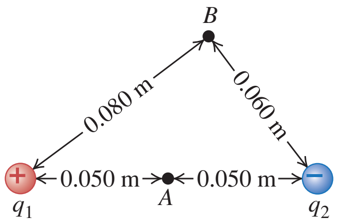
PEP 2017
Assignment 11

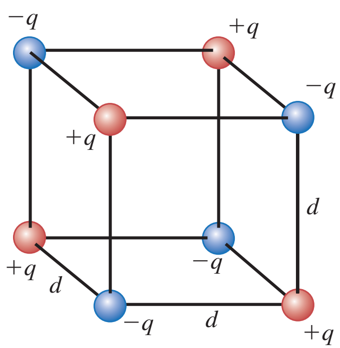
23.19 • Two point charges $q_1 = +2.40$ nC and $q_2 = -6.50$ nC are 0.100 m apart. Point A is midway between them; point B is 0.080 m from q_1 and 0.060 m from q_2 (Fig. E23.19). Take the electric potential to be zero at infinity. Find (a) the potential at point A; (b) the potential at point B; (c) the work done by the electric field on a charge of 2.50 nC that travels from point B to point A.

Figure **E23.19**



23.59 •• **An Ionic Crystal.** Figure P23.59 shows eight point charges arranged at the corners of a cube with sides of length d. The values of the charges are $+q$ and $-q$, as shown. This is a model of one cell of a cubic ionic crystal. In sodium chloride (NaCl), for instance, the positive ions are Na^+ and the negative ions are Cl^-. (a) Calculate the potential energy U of this arrangement. (Take as zero the potential energy of the eight charges when they are infinitely far apart.) (b) In part (a), you should have found that $U < 0$. Explain the relationship between this result and the observation that such ionic crystals exist in nature.

Figure **P23.59**



23.29 •• A uniformly charged, thin ring has radius 15.0 cm and total charge +24.0 nC. An electron is placed on the ring's axis a distance 30.0 cm from the center of the ring and is constrained to stay on the axis of the ring. The electron is then released from rest. (a) Describe the subsequent motion of the electron. (b) Find the speed of the electron when it reaches the center of the ring.

23.47 •• **CALC** A metal sphere with radius r_a is supported on an insulating stand at the center of a hollow, metal, spherical shell with radius r_b. There is charge $+q$ on the inner sphere and charge $-q$ on the outer spherical shell. (a) Calculate the potential $V(r)$ for (i) $r < r_a$; (ii) $r_a < r < r_b$; (iii) $r > r_b$. (*Hint:* The net potential is the sum of the potentials due to the individual spheres.) Take V to be zero when r is infinite. (b) Show that the potential of the inner sphere with respect to the outer is

$$V_{ab} = \frac{q}{4\pi\epsilon_0}\left(\frac{1}{r_a} - \frac{1}{r_b}\right)$$

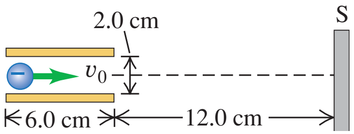
(c) Use Eq. (23.23) and the result from part (a) to show that the electric field at any point between the spheres has magnitude

$$E(r) = \frac{V_{ab}}{(1/r_a - 1/r_b)}\frac{1}{r^2}$$

(d) Use Eq. (23.23) and the result from part (a) to find the electric field at a point outside the larger sphere at a distance r from the center, where $r > r_b$. (e) Suppose the charge on the outer sphere is not $-q$ but a negative charge of different magnitude, say $-Q$. Show that the answers for parts (b) and (c) are the same as before but the answer for part (d) is different.

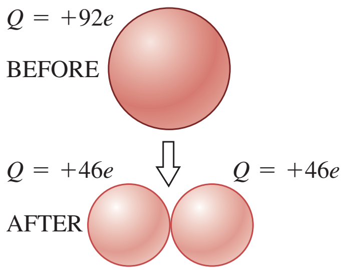
23.65 • **CP** **Deflection in a CRT.** Cathode-ray tubes (CRTs) are often found in oscilloscopes and computer monitors. In Fig. P23.65 an electron with an initial speed of 6.50×10^6 m/s is projected along the axis midway between the deflection plates of a cathode-ray tube. The potential difference between the two plates is 22.0 V and the lower plate is the one at higher potential. (a) What is the force (magnitude and direction) on the electron when it is between the plates? (b) What is the acceleration of the electron (magnitude and direction) when acted on by the force in part (a)? (c) How far below the axis has the electron moved when it reaches the end of the plates? (d) At what angle with the axis is it moving as it leaves the plates? (e) How far below the axis will it strike the fluorescent screen S?

