Chapter 18  Electric Forces and Electric Fields

Key Concepts:

- electric charge
- principle of conservation of charge
- charge polarization, both permanent and induced
- good electrical conductors vs. good electrical insulators
- Coulomb's law for the force exerted by one charged particle on another
- the electric field concept; representation of an electric field using field lines or field vectors
- electric field of a point charge (formula and field pattern, both for a positive point charge and a negative point charge)
- field pattern for a constant (i.e., uniform) electric field
- field pattern for an electric dipole
- properties of electric field lines in the vicinity of conductors (20.6)

(Review vectors and Newton's law of gravity from first semester mechanics)

Recall: two objects attract each other with a gravitational force that is proportional to the product of the masses of the two objects divided by the square of the distance between them:

\[ F = \frac{G m_1 m_2}{r^2} \]
\[
F = \frac{G m_1 m_2}{r^2}
\]
where \(G\) is a constant.

There is a similar law for the force between two objects that have charge, but the difference is that there is only one kind of mass, but there are two types of electric charge \(\rightarrow \oplus\) and \(\ominus\).

As we'll see in an example later in this chapter, electrical forces are typically much stronger (in a certain sense) than gravitational forces. However, most objects in our experience are either electrically neutral (i.e., have an equal number of positive and negative charges) or nearly neutral. Nevertheless, electrical forces are noticeable in every-day life.

Microscopically:

protons: \(\oplus\)
neutrons: no charge (neutral)
electrons: \(\ominus\)

Protons and neutrons have internal structure; they are each made of three quarks. Quarks come in several varieties, with charges that are \(\pm \frac{1}{3}\) or \(\pm \frac{2}{3}\) of a proton charge. Probing to smaller and smaller distances, no internal...
structure has yet been discovered for the electron

Every-day objects become charged when charged particles are transferred from one object to another. In most situations, it is electrons that are transferred.

Examples

1. When you were a child, do you remember rubbing your feet vigorously on a carpet, then bringing a pointed finger next to someone so as to shock them?

2. Run a comb or brush through your hair a few times, then bring it near a stream of tap water. Notice how the stream bends.
Both of these examples of charge transfer by rubbing work best when the humidity is very low — in our part of the world, this is typically the case indoors in winter. Excess charge can "leak" from a charged object via moisture in the air; the greater the humidity, the faster this process will occur.

There are other ways charge can be transferred, such as atomic collisions, absorption of light, etc. We'll talk about some of these means later in the course.

Principle of conservation of electric charge

The net amount of charge in any closed system is always constant.

Like all the fundamental conservation principles, conservation of charge has been verified in countless experiments.

Note that there are some exotic processes where charge can be created or destroyed, but in all of these processes, the NET amount of charge remains constant.

Example: Each fundamental particle has a matching "anti-particle", with the same mass.
but opposite electric charge. If we say that an electron has \(-1\) units of electric charge, then its anti-particle, the positron (this is NOT a proton \(^1\)) has the same mass as an electron, but a charge of \(+1\).

However, one doesn’t detect positrons in nature very often, because as soon as one encounters an electron, they destroy each other ("pair annihilation") and gamma rays are created. The net charge before pair annihilation was zero \((+1)+(-1)=0\) and the net charge after it also zero, since gamma rays have no electric charge.

The opposite process can also occur under the right circumstances ("pair-creation"), but again net charge is conserved.

In each process, energy, momentum, etc., are also conserved.

\[
\text{Charge polarization} \quad \begin{align*}
\text{\( + \)} & \quad \text{\( - \)} \\
\text{\( \circ \)} & \quad \text{\( \circ \)}
\end{align*}
\]

It’s possible for two neutral objects to exert electrical forces on each other if they are polarized. This means that there is an excess of positive charge on one side of the object and an excess of negative charge on the other side.
Sometimes charge polarization is induced by bringing a charged object near to a neutral one.

The neutral sphere contains equal amounts of positive and negative charge.

