Problem 3. Nobel laureate Richard Feynman once said that if two persons stood at arm’s length from each other and each person had \( p = 1\% \) more electrons than protons, the force of repulsion between them would be enough to lift a “weight” equal to that of the entire Earth. Carry out an order of magnitude calculation to substantiate this assertion.

Let \( m = 70 \text{ kg} \) be the mass of one person, and \( q_e \) be the charge of one electron. Assume that there are approximately equal numbers of protons, electrons, and neutrons in a person. Electrons have much less mass than protons or neutrons, so we ignore their mass contribution. Protons and neutrons have very similar masses, so \( N = \frac{m}{2} \) is the number of protons, and \( N_e = N \cdot p \) is the number of extra electrons in each person. Assume they are separated by \( r = 1 \text{ m} \). The force of repulsion \( F \) is given by

\[
F = k_e \left( \frac{q^2}{r^2} \right) = k_e \left( \frac{mp}{2mp^2} \right)^2 = 9.0 \cdot 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \left( \frac{70 \text{ kg} \cdot 0.01 \cdot 1.6 \cdot 10^{-19} \text{ C}}{2 \cdot 1.7 \cdot 10^{-27} \text{ kg} \cdot 1 \text{ m}} \right)^2 \approx 1 \cdot 10^{10} \left( \frac{0.3 \cdot 10^{-19} \text{ C}}{1 \cdot 10^{-27} \text{ kg}} \right)^2 N = 1 \cdot 10^{25} \text{ N} \quad (1)
\]

And a “weight” the mass of the earth would be \( F_g = Mg \approx 6 \cdot 10^{24} \text{ kg} \cdot 9.8 \text{ m/s}^2 \approx 6 \cdot 10^{25} \text{ N} \sim F \).

Problem 4. Two protons in an atomic nucleus are typically separated by a distance of \( r = 2.00 \cdot 10^{-15} \text{ m} \). The electric repulsion force \( F \) between the protons is huge, but the attractive nuclear force is even stronger and keeps the nucleus from bursting apart. What is the magnitude of \( F \)?

\[
F = k_e \left( \frac{q^2}{r^2} \right) = 8.99 \cdot 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \left( \frac{1.60 \cdot 10^{-19} \text{ C}}{2.00 \cdot 10^{-15} \text{ m}} \right)^2 = 57.7 \text{ N} \quad (2)
\]

Problem 9. In the Bohr theory of the hydrogen atom, an electron moves in a circular orbit about a proton, where the radius of the orbit is \( r = 0.529 \cdot 10^{-10} \text{ m} \). (a) Find the magnitude of the electric force each exerts on the other. (b) If this force causes the centripetal acceleration of the electron, what is the speed of the electron?

\[
F = k_e \left( \frac{q^2}{r^2} \right) = 8.99 \cdot 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \left( \frac{1.60 \cdot 10^{-19} \text{ C}}{0.529 \cdot 10^{-10} \text{ m}} \right)^2 = 8.22 \cdot 10^{-8} \text{ N} \quad (3)
\]

(b) Using \( F_c = ma_c = mv^2/r \)

\[
v = \sqrt{\frac{Fr}{m}} = \sqrt{\frac{8.24 \cdot 10^{-8} \text{ N} \cdot 0.529 \cdot 10^{-10} \text{ m}}{9.11 \cdot 10^{-31} \text{ kg}}} = 2.19 \cdot 10^6 \text{ m/s} \quad (4)
\]

Problem 11. In Figure P19.11, determine the point (other than infinity) at which the electric field is zero. \( q_1 = -2.50 \mu \text{C} \) and \( q_2 = 6.00 \mu \text{C} \).
First, we need a coordinate system. Let \( q_1 \) be the origin \((x_1 = 0)\), and \( q_2 \) be at \( x_2 = 1.00 \) m.

The electric field of a finite number of point charge is given by (p. 612, 19.6)

\[
E = k_e \sum_i \frac{q_i}{r_i^2} \hat{r}_i
\]  

(5)

For any point off the \( x \) axis, there would be some force moving the charge in the vertical \( y \) direction, so we only need to look at positions on the \( x \) axis.

