Some useful constants: $m_{electron} = 9.11 \times 10^{-31}$ kg, $m_{proton} = 1.67 \times 10^{-27}$ kg, magnitude of charge of proton or electron = 1.6×10^{-19} C, $k = 9 \times 10^9$ Nm^2/C^2

4. **IDENTIFY:** In a space satellite, the only force accelerating the free proton is the electrical repulsion of the other proton.
SET UP: Coulomb's law gives the force, and Newton's second law gives the acceleration: $a = F/m = (1/4\pi\epsilon_0)(e^2/r^2)/m$.

$a = (9.00\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(1.60\times10^{-19}\ \text{C})^2/[(0.00250\ \text{m})^2(1.67\times10^{-27}\ \text{kg})] = 2.21\times10^4\ \text{m/s}^2$.

EVALUATE: The electrical force of a single stationary proton gives the moving proton an initial acceleration about 20,000 times as great as the acceleration caused by the gravity of the entire earth. As the protons move farther apart, the electrical force gets weaker, so the acceleration decreases. Since the protons continue to repel, the velocity keeps increasing, but at a decreasing rate.

5. **IDENTIFY:** The acceleration that stops the charge is produced by the force that the electric field exerts on it. Since the field and the acceleration are constant, we can use the standard kinematics formulas to find acceleration and time.
(a) SET UP: First use kinematics to find the proton's acceleration. $v_x = 0$ when it stops. Then find the electric field needed to cause this acceleration using the fact that $F = qE$.

EXECUTE: $v_x^2 = v_{0x}^2 + 2a_x(x - x_0)$. $0 = (4.50\times10^6\ \text{m/s})^2 + 2a(0.0320\ \text{m})$ and $a = 3.16\times10^{14}\ \text{m/s}^2$. Now find the electric field, with $q = e$. $eE = ma$ and

$E = ma/e = (1.67\times10^{-27}\ \text{kg})(3.16\times10^{14}\ \text{m/s}^2)/(1.60\times10^{-19}\ \text{C}) = 3.30\times10^6\ \text{N/C}$, to the left.

(b) SET UP: Kinematics gives $v = v_0 + at$, and $v = 0$ when the electron stops, so $t = v_0/a$.

EXECUTE: $t = v_0/a = (4.50\times10^6\ \text{m/s})/(3.16\times10^{14}\ \text{m/s}^2) = 1.42\times10^{-8}\ \text{s} = 14.2\ \text{ns}$

(c) SET UP: In part (a) we saw that the electric field is proportional to m, so we can use the ratio of the electric fields. $E_e/E_p = m_e/m_p$ and $E_e = (m_e/m_p)E_p$.

EXECUTE: $E_e = [(9.11\times10^{-31}\ \text{kg})/(1.67\times10^{-27}\ \text{kg})](3.30\times10^6\ \text{N/C}) = 1.80\times10^3\ \text{N/C}$, to the right

EVALUATE: Even a modest electric field, such as the ones in this situation, can produce enormous accelerations for electrons and protons.

6. **IDENTIFY:** The net force on each charge must be zero.
SET UP: The force diagram for the $-6.50\ \mu\text{C}$ charge is given in Figure. F_E is the force exerted on the charge by the uniform electric field. The charge is negative and the field is to the right, so the force exerted by the field is to the left. F_q is the force exerted by the other point charge. The two charges have opposite signs, so the force is attractive. Take the $+x$ axis to be to the right, as shown in the figure.

EXECUTE: **(a)** $F_E = |q|E = (6.50\times10^{-6}\ \text{C})(1.85\times10^8\ \text{N/C}) = 1.20\times10^3\ \text{N}$

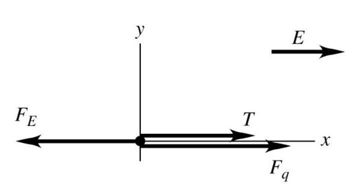
$$F_q = k\frac{|q_1q_2|}{r^2} = (8.99\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(6.50\times10^{-6}\ \text{C})(8.75\times10^{-6}\ \text{C})}{(0.0250\ \text{m})^2} = 8.18\times10^2\ \text{N}$$

$\sum F_x = 0$ gives $T + F_q - F_E = 0$ and $T = F_E - F_q = 382$ N.