Negative charge is attracted to the positive rod. This leaves behind positive charge on the other side of the sphere.

The rod doesn’t touch the sphere.

The negative charge on the sphere is close to the rod so it is strongly attracted to the rod.

The positive charge on the sphere is far from the rod, so it is weakly repelled by the rod.

For example, suppose you bring a negatively-charged plastic rod close to a neutral metal block as follows.

The metal block stays neutral, but the plastic rod repels some of the electrons to the far side of the block, leaving the near side with an excess of positive charge. The positively-charged near side of the block is attracted to the plastic rod, and the negatively-charged far side of the block is repelled by the plastic rod. Because the near side of the block is closer to the plastic rod than the far side of the block, there is a small attraction between the rod and the block. (This follows from Coulomb’s law; see Section 20.3.)

Some examples of charge polarization in...
every-day life:

1. Peeling scotch tape from the roll transfers charge, and the piece of tape ripped off ends up being charged. The charged tape then attracts small bits of paper.

2. Bees become charged when their flapping wings rub against the air. They then attract neutral pollen from the flowers they visit.

3. Empty a bag of rice into a pot and you’ll observe that some of the rice grains stick to the plastic bag. Why?

Polarization also has implications for biology and chemistry, because many molecules of interest in biology and chemistry are polarized.
example, the water molecule is polarized, which explains some of water's unusual properties. For instance, water's volume increases in the span of a few degrees before the freezing point. (Search "hydrogen bonding," if you want to learn more about the biochemistry of polarized molecules.)

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**Insulators and Conductors**
- review their properties

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**Coulomb's law**

**Magnitude:** If two charged particles having charges \( q_1 \) and \( q_2 \) are a distance \( r \) apart, the particles exert forces on each other of magnitude

\[
F_{1\text{on}2} = F_{2\text{on}1} = \frac{K|q_1||q_2|}{r^2}
\]

(20.1)

where the charges are in coulombs (C), and \( K = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \) is called the **electrostatic constant**. These forces are an action/reaction pair, equal in magnitude and opposite in direction. It is customary to round \( K \) to \( 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \) for all but extremely precise calculations, and we will do so.

**Direction:** The forces are directed along the line joining the two particles. The forces are **repulsive** for two like charges and **attractive** for two opposite charges.

\[
F = \frac{K|q_1||q_2|}{r^2}
\]
compare to Newton’s law of

\[ F = \frac{GM_1M_2}{r^2} \]

for Coulomb’s law, \(|q_1|\) and \(|q_2|\) are measured in Coulombs (C),
the distance between the charges (r) is measured in metres, and using
\[ k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \]
then the
force \( F \) comes out in Newtons.

Example In which case is the magnitude of the force on a + charge at

the *position (1) the greatest?
(ii) the least?

A) + Θ *
B) Θ + *
C) * + +
D) Θ * Θ

Solution:
A) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) 

B) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) 

C) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) \( \text{greatest net force on } * \) 

D) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) \( \bigcirc \) \( \text{least net force on } * \) 

Example:

Let’s calculate the electrostatic force between two honey bees of mass 

\( m = 0.1 \text{g} = 1 \times 10^{-4} \text{kg} \) and charge 

\( q = 2.3 \times 10^{-12} \text{C} \) and distance 

\( r = 1 \text{cm} = 1 \times 10^{-2} \text{m} \)

\[
F = \frac{K |q_1||q_2|}{r^2}
\]

\[
= \frac{(9 \times 10^9)(2.3 \times 10^{-12})(2.3 \times 10^{-12})}{(10^{-2})^2}
\]

\[
F = 4.7 \times 10^{-8} \text{ N} \quad \text{very small force}
\]

How much acceleration do they feel?

Calculate \( \ddot{a} \) using \( F = ma \)? Do this!

