V_a = \frac{\text{PE}_a}{q}. \tag{17–2a}$$

The **electric potential difference** between any two points is defined as the work done to move a 1 C electric charge between the two points. Potential difference is measured in volts (1 V = 1 J/C) and is sometimes referred to as **voltage**.

The change in potential energy when a charge q moves through a potential difference V_{ba} is

$$\Delta\text{PE} = qV_{ba}. \tag{17–3}$$

The potential difference V_{ba} between two points a and b where a uniform electric field E exists is given by

$$V_{ba} = -Ed, \tag{17–4a}$$

where d is the distance between the two points.

An **equipotential line** or **surface** is all at the same potential, and is perpendicular to the electric field at all points.

The electric potential at a position P due to a single point charge Q, relative to zero potential at infinity, is given by

$$V = \frac{kQ}{r}, \tag{17–5}$$

where r is the distance from Q to the position P.

[*The potential due to an **electric dipole** drops off as $1/r^2$. The **dipole moment** is $p = Ql$, where l is the distance between the two equal but opposite charges of magnitude Q.]

A **capacitor** is a device used to store charge (and electric energy), and consists of two nontouching conductors. The two conductors can hold equal and opposite charges, of magnitude Q, and the ratio of this charge to the potential difference V between the conductors is called the **capacitance**, C:

$$C = \frac{Q}{V}, \quad \text{or} \quad Q = CV. \tag{17–7}$$

The capacitance of a parallel-plate capacitor is proportional to the area of each plate and inversely proportional to their separation:

$$C = \epsilon_0 \frac{A}{d}. \tag{17–8}$$

The space between the two conductors of a capacitor contains a nonconducting material such as air, paper, or plastic; these materials are referred to as **dielectrics**, and the capacitance is proportional to a property of dielectrics called the **dielectric constant**, K (nearly equal to 1 for air).

A charged capacitor stores an amount of electric energy given by

$$\text{PE} = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}. \tag{17–10}$$

This energy can be thought of as stored in the electric field between the plates.

The energy stored in any electric field E has a density (energy per unit volume) of

$$\frac{\text{PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2. \tag{17–11}$$

[*Television and computer monitors traditionally use a **cathode ray tube** (CRT) that accelerates electrons by high voltage, and sweeps them across the screen in a regular way using deflection plates.]

[*An **electrocardiogram** (EKG or ECG) records the millivolt potential changes of each heart beat as the cells depolarize and repolarize, and displays these changes on a monitor screen or chart recorder printout.]

Questions

1. If two points are at the same potential, does this mean that no work is done in moving a test charge from one point to the other? Does this imply that no force need be exerted? Explain.
2. If a negative charge is initially at rest in an electric field, will it move toward a region of higher potential or lower potential? What about a positive charge? How does the potential energy of the charge change in each instance?
3. State clearly the difference (*a*) between electric potential and electric field, (*b*) between electric potential and electric potential energy.
4. An electron is accelerated by a potential difference of, say, 0.10 V. How much greater would its final speed be if it is accelerated with four times as much voltage? Explain.
5. Is there a point along the line joining two equal positive charges where the electric field is zero? Where the electric potential is zero? Explain.
6. Can a particle ever move from a region of low electric potential to one of high potential and yet have its electric potential energy decrease? Explain.
7. Compare the kinetic energy gained by a proton ($q = +e$) to the energy gained by an alpha particle ($q = +2e$) accelerated by the same voltage V.
8. If $V = 0$ at a point in space, must $\vec{\mathbf{E}} = 0$ there? If $\vec{\mathbf{E}} = 0$ at some point, must $V = 0$ at that point? Explain. Give examples for each.
9. Can two equipotential lines cross? Explain.
10. Draw in a few equipotential lines in Fig. 16–31b.
* 11. What can you say about the electric field in a region of space that has the same potential throughout?
12. A satellite orbits the Earth along a gravitational equipotential line. What shape must the orbit be?
13. When dealing with practical devices, we often take the ground (the Earth) to be 0 V. If, instead, we said the ground was −10 V, how would this affect (*a*) the potential V, and (*b*) the electric field E, at other points?
14. When a battery is connected to a capacitor, why do the two plates acquire charges of the same magnitude? Will this be true if the two conductors are different sizes or shapes?
15. We have seen that the capacitance C depends on the size, shape, and position of the two conductors, as well as on the dielectric constant K. What then did we mean when we said that C is a constant in Eq. 17–7?