Figure **P23.65**



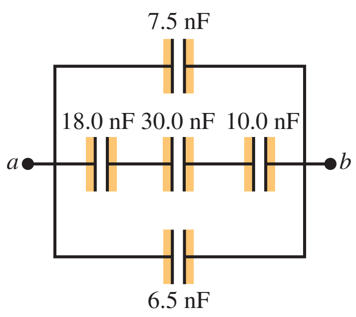
23.87 •• **Nuclear Fission.** The unstable nucleus of uranium-236 can be regarded as a uniformly charged sphere of charge $Q = +92e$ and radius $R = 7.4 \times 10^{-15}$ m. In nuclear fission, this can divide into two smaller nuclei, each with half the charge and half the volume of the original uranium-236 nucleus. This is one of the reactions that occurred in the nuclear weapon that exploded over Hiroshima, Japan, in August 1945. (a) Find the radii of the two "daughter" nuclei of charge $+46e$. (b) In a simple model for the fission process, immediately after the uranium-236 nucleus has undergone fission, the "daughter" nuclei are at rest and just touching, as shown in Fig. P23.87. Calculate the kinetic energy that each of the "daughter" nuclei will have when they are very far apart. (c) In this model the sum of the kinetic energies of the two "daughter" nuclei, calculated in part (b), is the energy released by the fission of one uranium-236 nucleus. Calculate the energy released by the fission of 10.0 kg of uranium-236. The atomic mass of uranium-236 is 236 u, where 1 u = 1 atomic mass unit = 1.66×10^{-24} kg. Express your answer both in joules and in kilotons of TNT (1 kiloton of TNT releases 4.18×10^{12} J when it explodes). (d) In terms of this model, discuss why an atomic bomb could just as well be called an "electric bomb."

Figure **P23.87**



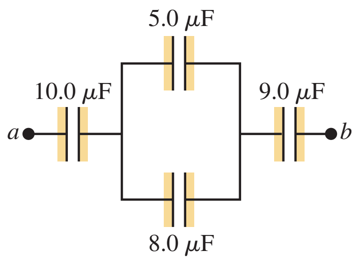
24.21 •• For the system of capacitors shown in Fig. E24.21, a potential difference of 25 V is maintained across *ab*. (a) What is the equivalent capacitance of this system between *a* and *b*? (b) How much charge is stored by this system? (c) How much charge does the 6.5-nF capacitor store? (d) What is the potential difference across the 7.5-nF capacitor?

Figure **E24.21**



24.22 • Figure E24.22 shows a system of four capacitors, where the potential difference across *ab* is 50.0 V. (a) Find the equivalent capacitance of this system between *a* and *b*. (b) How much charge is stored by this combination of capacitors? (c) How much charge is stored in each of the 10.0-μF and the 9.0-μF capacitors?

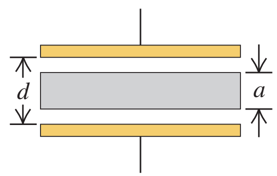
Figure **E24.22**



24.52 ••• In one type of computer keyboard, each key holds a small metal plate that serves as one plate of a parallel-plate, air-filled capacitor. When the key is depressed, the plate separation decreases and the capacitance increases. Electronic circuitry detects the change in capacitance and thus detects that the key has been pressed. In one particular keyboard, the area of each metal plate is 42.0 mm^2, and the separation between the plates is 0.700 mm before the key is depressed. (a) Calculate the capacitance before the key is depressed. (b) If the circuitry can detect a change in capacitance of 0.250 pF, how far must the key be depressed before the circuitry detects its depression?

24.66 •• An air capacitor is made by using two flat plates, each with area *A*, separated by a distance *d*. Then a metal slab having thickness *a* (less than *d*) and the same shape and size as the plates is inserted between them, parallel to the plates and not touching either plate (Fig. P24.66). (a) What is the capacitance of this arrangement? (b) Express the capacitance as a multiple of the capacitance C_0 when the metal slab is not present. (c) Discuss what happens to the capacitance in the limits $a \to 0$ and $a \to d$.