Weight of each bee:

\[
m g \approx (10^{-4})(10) = 10^{-3} \text{ N}
\]
Puzzles about Coulomb's law:

1. "Instantaneous action at a distance"
   - How can it be that two objects that are not touching can nevertheless exert a force on each other? The same issue arises in Newton's law of gravity. When Newton was asked how this could be, he replied "I feign no hypotheses", meaning something along the lines of, "Look, I've discovered how to calculate the force, but I'm not willing to speculate how the force is transmitted."

   He thereby revolutionized our understanding of the universe (unifying what were previously thought to be two separate realms: the earthly and the heavenly), so it would be very unfair to criticize him from going further. It remained a puzzle for more than a century.

2. The "butter sprayer"
Imagine buttering toast using a butter-sprayer. Note that if you double the distance, you can cover 4 times as much toast, albeit with a density that is \( \frac{1}{4} \) as much.

Compare Coulomb's law: if you double the denominator, the force is multiplied by \( \frac{1}{4} \) \( \rightarrow \) Same as the toast - double the distance each slice of toast is sprayed with \( \frac{1}{4} \) as much butter as the original.

This leads to a thought: Could it be that some "electric fluid" flows out of an electric charge, spreading evenly in all directions, like the butter sprayer?

That is not the way we currently see this, but thinking along these lines motivates the idea of a "force field". Faraday spoke of "tentacles of force" in his attempt to understand and explain the field concept. Nowadays we speak of "lines of force".

Definition of Electric Field. Alternative
Definition of Electric Field.

\[ \mathbf{F} = \mathbf{q}_2 \mathbf{E}_2 \]

This is the electric field created by particle \( q_1 \).

\[ \mathbf{E}_1 = \frac{k \mathbf{q}_1 \mathbf{q}_2}{r^2} \]

\[ \text{Thus, } \mathbf{F}_{1\text{on}2} = \mathbf{E}_1 | \mathbf{q}_2 | \]

The idea is that charge 1 creates an electric field \( \mathbf{E}_1 \) throughout space; then charge 2 feels a force \( \mathbf{F}_{1\text{on}2} = \mathbf{E}_1 | \mathbf{q}_2 | \) because it experiences the field \( \mathbf{E}_1 \) in its immediate location. This takes away some of the action-at-a-distance mystery.

**Electric field at a point defined by the force on charge \( q \)**

\[ \mathbf{E} \text{ at } (x, y, z) = \frac{\mathbf{F}_{\text{on}q} \text{ at } (x, y, z)}{q} \quad (20.3) \]

**Electric field of point charge \( q \) at a distance \( r \) from the charge**

\[ \mathbf{E} = \left( \frac{k |q|}{r^2} \right) \begin{cases} \text{away from } q \text{ if } q > 0 \, \text{ or } \, \text{toward } q \text{ if } q < 0 \end{cases} \quad (20.6) \]

Example: Calculate the electric field.
due to a proton in a hydrogen atom.

Solution \( K = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^2 \)

charge of proton: \( q_1 = 1.60 \times 10^{-19} \text{ C} \)

Electric field of proton is:

\[
E = \frac{K q_1}{r^2}
\]

\[
E = \left( 8.99 \times 10^9 \right) \left( 1.60 \times 10^{-19} \right) \frac{1}{r^2}
\]

\[
E_p = 1.44 \times 10^{-4} \frac{\text{N}}{\text{C}} \frac{1}{r^2}
\]

This is the magnitude of the field, the direction is radially outward from the proton. See pictures on page 657 of the textbook.
(a) The electric field diagram of a positive point charge

The field vectors point away from a positive charge.

(b) The electric field diagram of a negative point charge

The field vectors point toward a negative charge.

Example

Calculate the force exerted by a proton in a hydrogen atom on an electron a distance $5.29 \times 10^{-10}$ m away.