Problems

17–1 to 17–4 Electric Potential

1. (I) How much work does the electric field do in moving a $-7.7\,\mu C$ charge from ground to a point whose potential is $+55$ V higher?
2. (I) How much work does the electric field do in moving a proton from a point with a potential of $+125$ V to a point where it is -55 V? Express your answer both in joules and electron volts.
3. (I) How much kinetic energy will an electron gain (in joules and eV) if it accelerates through a potential difference of 23,000 V in a TV picture tube?
4. (I) An electron acquires 7.45×10^{-16} J of kinetic energy when it is accelerated by an electric field from plate A to plate B. What is the potential difference between the plates, and which plate is at the higher potential?
5. (I) How strong is the electric field between two parallel plates 5.8 mm apart if the potential difference between them is 220 V?
6. (I) An electric field of 640 V/m is desired between two parallel plates 11.0 mm apart. How large a voltage should be applied?
7. (I) The electric field between two parallel plates connected to a 45-V battery is 1500 V/m. How far apart are the plates?
8. (I) What potential difference is needed to give a helium nucleus ($Q = 2e$) 65.0 keV of kinetic energy?
9. (II) Two parallel plates, connected to a 200-V power supply, are separated by an air gap. How small can the gap be if the air is not to become conducting by exceeding its breakdown value of $E = 3 \times 10^6$ V/m?
10. (II) The work done by an external force to move a $-8.50\,\mu C$ charge from point a to point b is 15.0×10^{-4} J. If the charge was started from rest and had 4.82×10^{-4} J of kinetic energy when it reached point b, what must be the potential difference between a and b?
11. (II) What is the speed of an electron with kinetic energy (*a*) 750-eV, and (*b*) 3.2-keV?
12. (II) What is the speed of a proton whose kinetic energy is 3.2 keV?
13. (II) An alpha particle (which is a helium nucleus, $Q = +2e$, $m = 6.64 \times 10^{-27}$ kg) is emitted in a radioactive decay with KE $= 5.53$ MeV. What is its speed?

17–5 Potential Due to Point Charges

14. (I) What is the electric potential 15.0 cm from a $4.00\,\mu C$ point charge?
15. (I) A point charge Q creates an electric potential of $+125$ V at a distance of 15 cm. What is Q?
16. (II) A $+35\,\mu C$ point charge is placed 32 cm from an identical $+35\,\mu C$ charge. How much work would be required to move a $+0.50\,\mu C$ test charge from a point midway between them to a point 12 cm closer to either of the charges?
17. (II) Draw a conductor in the shape of a football. This conductor carries a net negative charge, $-Q$. Draw in a dozen electric field lines and two equipotential lines.
18. (II) (*a*) What is the electric potential a distance of 2.5×10^{-15} m away from a proton? (*b*) What is the electric potential energy of a system that consists of two protons 2.5×10^{-15} m apart—as might occur inside a typical nucleus?
19. (II) Three point charges are arranged at the corners of a square of side L as shown in Fig. 17–25. What is the potential at the fourth corner (point A), taking $V = 0$ at a great distance?

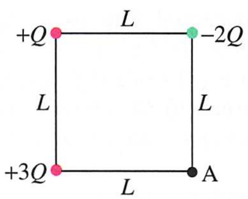

FIGURE 17–25 Problem 19.

20. (II) An electron starts from rest 32.5 cm from a fixed point charge with $Q = -0.125\,\mu C$. How fast will the electron be moving when it is very far away?
21. (II) Two identical $+9.5\,\mu C$ point charges are initially 3.5 cm from each other. If they are released at the same instant from rest, how fast will each be moving when they are very far away from each other? Assume they have identical masses of 1.0 mg.
22. (II) Two point charges, $3.0\,\mu C$ and $-2.0\,\mu C$, are placed 5.0 cm apart on the x axis. At what points along the x axis is (*a*) the electric field zero and (*b*) the potential zero? Let $V = 0$ at $r = \infty$.
23. (II) How much work must be done to bring three electrons from a great distance apart to 1.0×10^{-10} m from one another (at the corners of an equilateral triangle)?
24. (II) Consider point a which is 72 cm north of a $-3.8\,\mu C$ point charge, and point b which is 88 cm west of the charge (Fig. 17–26). Determine (*a*) $V_{ba} = V_b - V_a$ and (*b*) $\vec{\mathbf{E}}_b - \vec{\mathbf{E}}_a$ (magnitude and direction).