A positive test charge placed between the two charges would be pulled to the left by \( F \).

\[
\hat{i}
\]

\( \theta \)

\( \hat{j} \)

\( \hat{k} \)

\( \mathbf{E} = k_e \left( -\frac{q_1}{r_1^2} - \frac{q_2}{(r_1 + x_2)^2} \right) = 0
\]  

(6)

\[
\frac{q_1}{r_1^2} = \frac{q_2}{(r_1 + x_2)^2}
\]  

(7)

\[
\frac{r_1 + x_2}{r_1} = 1 + \frac{x_2}{r_1} = \pm \sqrt{-\frac{q_2}{q_1} \frac{x_2}{r_1}} = 1.82 \text{ m}, -0.392 \text{ m}
\]  

(8)

But \( r_1 = -0.392 \) m is between the two charges (where our assumption about the electric fields opposing each other doesn’t hold), so \( \mathbf{E} = 0 \) only at a \( r_1 = 1.82 \) m \((x = -1.82 \) m).

Problem 15. Four point charges are at the corners of a square of side \( a \) as shown in Figure P19.15, with \( q_1 = 2q \), \( q_2 = 3q \), \( q_3 = 4q \), and \( q_4 = q \). (a) Determine the magnitude and direction of the electric field at the location of charge \( q_4 \). (b) What is the resultant force on \( q_4 \)?

\[
\begin{align*}
\mathbf{E} &= k_e \sum_i \frac{q_i}{r_i^2} \hat{r}_i = k_e \left( \frac{2q}{a^2} \frac{\hat{i}}{\sqrt{2}} + \frac{3q}{\sqrt{2}a^2} \frac{\hat{j}}{\sqrt{2}} + \frac{4q}{a^2} \frac{\hat{k}}{\sqrt{2}} \right) = k_e \frac{q}{a^2} \left( 2\frac{\hat{i}}{a^2} + \frac{3}{2\sqrt{2}} \frac{\hat{j}}{a^2} + 4\frac{\hat{k}}{a^2} \right)
\end{align*}
\]  

(10)

So the magnitude of \( \mathbf{E} \) is given by

\[
E = k_e \frac{q}{a^2} \sqrt{ \left( 2 + \frac{3}{2\sqrt{2}} \right)^2 + \left( 4 + \frac{3}{2\sqrt{2}} \right)^2 } = 5.91k_e \frac{q}{a^2}
\]  

(11)

And the direction \( \theta \) (measured counter clockwise from \( \hat{i} \)) of \( \mathbf{E} \) is given by

\[
\theta = \arctan \left( \frac{4 + \frac{3}{2\sqrt{2}}}{2 + \frac{3}{2\sqrt{2}}} \right) = 58.8^\circ
\]  

(12)

(b) \( \mathbf{F} = q\mathbf{E} \) so the direction of \( \mathbf{F} \) is the same as the direction of \( \mathbf{E} \). The magnitude of \( \mathbf{F} \) is given by \( F = 5.91k_e q^2/a^2 \)

Problem 19. A uniformly charged ring of radius \( r = 10.0 \) cm has a total charge of \( q = 75.0 \mu \text{C} \). Find the electric field on the axis of the ring at (a) \( x_a = 1.00 \) cm, (b) \( x_b = 5.00 \) cm, (c) \( x_c = 30.0 \) cm, and (d) \( x_d = 100 \) cm from the center of the ring.
From Example 19.5 (p. 616) we see the electric field along the axis ($\hat{i}$) of a uniformly charged ring is given by

$$E = \frac{k_e x q}{(x^2 + r^2)^{3/2}} \hat{i}$$

(13)

So applying this to our 4 distances (remembering to convert the distances to meters), we have

$$E_a = 6.64 \cdot 10^6 \text{ N/C} \hat{i}$$

(14)

$$E_b = 24.1 \cdot 10^6 \text{ N/C} \hat{i}$$

(15)

$$E_c = 6.40 \cdot 10^6 \text{ N/C} \hat{i}$$

(16)

$$E_d = 0.664 \cdot 10^6 \text{ N/C} \hat{i}$$

(17)