Solution: The magnitude of the force exerted by
The proton on the electron ($F_{p\ to\ e}$) is:

$$F_{p\ to\ e} = \frac{E_p\ |q_e|}{r^2}$$

$$F_{p\ to\ e} = \left(\frac{\text{1.644} \times 10^{-9}}{r^2}\right) \left(1.60 \times 10^{-19}\right)$$

$$= \frac{1.44 \times 10^{-9}}{(5.29 \times 10^{-11})^2} \cdot (1.60 \times 10^{-19})$$

$$F_{p\ to\ e} = 8.22 \times 10^{-8} \text{ N}$$

- magnitude
- direction of $F_{p\ to\ e}$: towards the proton

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**Example**: Continue the previous example by calculating the speed of the electron, assuming that the electron travels in a circle of radius $r$ (This is not our current understanding of how atoms work, but let's play along. )

**Solution**: Recall from first semester that the acceleration $a$ of an object travelling in a circle of radius $r$ is related to its speed $v$ by

$$a = \frac{v^2}{r}$$

Combining this with $F=ma$, and using the force calculated in the previous example, we get

$$ma = F$$
\[
\frac{mv^2}{r} = 8.22 \times 10^{-8}
\]
\[v^2 = \frac{8.22 \times 10^{-8}}{m}
\]
\[v^2 = \frac{8.22 \times 10^{-8}}{9.11 \times 10^{-31}}
\]
\[v^2 = 4.7756 \times 10^2
\]
\[v = 2.18 \times 10^6 \text{ m/s}
\]
\[\approx 2000 \text{ km/s}
\]

Now let's calculate the gravitational force that a proton exerts on an electron in a hydrogen atom (Again we'll pretend the electron is in a circular orbit of radius \(5.29 \times 10^{-11}\) m)

\[F = \frac{G m_1 m_2}{r^2}
\]
\[= \frac{(6.67 \times 10^{-11})(1.67 \times 10^{-27})(9.11 \times 10^{-31})}{(5.29 \times 10^{-11})^2}
\]
\[F = 3.63 \times 10^{-47} \text{ N}
\]

Compare this gravitational force with the electric force of the proton on the electron (calculated above): \(8.22 \times 10^{-8} \text{ N}\). The gravitational force of the proton on the electron is EXTREMELY TINY.
The word "linear" is used to mean several different things in mathematics and physics. The classical theory of electricity and magnetism is a linear theory (at least in vacuum; in some materials it's a more complex story). This means that the fundamental differential equations of the theory are linear. This also means that a superposition principle is operative for electric fields.

That is, suppose you wish to calculate the net electric field due to several point charges. The principle of superposition states that it's possible to calculate the electric field due to each point charge separately, and then just add the resulting fields (vector sum) to determine the net electric field.

This is about as simple as it could possibly be, and makes our lives a lot easier. This is one reason why Einstein's theory of gravity is so hard to work with; it's a nonlinear theory, because its basic differential equations are nonlinear. Thus, if you use Einstein's theory of gravity to calculate the total gravitational field due to two massive objects, you can't just find the field of each object separately and then form the vector sum to determine the net field. You have to treat each configuration of masses as a new problem that you have to solve "from scratch."
Newton's theory of gravity is a linear theory, so the superposition principle is valid for it. One way of looking at Newton's theory of gravity is that it's a linear approximation to Einstein's (nonlinear) theory of gravity. This perspective might appeal to all you calculus lovers out there.

The following example illustrates the superposition principle in action.

Strategy: by the principle of superposition, the field at \( \star \) due to the two charges is the vector sum of the fields \( \vec{E}_1 \) and \( \vec{E}_2 \) due to each charge.

\[
\vec{E}_1 = \frac{kq_1}{r^2}
\]
\[ r^2 = (0.05)^2 + (0.05)^2 \]
\[ = 2(0.05)^2 = 2 \times 5 \times 10^{-2} \times 5 \times 10^{-2} \]
\[ = 5 \times 10^{-3} \]
\[ E_1 = \frac{k\varphi_1}{r^2} = \frac{(9 \times 10^9)(1 \times 10^{-9})}{5 \times 10^{-3}} \]
\[ E_1 = 1.8 \times 10^3 \text{ N/C} \]

Notice, \( E_2 = E_1 \); therefore,
\[ E_2 = 1.8 \times 10^3 \text{ N/C} \]