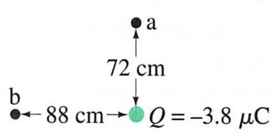

FIGURE 17–26 Problem 24.

25. (III) How much voltage must be used to accelerate a proton (radius 1.2×10^{-15} m) so that it has sufficient energy to just penetrate a silicon nucleus? A silicon nucleus has a charge of $+14e$, and its radius is about 3.6×10^{-15} m. Assume the potential is that for point charges.
26. (III) Two equal but opposite charges are separated by a distance d, as shown in Fig. 17–27. Determine a formula for $V_{BA} = V_B - V_A$ for points B and A on the line between the charges.

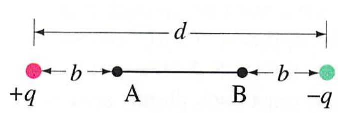

FIGURE 17–27 Problem 26.

27. (III) In the Bohr model of the hydrogen atom, an electron orbits a proton (the nucleus) in a circular orbit of radius 0.53×10^{-10} m. (*a*) What is the electric potential at the electron's orbit due to the proton? (*b*) What is the kinetic energy of the electron? (*c*) What is the total energy of the electron in its orbit? (*d*) What is the *ionization energy*—that is, the energy required to remove the electron from the atom and take it to $r = \infty$, at rest? Express the results of parts b, c and d in joules and eV.

* 17–6 Electric Dipoles

*28. (I) An electron and a proton are 0.53×10^{-10} m apart. What is their dipole moment if they are at rest?

*29. (II) Calculate the electric potential due to a dipole whose dipole moment is $4.8 \times 10^{-30}\,\mathrm{C \cdot m}$ at a point 1.1×10^{-9} m away if this point is (*a*) along the axis of the dipole nearer the positive charge; (*b*) 45° above the axis but nearer the positive charge; (*c*) 45° above the axis but nearer the negative charge.

*30. (III) The dipole moment, considered as a vector, points from the negative to the positive charge. The water molecule, Fig. 17–28, has a dipole moment $\vec{\mathbf{p}}$ which can be considered as the vector sum of the two dipole moments, $\vec{\mathbf{p}}_1$ and $\vec{\mathbf{p}}_2$, as shown. The distance between each H and the O is about 0.96×10^{-10} m. The lines joining the center of the O atom with each H atom make an angle of 104°, as shown, and the net dipole moment has been measured to be $p = 6.1 \times 10^{-30}\,\mathrm{C \cdot m}$. Determine the charge q on each H atom.

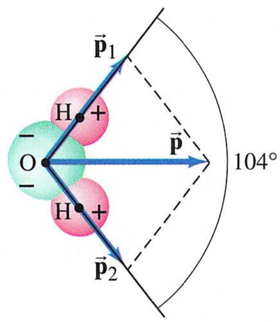

FIGURE 17–28
Problem 30.

17–7 Capacitance

31. (I) The two plates of a capacitor hold $+2500\,\mu\mathrm{C}$ and $-2500\,\mu\mathrm{C}$ of charge, respectively, when the potential difference is 850 V. What is the capacitance?

32. (I) A 9500-pF capacitor holds plus and minus charges of 16.5×10^{-8} C. What is the voltage across the capacitor?

33. (I) The potential difference between two short sections of parallel wire in air is 120 V. They carry equal and opposite charge of magnitude 95 pC. What is the capacitance of the two wires?

34. (I) How much charge flows from each terminal of a 12.0-V battery when it is connected to a 7.00-μF capacitor?

35. (I) A 0.20-F capacitor is desired. What area must the plates have if they are to be separated by a 2.2-mm air gap?