(b) Now F_q is to the left, since like charges repel.

$\sum F_x = 0$ gives $T - F_q - F_E = 0$ and $T = F_E + F_q = 2.02\times10^3$ N.

EVALUATE: The tension is much larger when both charges have the same sign, so the force one charge exerts on the other is repulsive.



7. **IDENTIFY:** Calculate the field due to each charge and then calculate the vector sum of those fields.

SET UP: The fields due to q_1 and to q_2 are sketched in Figure.

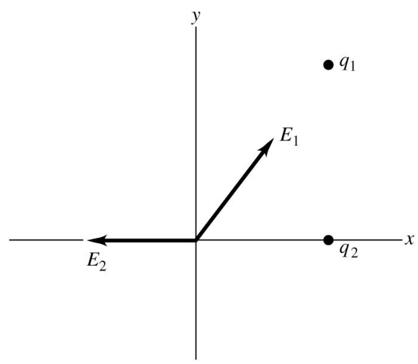
EXECUTE: $\vec{E}_2 = \dfrac{1}{4\pi\epsilon_0}\dfrac{(6.00\times10^{-9}\ \text{C})}{(0.6\ \text{m})^2}(-\hat{\boldsymbol{i}}) = -150\hat{\boldsymbol{i}}\ \text{N/C}.$

$$\vec{E}_1 = \frac{1}{4\pi\epsilon_0}(4.00\times10^{-9}\ \text{C})\left(\frac{1}{(1.00\ \text{m})^2}(0.600)\hat{\boldsymbol{i}} + \frac{1}{(1.00\ \text{m})^2}(0.800)\hat{\boldsymbol{j}}\right) = (21.6\hat{\boldsymbol{i}} + 28.8\hat{\boldsymbol{j}})\text{N/C}.$$

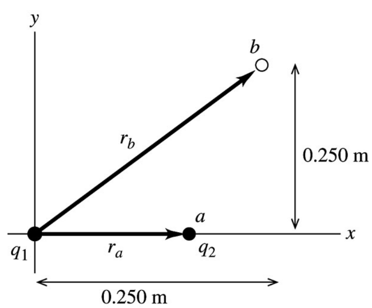
$\vec{E} = \vec{E}_1 + \vec{E}_2 = (-128.4\ \text{N/C})\hat{\boldsymbol{i}} + (28.8\ \text{N/C})\hat{\boldsymbol{j}}$. $E = \sqrt{(128.4\ \text{N/C})^2 + (28.8\ \text{N/C})^2} = 131.6\ \text{N/C}$ at

$\theta = \tan^{-1}\left(\dfrac{28.8}{128.4}\right) = 12.6°$ above the $-x$-axis and therefore $167.4°$ counterclockwise from the $+x$-axis.

EVALUATE: $\vec{E}_1$ is directed toward q_1 because q_1 is negative and $\vec{E}_2$ is directed away from q_2 because q_2 is positive.



8. **SET UP:** Let the initial position of q_2 be point *a* and the final position be point *b*, as shown in Figure.