Figure **P24.66**



23.19. **IDENTIFY:** $V = \frac{1}{4\pi\epsilon_0}\sum_i \frac{q_i}{r_i}$

SET UP: The locations of the changes and points A and B are sketched in Figure 23.19.

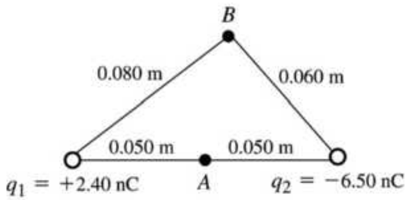


Figure 23.19

EXECUTE: **(a)** $V_A = \frac{1}{4\pi\epsilon_0}\left(\frac{q_1}{r_{A1}} + \frac{q_2}{r_{A2}}\right)$

$$V_A = (8.988\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\left(\frac{+2.40\times10^{-9}\ \text{C}}{0.050\ \text{m}} + \frac{-6.50\times10^{-9}\ \text{C}}{0.050\ \text{m}}\right) = -737\ \text{V}$$

(b) $V_B = \frac{1}{4\pi\epsilon_0}\left(\frac{q_1}{r_{B1}} + \frac{q_2}{r_{B2}}\right)$

$$V_B = (8.988\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\left(\frac{+2.40\times10^{-9}\ \text{C}}{0.080\ \text{m}} + \frac{-6.50\times10^{-9}\ \text{C}}{0.060\ \text{m}}\right) = -704\ \text{V}$$

(c) IDENTIFY and **SET UP:** Use Eq. (23.13) and the results of parts (a) and (b) to calculate W.

EXECUTE: $W_{B\to A} = q'(V_B - V_A) = (2.50\times10^{-9}\ \text{C})(-704\ \text{V} - (-737\ \text{V})) = +8.2\times10^{-8}\ \text{J}$

EVALUATE: The electric force does positive work on the positive charge when it moves from higher potential (point B) to lower potential (point A).

23.29. **(a) IDENTIFY** and **SET UP**: The electric field on the ring's axis is calculated in Example 21.9. The force on the electron exerted by this field is given by Eq. (21.3).

EXECUTE: When the electron is on either side of the center of the ring, the ring exerts an attractive force directed toward the center of the ring. This restoring force produces oscillatory motion of the electron along the axis of the ring, with amplitude 30.0 cm. The force on the electron is *not* of the form $F = -kx$ so the oscillatory motion is not simple harmonic motion.

(b) IDENTIFY: Apply conservation of energy to the motion of the electron.

SET UP: $K_a + U_a = K_b + U_b$ with a at the initial position of the electron and b at the center of the ring.

From Example 23.11, $V = \dfrac{1}{4\pi\epsilon_0}\dfrac{Q}{\sqrt{x^2+R^2}}$, where R is the radius of the ring.

EXECUTE: $x_a = 30.0\text{ cm}, x_b = 0.$

$K_a = 0$ (released from rest), $K_b = \frac{1}{2}mv^2$

Thus $\frac{1}{2}mv^2 = U_a - U_b$

And $U = qV = -eV$ so $v = \sqrt{\dfrac{2e(V_b - V_a)}{m}}$.

$$V_a = \frac{1}{4\pi\epsilon_0}\frac{Q}{\sqrt{x_a^2+R^2}} = (8.988\times10^9\text{ N}\cdot\text{m}^2/\text{C}^2)\frac{24.0\times10^{-9}\text{ C}}{\sqrt{(0.300\text{ m})^2+(0.150\text{ m})^2}}$$

$$V_a = 643\text{ V}$$

$$V_b = \frac{1}{4\pi\epsilon_0}\frac{Q}{\sqrt{x_b^2+R^2}} = (8.988\times10^9\text{ N}\cdot\text{m}^2/\text{C}^2)\frac{24.0\times10^{-9}\text{ C}}{0.150\text{ m}} = 1438\text{ V}$$

$$v = \sqrt{\frac{2e(V_b - V_a)}{m}} = \sqrt{\frac{2(1.602\times10^{-19}\text{ C})(1438\text{ V} - 643\text{ V})}{9.109\times10^{-31}\text{ kg}}} = 1.67\times10^7\text{ m/s}$$

EVALUATE: The positively charged ring attracts the negatively charged electron and accelerates it. The electron has its maximum speed at this point. When the electron moves past the center of the ring the force on it is opposite to its motion and it slows down.