36. (II) The charge on a capacitor increases by $18\,\mu\mathrm{C}$ when the voltage across it increases from 97 V to 121 V. What is the capacitance of the capacitor?

37. (II) An electric field of 8.50×10^5 V/m is desired between two parallel plates, each of area $35.0\,\mathrm{cm}^2$ and separated by 2.45 mm of air. What charge must be on each plate?

38. (II) If a capacitor has opposite $5.2\,\mu\mathrm{C}$ charges on the plates, and an electric field of 2.0 kV/mm is desired between the plates, what must each plate's area be?

39. (II) How strong is the electric field between the plates of a 0.80-μF air-gap capacitor if they are 2.0 mm apart and each has a charge of $72\,\mu\mathrm{C}$?

40. (III) A 7.7-μF capacitor is charged by a 125-V battery (Fig. 17–29a) and then is disconnected from the battery. When this capacitor (C_1) is then connected (Fig. 17–29b) to a second (initially uncharged) capacitor, C_2, the final voltage on each capacitor is 15 V. What is the value of C_2? [*Hint*: charge is conserved.]

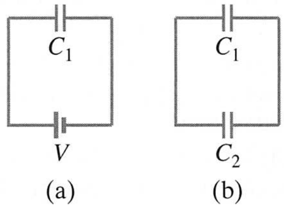

FIGURE 17–29
Problems 40 and 52.

41. (III) A 2.50-μF capacitor is charged to 857 V and a 6.80-μF capacitor is charged to 652 V. These capacitors are then disconnected from their batteries. Next the positive plates are connected to each other and the negative plates are connected to each other. What will be the potential difference across each and the charge on each? [*Hint*: charge is conserved.]

17–8 Dielectrics

42. (I) What is the capacitance of two square parallel plates 5.5 cm on a side that are separated by 1.8 mm of paraffin?

43. (I) What is the capacitance of a pair of circular plates with a radius of 5.0 cm separated by 3.2 mm of mica?

44. (II) A 3500-pF air-gap capacitor is connected to a 22-V battery. If a piece of mica is placed between the plates, how much charge will flow from the battery?

*45. (II) The electric field between the plates of a paper-separated $(K = 3.75)$ capacitor is 8.24×10^4 V/m. The plates are 1.95 mm apart, and the charge on each plate is $0.775\,\mu\mathrm{C}$. Determine the capacitance of this capacitor and the area of each plate.

17–9 Electric Energy Storage

46. (I) 650 V is applied to a 2200-pF capacitor. How much energy is stored?

47. (I) A cardiac defibrillator is used to shock a heart that is beating erratically. A capacitor in this device is charged to 5.0 kV and stores 1200 J of energy. What is its capacitance?

48. (II) How much energy is stored by the electric field between two square plates, 8.0 cm on a side, separated by a 1.5-mm air gap? The charges on the plates are equal and opposite and of magnitude $420\,\mu\mathrm{C}$.

49. (II) A homemade capacitor is assembled by placing two 9-in. pie pans 5 cm apart and connecting them to the opposite terminals of a 9-V battery. Estimate (*a*) the capacitance, (*b*) the charge on each plate, (*c*) the electric field halfway between the plates, and (*d*) the work done by the battery to charge the plates. (*e*) Which of the above values change if a dielectric is inserted?

50. (II) A parallel-plate capacitor has fixed charges $+Q$ and $-Q$. The separation of the plates is then doubled. (*a*) By what factor does the energy stored in the electric field change? (*b*) How much work must be done in doubling the plate separation from d to $2d$? The area of each plate is A.

51. (II) How does the energy stored in a capacitor change if (*a*) the potential difference is doubled, and (*b*) the charge on each plate is doubled, as the capacitor remains connected to a battery?

52. (III) A 2.70-μF capacitor is charged by a 12.0-V battery. It is disconnected from the battery and then connected to an uncharged 4.00-μF capacitor (Fig. 17–29). Determine the total stored energy (*a*) before the two capacitors are connected, and (*b*) after they are connected. (*c*) What is the change in energy?

* 17–10 Cathode Ray Tube

* 53. (III) In a given CRT, electrons are accelerated horizontally by 7.0 kV. They then pass through a uniform electric field E for a distance of 2.8 cm, which deflects them upward so they reach the screen top 22 cm away, 11 cm above the center. Estimate the value of E.