$r_a = 0.150\ \text{m}$

$r_b = \sqrt{(0.250\ \text{m})^2 + (0.250\ \text{m})^2}$

$r_b = 0.3536\ \text{m}$

EXECUTE: $W_{a\to b} = U_a - U_b$

$$U_a = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r_a} = (8.988\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(+2.40\times10^{-6}\ \text{C})(-4.30\times10^{-6}\ \text{C})}{0.150\ \text{m}}$$

$U_a = -0.6184\ \text{J}$

$$U_b = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r_b} = (8.988\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(+2.40\times10^{-6}\ \text{C})(-4.30\times10^{-6}\ \text{C})}{0.3536\ \text{m}}$$

$U_b = -0.2623\ \text{J}$

$$W_{a\to b} = U_a - U_b = -0.6184\ \text{J} - (-0.2623\ \text{J}) = -0.356\ \text{J}$$

EVALUATE: The attractive force on q_2 is toward the origin, so it does negative work on q_2 when q_2 moves to larger *r*.

9. **IDENTIFY:** Apply $W_{a\to b} = U_a - U_b$.

SET UP: $U_a = +5.4\times10^{-8}$ J. Solve for U_b.

EXECUTE: $W_{a\to b} = -1.9\times10^{-8}\ \text{J} = U_a - U_b$. $U_b = U_a - W_{a\to b} = +5.4\times10^{-8}\ \text{J} - (-1.9\times10^{-8}\ \text{J}) = 7.3\times10^{-8}$ J.

EVALUATE: When the electric force does negative work the electrical potential energy increases.

10. **IDENTIFY:** The potential at any point is the scalar sum of the potentials due to individual charges.

SET UP: $V = kq/r$ and $W_{ab} = q(V_a - V_b)$.

EXECUTE: **(a)** $r_{a1} = r_{a2} = \frac{1}{2}\sqrt{(0.0300\ \text{m})^2 + (0.0300\ \text{m})^2} = 0.0212$ m. $V_a = k\left(\frac{q_1}{r_{a1}} + \frac{q_2}{r_{a2}}\right) = 0$.

(b) $r_{b1} = 0.0424$ m, $r_{b2} = 0.0300$ m.

$$V_b = k\left(\frac{q_1}{r_{b1}} + \frac{q_2}{r_{b2}}\right) = (8.99\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\left(\frac{+2.00\times10^{-6}\ \text{C}}{0.0424\ \text{m}} + \frac{-2.00\times10^{-6}\ \text{C}}{0.0300\ \text{m}}\right) = -1.75\times10^5\ \text{V}.$$

(c) $W_{ab} = q_3(V_a - V_b) = (-5.00\times10^{-6}\ \text{C})[0 - (-1.75\times10^5\ \text{V})] = -0.875$ J.

EVALUATE: Since $V_b < V_a$, a positive charge would be pulled by the existing charges from a to b, so they would do positive work on this charge. But they would repel a negative charge and hence do negative work on it, as we found in part (c).

11. **IDENTIFY:** For a point charge, $V = \frac{kq}{r}$. The total potential at any point is the algebraic sum of the potentials of the two charges.

SET UP: Consider the distances from the point on the *y*-axis to each charge for the three regions $-a \le y \le a$ (between the two charges), $y > a$ (above both charges) and $y < -a$ (below both charges).

EXECUTE: **(a)** $|y| < a: V = \frac{kq}{(a+y)} - \frac{kq}{(a-y)} = \frac{2kqy}{y^2 - a^2}$. $y > a: V = \frac{kq}{(a+y)} - \frac{kq}{y-a} = \frac{-2kqa}{y^2 - a^2}$.

$y < -a: V = \frac{-kq}{(a+y)} - \frac{kq}{(-y+a)} = \frac{2kqa}{y^2 - a^2}$.

A general expression valid for any *y* is $V = k\left(\frac{-q}{|y-a|} + \frac{q}{|y+a|}\right)$.

(b) The graph of *V* versus *y* is sketched in Figure 23.20.

(c) $y >> a: V = \frac{-2kqa}{y^2 - a^2} \approx \frac{-2kqa}{y^2}$.

Answers

1. $F_e = 8.2 \times 10^{-8}$ N
2. x = 0.77 m
3. $E = 2.71\times10^5$ N/C, $\phi = 66.6^\circ$, $F = 5.42\times10^{-3}$ N