23.47. **IDENTIFY and SET UP:** For a solid metal sphere or for a spherical shell, $V = \frac{kq}{r}$ outside the sphere and $V = \frac{kq}{R}$ at all points inside the sphere, where R is the radius of the sphere. When the electric field is radial, $E = -\frac{\partial V}{\partial r}$.

EXECUTE: **(a)** (i) $r < r_a$: This region is inside both spheres. $V = \frac{kq}{r_a} - \frac{kq}{r_b} = kq\left(\frac{1}{r_a} - \frac{1}{r_b}\right)$.

(ii) $r_a < r < r_b$: This region is outside the inner shell and inside the outer shell. $V = \frac{kq}{r} - \frac{kq}{r_b} = kq\left(\frac{1}{r} - \frac{1}{r_b}\right)$.

(iii) $r > r_b$: This region is outside both spheres and $V = 0$ since outside a sphere the potential is the same as for a point charge. Therefore the potential is the same as for two oppositely charged point charges at the same location. These potentials cancel.

(b) $V_a = \frac{1}{4\pi\epsilon_0}\left(\frac{q}{r_a} - \frac{q}{r_b}\right)$ and $V_b = 0$, so $V_{ab} = \frac{1}{4\pi\epsilon_0} q\left(\frac{1}{r_a} - \frac{1}{r_b}\right)$.

(c) Between the spheres $r_a < r < r_b$ and $V = kq\left(\frac{1}{r} - \frac{1}{r_b}\right)$.

$$E = -\frac{\partial V}{\partial r} = -\frac{q}{4\pi\epsilon_0}\frac{\partial}{\partial r}\left(\frac{1}{r} - \frac{1}{r_b}\right) = +\frac{1}{4\pi\epsilon_0}\frac{q}{r^2} = \frac{V_{ab}}{\left(\frac{1}{r_a} - \frac{1}{r_b}\right)}\frac{1}{r^2}.$$

(d) From Eq. (23.23): $E = 0$, since V is constant (zero) outside the spheres.

(e) If the outer charge is different, then outside the outer sphere the potential is no longer zero but is $V = \frac{1}{4\pi\epsilon_0}\frac{q}{r} - \frac{1}{4\pi\epsilon_0}\frac{Q}{r} = \frac{1}{4\pi\epsilon_0}\frac{(q-Q)}{r}$. All potentials inside the outer shell are just shifted by an amount $V = \frac{1}{4\pi\epsilon_0}\frac{Q}{r_b}$. Therefore relative potentials within the shells are not affected. Thus (b) and (c) do not change. However, now that the potential does vary outside the spheres, there is an electric field there:

$$E = -\frac{\partial V}{\partial r} = -\frac{\partial}{\partial r}\left(\frac{kq}{r} + \frac{-kQ}{r}\right) = \frac{kq}{r^2}\left(1 - \frac{Q}{q}\right) = \frac{k}{r^2}(q - Q).$$

EVALUATE: In part (a) the potential is greater than zero for all $r < r_b$.

23.59. **IDENTIFY:** $U = \frac{kq_1q_2}{r}$

SET UP: Eight charges means there are $8(8-1)/2 = 28$ pairs. There are 12 pairs of q and $-q$ separated by d, 12 pairs of equal charges separated by $\sqrt{2}d$ and 4 pairs of q and $-q$ separated by $\sqrt{3}d$.

EXECUTE: **(a)** $U = kq^2\left(-\frac{12}{d} + \frac{12}{\sqrt{2}d} - \frac{4}{\sqrt{3}d}\right) = -\frac{12kq^2}{d}\left(1 - \frac{1}{\sqrt{2}} + \frac{1}{3\sqrt{3}}\right) = -1.46q^2/\pi\epsilon_0 d$

EVALUATE: **(b)** The fact that the electric potential energy is less than zero means that it is energetically favorable for the crystal ions to be together.

23.65. **IDENTIFY** and **SET UP:** Use Eq. (21.3) to calculate $\vec{F}$ and then $\vec{F} = m\vec{a}$ gives $\vec{a}$. $E = V/d$.