* 54. (III) Electrons are accelerated by 6.0 kV in a CRT. The screen is 30 cm wide and is 34 cm from the 2.6-cm-long deflection plates. Over what range must the horizontally deflecting electric field vary to sweep the beam fully across the screen?

General Problems

55. An electron starting from rest acquires 6.3 keV of KE in moving from point A to point B. (*a*) How much KE would a proton acquire, starting from rest at B and moving to point A? (*b*) Determine the ratio of their speeds at the end of their respective trajectories.

56. A lightning flash transfers 4.0 C of charge and 4.2 MJ of energy to the Earth. (*a*) Across what potential difference did it travel? (*b*) How much water could this boil and vaporize, starting from room temperature?

57. There is an electric field near the Earth's surface whose magnitude is about 150 V/m. How much energy is stored per cubic meter in this field?

58. In a television picture tube, electrons are accelerated by thousands of volts through a vacuum. If a television set were laid on its back, would electrons be able to move upward against the force of gravity? What potential difference, acting over a distance of 3.0 cm, would be needed to balance the downward force of gravity so that an electron would remain stationary? Assume that the electric field is uniform.

59. A huge 4.0-F capacitor has enough stored energy to heat 2.5 kg of water from 21° C to 95° C. What is the potential difference across the plates?

60. An uncharged capacitor is connected to a 24.0-V battery until it is fully charged, after which it is disconnected from the battery. A slab of paraffin is then inserted between the plates. What will now be the voltage between the plates?

61. Dry air will break down if the electric field exceeds 3.0×10^6 V/m. What amount of charge can be placed on a parallel-plate capacitor if the area of each plate is 56 cm^2?

62. Three charges are at the corners of an equilateral triangle (side L) as shown in Fig. 17–30. Determine the potential at the midpoint of each of the sides.

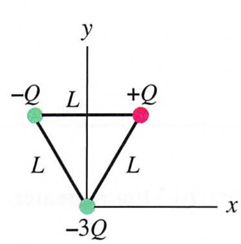

FIGURE 17–30 Problem 62.

63. A 3.4 μC and a −2.6 μC charge are placed 1.6 cm apart. At what points along the line joining them is (*a*) the electric field zero, and (*b*) the electric potential zero?

64. A 2600-pF air-gap capacitor is connected to a 9.0-V battery. If a piece of Pyrex glass is placed between the plates, how much charge will then flow from the battery?

65. An electron is accelerated horizontally from rest in a television picture tube by a potential difference of 5500 V. It then passes between two horizontal plates 6.5 cm long and 1.3 cm apart that have a potential difference of 250 V (Fig. 17–31). At what angle θ will the electron be traveling after it passes between the plates?

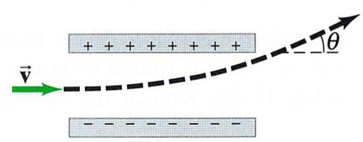

FIGURE 17–31 Problem 65.

66. A capacitor of capacitance C_1 carries a charge Q_0. It is then connected directly to a second, uncharged, capacitor of capacitance C_2, as shown in Fig. 17–32. What charge will each carry now? What will be the potential difference across each?

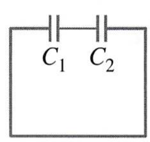

FIGURE 17–32 Problem 66.

67. To get an idea how big a farad is, suppose you want to make a 1-F air-filled parallel-plate capacitor for a circuit you are building. To make it a reasonable size, suppose you limit the plate area to 1.0 cm^2. What would the gap have to be between the plates? Is this practically achievable?

68. Near the surface of the Earth there is an electric field of about 150 V/m which points downward. Two identical balls with mass $m = 0.540$ kg are dropped from a height of 2.00 m, but one of the balls is positively charged with $q_1 = 650\ \mu$C, and the second is negatively charged with $q_2 = -650\ \mu$C. Use conservation of energy to determine the difference in the speed of the two balls when they hit the ground. (Neglect air resistance.)

69. The power supply for a pulsed nitrogen laser has a 0.050-μF capacitor with a maximum voltage rating of 30 kV. (*a*) Estimate how much energy could be stored in this capacitor. (*b*) If 12% of this stored electrical energy is converted to light energy in a pulse that is 8.0 microseconds long, what is the power of the laser pulse?

70. In lightning storms, the potential difference between the Earth and the bottom of the thunderclouds can be as high as 35,000,000 V. The bottoms of the thunderclouds are typically 1500 m above the Earth, and can have an area of 110 km^2. Modeling the Earth–cloud system as a huge capacitor, calculate (*a*) the capacitance of the Earth–cloud system, (*b*) the charge stored in the "capacitor," and (*c*) the energy stored in the "capacitor."

71. In a photocell, ultraviolet (UV) light provides enough energy to some electrons in barium metal to eject them from a surface at high speed. See Fig. 17–33. To measure the maximum energy of the electrons, another plate above the barium surface is kept at a negative enough potential that the emitted electrons are slowed down and stopped, and return to the barium surface. If the plate voltage is −3.02 V (compared to the barium) when the fastest electrons are stopped, what was the speed of these electrons when they were emitted?

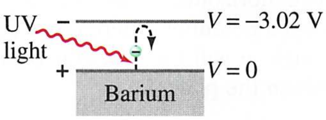

FIGURE 17–33 Problem 71.

72. A +33 μC point charge is placed 36 cm from an identical +33 μC charge. A −1.5 μC charge is moved from point a to point b in Fig. 17–34. What is the change in potential energy?

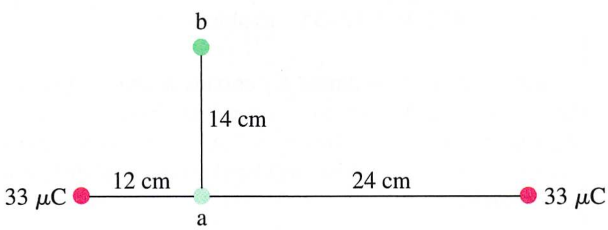

FIGURE 17–34 Problem 72.

73. A capacitor is made from two 1.1-cm-diameter coins separated by a 0.15-mm-thick piece of paper ($K = 3.7$). A 12-V battery is connected to the capacitor. How much charge is on each coin?

74. A +4.5 μC charge is 23 cm to the right of a −8.2 μC charge. At the midpoint between the two charges, (*a*) what are the potential and (*b*) the electric field?

75. A parallel-plate capacitor with plate area 2.0 cm^2 and air-gap separation 0.50 mm is connected to a 12-V battery, and fully charged. The battery is then disconnected. (*a*) What is the charge on the capacitor? (*b*) The plates are now pulled to a separation of 0.75 mm. What is the charge on the capacitor now? (*c*) What is the potential difference across the plates now? (*d*) How much work was required to pull the plates to their new separation?

76. A 2.5-μF capacitor is fully charged by a 6.0-V battery. The battery is then disconnected. The capacitor is not ideal and the charge slowly leaks out from the plates. The next day, the capacitor has lost half its stored energy. Calculate the amount of charge lost.

77. Two point charges are fixed 4.0 cm apart from each other. Their charges are $Q_1 = Q_2 = 5.0\,\mu$C, and their masses are $m_1 = 1.5$ mg and $m_2 = 2.5$ mg. (*a*) If Q_1 is released from rest, what will be its speed after a very long time? (*b*) If both charges are released from rest at the same time, what will be the speed of Q_1 after a very long time?

78. Two charges are placed as shown in Fig. 17–35 with $q_1 = 1.5\,\mu$C and $q_2 = -3.3\,\mu$C. Find the potential difference between points A and B.

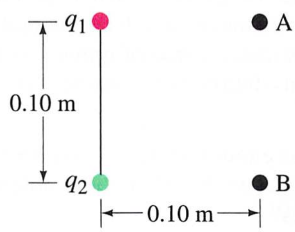

FIGURE 17–35 Problem 78.

Answers to Exercises

A: (*a*) -8.0×10^{-16} J; (*b*) 9.8×10^5 m/s.
B: 0.72 J.
C: 8.3×10^{-9} C.
D: (*a*) 3 times greater; (*b*) 3 times greater.
E: 12 mF.