EXECUTE: **(a)** $\vec{F}_E = q\vec{E}$. Since $q = -e$ is negative $\vec{F}_E$ and $\vec{E}$ are in opposite directions; $\vec{E}$ is upward so $\vec{F}_E$ is downward. The magnitude of E is $E = \frac{V}{d} = \frac{22.0\text{ V}}{0.0200\text{ m}} = 1.10\times10^{3}\text{ V/m} = 1.10\times10^{3}\text{ N/C}$. The magnitude of F_E is $F_E = |q|E = eE = (1.602\times10^{-19}\text{ C})(1.10\times10^{3}\text{ N/C}) = 1.76\times10^{-16}\text{ N}$.

(b) Calculate the acceleration of the electron produced by the electric force:

$$a = \frac{F}{m} = \frac{1.76\times10^{-16}\text{ N}}{9.109\times10^{-31}\text{ kg}} = 1.93\times10^{14}\text{ m/s}^2.$$

EVALUATE: This acceleration is much larger than $g = 9.80\text{ m/s}^2$, so the gravity force on the electron can be neglected. $\vec{F}_E$ is downward, so $\vec{a}$ is downward.

(c) IDENTIFY and **SET UP:** The acceleration is constant and downward, so the motion is like that of a projectile. Use the horizontal motion to find the time and then use the time to find the vertical displacement.

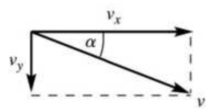
EXECUTE: x-component: $v_{0x} = 6.50\times10^{6}\text{ m/s}$; $a_x = 0$; $x - x_0 = 0.060\text{ m}$; $t = ?$

$x - x_0 = v_{0x}t + \frac{1}{2}a_xt^2$ and the a_x term is zero, so $t = \frac{x - x_0}{v_{0x}} = \frac{0.060\text{ m}}{6.50\times10^{6}\text{ m/s}} = 9.231\times10^{-9}\text{ s}$.

y-component: $v_{0y} = 0$; $a_y = 1.93\times10^{14}\text{ m/s}^2$; $t = 9.231\times10^{-9}\text{ m/s}$; $y - y_0 = ?$

$y - y_0 = v_{0y}t + \frac{1}{2}a_yt^2$. $y - y_0 = \frac{1}{2}(1.93\times10^{14}\text{ m/s}^2)(9.231\times10^{-9}\text{ s})^2 = 0.00822\text{ m} = 0.822\text{ cm}$.

(d) The velocity and its components as the electron leaves the plates are sketched in Figure 23.65.



$v_x = v_{0x} = 6.50\times10^{6}\text{ m/s}$ (since $a_x = 0$)

$v_y = v_{0y} + a_yt$

$v_y = 0 + (1.93\times10^{14}\text{ m/s}^2)(9.231\times10^{-9}\text{ s})$

$v_y = 1.782\times10^{6}\text{ m/s}$

Figure 23.65

$$\tan\alpha = \frac{v_y}{v_x} = \frac{1.782\times10^{6}\text{ m/s}}{6.50\times10^{6}\text{ m/s}} = 0.2742 \text{ so } \alpha = 15.3°.$$

EVALUATE: The greater the electric field or the smaller the initial speed the greater the downward deflection.

(e) IDENTIFY and **SET UP:** Consider the motion of the electron after it leaves the region between the plates. Outside the plates there is no electric field, so $a = 0$. (Gravity can still be neglected since the electron is traveling at such high speed and the times are small.) Use the horizontal motion to find the time it takes the electron to travel 0.120 m horizontally to the screen. From this time find the distance downward that the electron travels.

EXECUTE: x-component: $v_{0x} = 6.50\times10^{6}\text{ m/s}$; $a_x = 0$; $x - x_0 = 0.120\text{ m}$; $t = ?$

$x - x_0 = v_{0x}t + \frac{1}{2}a_xt^2$ and the a_x term is term is zero, so $t = \frac{x - x_0}{v_{0x}} = \frac{0.120\text{ m}}{6.50\times10^{6}\text{ m/s}} = 1.846\times10^{-8}\text{ s}$.

y-component: $v_{0y} = 1.782\times10^{6}\text{ m/s}$ (from part (b)); $a_y = 0$; $t = 1.846\times10^{-8}\text{ m/s}$; $y - y_0 = ?$

$y - y_0 = v_{0y}t + \frac{1}{2}a_yt^2 = (1.782\times10^{6}\text{ m/s})(1.846\times10^{-8}\text{ s}) = 0.0329\text{ m} = 3.29\text{ cm}$.

EVALUATE: The electron travels downward a distance 0.822 cm while it is between the plates and a distance 3.29 cm while traveling from the edge of the plates to the screen. The total downward deflection is 0.822 cm + 3.29 cm = 4.11 cm. The horizontal distance between the plates is half the horizontal distance the electron travels after it leaves the plates. And the vertical velocity of the electron increases as it travels between the plates, so it makes sense for it to have greater downward displacement during the motion after it leaves the plates.

perpendicular to the equipotential circles.

23.87. **IDENTIFY:** Apply conservation of energy to the motion of the daughter nuclei.

SET UP: Problem 23.72 shows that the electrical potential energy of the two nuclei is the same as if all their charge was concentrated at their centers.

EXECUTE: **(a)** The two daughter nuclei have half the volume of the original uranium nucleus, so their radii are smaller by a factor of the cube root of 2: $r = \dfrac{7.4\times10^{-15}\text{ m}}{\sqrt[3]{2}} = 5.9\times10^{-15}\text{ m}.$

(b) $U = \dfrac{k(46e)^2}{2r} = \dfrac{k(46)^2(1.60\times10^{-19}\text{ C})^2}{1.18\times10^{-14}\text{ m}} = 4.14\times10^{-11}\text{ J}.$ $U = 2K,$ where K is the final kinetic energy of each nucleus. $K = U/2 = (4.14\times10^{-11}\text{ J})/2 = 2.07\times10^{-11}\text{ J}.$

(c) If we have 10.0 kg of uranium, then the number of nuclei is

$n = \dfrac{10.0\text{ kg}}{(236\text{ u})(1.66\times10^{-27}\text{ kg/u})} = 2.55\times10^{25}$ nuclei. And each releases energy U, so

$E = nU = (2.55\times10^{25})(4.14\times10^{-11}\text{ J}) = 1.06\times10^{15}\text{ J} = 253$ kilotons of TNT.

(d) We could call an atomic bomb an "electric" bomb since the electric potential energy provides the kinetic energy of the particles.

EVALUATE: This simple model considers only the electrical force between the daughter nuclei and neglects the nuclear force.

24.21. **IDENTIFY:** Three of the capacitors are in series, and this combination is in parallel with the other two capacitors.

SET UP: For capacitors in series the voltages add and the charges are the same;

$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$. For capacitors in parallel the voltages are the same and the charges add;

$C_{\text{eq}} = C_1 + C_2 + \text{L}.$ $C = \frac{Q}{V}$.

EXECUTE: **(a)** The equivalent capacitance of the 18.0 nF, 30.0 nF and 10.0 nF capacitors in series is 5.29 nF. When these capacitors are replaced by their equivalent we get the network sketched in Figure 24.21. The equivalent capacitance of these three capacitors in parallel is 19.3 nF, and this is the equivalent capacitance of the original network.

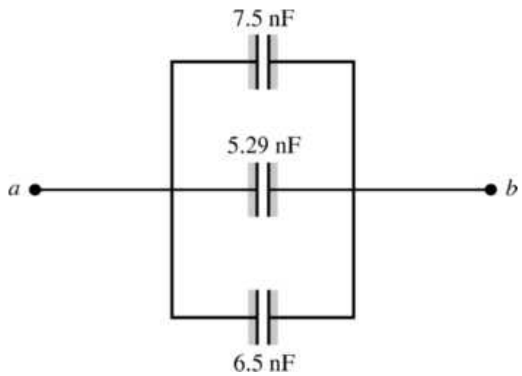


Figure 24.21

(b) $Q_{\text{tot}} = C_{\text{eq}}V = (19.3 \text{ nF})(25 \text{ V}) = 482 \text{ nC}.$

(c) The potential across each capacitor in the parallel network of Figure 24.21 is 25 V.

$Q_{6.5} = C_{6.5}V_{6.5} = (6.5 \text{ nF})(25 \text{ V}) = 162 \text{ nC}.$

d) 25 V.

EVALUATE: As with most circuits, we must go through a series of steps to simplify it as we solve for the unknowns.

24.22. **IDENTIFY:** Simplify the network by replacing series and parallel combinations of capacitors by their equivalents.

SET UP: For capacitors in series the voltages add and the charges are the same; $\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$ For capacitors in parallel the voltages are the same and the charges add; $C_{\text{eq}} = C_1 + C_2 + \cdots$ $C = \frac{Q}{V}$.

EXECUTE: **(a)** The equivalent capacitance of the $5.0\ \mu\text{F}$ and $8.0\ \mu\text{F}$ capacitors in parallel is $13.0\ \mu\text{F}$. When these two capacitors are replaced by their equivalent we get the network sketched in Figure 24.22. The equivalent capacitance of these three capacitors in series is $3.47\ \mu\text{F}$.

(b) $Q_{\text{tot}} = C_{\text{tot}}V = (3.47\ \mu\text{F})(50.0\ \text{V}) = 174\ \mu\text{C}$

(c) Q_{tot} is the same as Q for each of the capacitors in the series combination shown in Figure 24.22, so Q for each of the capacitors is $174\ \mu\text{C}$.

EVALUATE: The voltages across each capacitor in Figure 24.22 are $V_{10} = \frac{Q_{\text{tot}}}{C_{10}} = 17.4\ \text{V}$, $V_{13} = \frac{Q_{\text{tot}}}{C_{13}} = 13.4\ \text{V}$ and $V_9 = \frac{Q_{\text{tot}}}{C_9} = 19.3\ \text{V}$. $V_{10} + V_{13} + V_9 = 17.4\ \text{V} + 13.4\ \text{V} + 19.3\ \text{V} = 50.1\ \text{V}$. The sum of the voltages equals the applied voltage, apart from a small difference due to rounding.

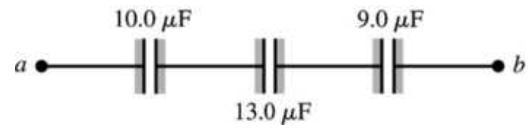


Figure 24.22

24.52. **IDENTIFY:** $C = \frac{\epsilon_0 A}{d}$

SET UP: $A = 4.2\times10^{-5}\ \text{m}^2$. The original separation between the plates is $d = 0.700\times10^{-3}$ m. d' is the separation between the plates at the new value of C.

EXECUTE: $C_0 = \frac{A\epsilon_0}{d} = \frac{(4.20\times10^{-5}\ \text{m}^2)\epsilon_0}{7.00\times10^{-4}\ \text{m}} = 5.31\times10^{-13}$ F. The new value of C is

$C = C_0 + 0.25\ \text{pF} = 7.81\times10^{-13}$ F. But $C = \frac{A\epsilon_0}{d'}$, so $d' = \frac{A\epsilon_0}{C} = \frac{(4.20\times10^{-5}\ \text{m}^2)\epsilon_0}{7.81\times10^{-13}\ \text{F}} = 4.76\times10^{-4}\text{m}.$

Therefore the key must be depressed by a distance of $7.00\times10^{-4}\ \text{m} - 4.76\times10^{-4}\ \text{m} = 0.224$ mm.

EVALUATE: When the key is depressed, d decreases and C increases.

24.66. IDENTIFY: This situation is analogous to having two capacitors C_1 in series, each with separation $\frac{1}{2}(d-a)$.

SET UP: For capacitors in series, $\dfrac{1}{C_{\text{eq}}}=\dfrac{1}{C_1}+\dfrac{1}{C_2}$.

EXECUTE: **(a)** $C=\left(\dfrac{1}{C_1}+\dfrac{1}{C_1}\right)^{-1}=\frac{1}{2}C_1=\frac{1}{2}\dfrac{\epsilon_0 A}{(d-a)/2}=\dfrac{\epsilon_0 A}{d-a}$

(b) $C=\dfrac{\epsilon_0 A}{d-a}=\dfrac{\epsilon_0 A}{d}\dfrac{d}{d-a}=C_0\dfrac{d}{d-a}$

(c) As $a\to 0$, $C\to C_0$. The metal slab has no effect if it is very thin. And as $a\to d$, $C\to\infty$. $V=Q/C$. $V=Ey$ is the potential difference between two points separated by a distance *y* parallel to a uniform electric field. When the distance is very small, it takes a very large field and hence a large *Q* on the plates for a given potential difference. Since $Q=CV$ this corresponds to a very large *C*.