Now for the components of \( E_1 \) and \( E_2 \)

\[ \cos 45^\circ = \frac{E_{1x}}{E_1} \]
\[ \cos 45^\circ = \frac{E_{1x}}{E_1} \]
\[ E_{1x} = E_1 \cos 45^\circ \]
\[ E_{1y} = -E_1 \sin 45^\circ \]

Similarly for \( E_2 \)
\[ \cos 45^\circ = \frac{E_{2x}}{E_2} \]
\[ \cos 45^\circ = \frac{E_{2x}}{E_2} \]
\[ E_{2x} = -E_2 \cos 45^\circ \]
\[ E_{2y} = -E_2 \sin 45^\circ \]

The total electric field is
\[ \vec{E} = \vec{E}_1 + \vec{E}_2 \]
\[ E_x = E_{1x} + E_{2x} = E_1 \cos 45^\circ - E_2 \cos 45^\circ = 0 \]
\[ E_y = E_{1y} + E_{2y} = -E_1 \sin 45^\circ - E_2 \sin 45^\circ \]
\[ E_y = (-1.8 \times 10^3)(\frac{\sqrt{2}}{2}) - (1.8 \times 10^3)(\frac{\sqrt{2}}{2}) \]
\[ E_y = -1.8 \times 10^3 N/C \]

Thus, the net electric field at \( P \) has magnitude \( 2.6 \times 10^3 N/C \), directed in the \((-y)\) direction.

Compare the calculation above with the field pattern for a dipole: (the electric field vector calculated above is indicated in red.)

Check out a good picture of an electric dipole field pattern on page 661; also see the figures on page 658.
Electric field of a parallel-plate capacitor

Note that the electric field is nearly constant (in magnitude and direction) towards the centre, the "fringe" field at the edges is not constant.

The electric field within a parallel-plate capacitor, near the central region (where it's approximately constant) has magnitude

\[ E = \frac{Q}{\varepsilon_0 A} \]

where \( Q \) is the magnitude of the charge on each plate (+Q on one plate, -Q on the other).
\( E_0 \) is a constant, and
\( A \) is the area of each plate (one face)

A practical application of a parallel-plate capacitor is an electric air filter that many people have in their home's forced-air gas furnace. Air is blown between the parallel plates of the filter. The electric field ionizes smoke or dust particles, which are then attracted to one of the plates and stick there.

Conductor in an electric field
(a) The electric field inside the conductor is zero.

All excess charge is on the surface.

(b) The electric field at the surface is perpendicular to the surface.

Surface charge
A void completely enclosed by the conductor

The electric field inside the enclosed void is zero.

The charges are closer together and the electric field is strongest at the pointed end.
When a conductor is placed in an electric field, charges move inside the conductor (they're pushed by the field). Once equilibrium is achieved (which happens in a very small fraction of a second), then:

* any excess charge is on the surface
* \( E = 0 \) inside the conductor
* \( E \) at the surface is \( \perp \) to the surface
* charge density and \( E \) are highest near any sharp points of the conductor

Review the textbook to make sure you understand why these properties of a conductor are true. (The last property will be easier to understand once we study electrical potential in Chapter 21.)

The fact that the electric field is greatest near a sharp point on a conductor explains why you pointed your finger before shocking your unsuspecting little brother when you were a mischievous kid. (Explain this!) It also explains why lightning rods end in a
sharp print. (Check the textbook to learn what lightning rods are and how they work.)

**Electrostatic Shielding**

The fact that the field inside a conductor is zero leads to a practical application. (As we'll see in Chapter 21, if there is a hollow inside a conductor, the electric field in the hollow is also zero.)

Sensitive electronic equipment is shipped in a foil bag for shipping; since the electric field inside the foil bag will be zero regardless of the fields outside, the equipment is effectively isolated and therefore shielded from any external electric fields.

Metal meshes can be nearly as good at shielding as solid conductors, especially if the mesh is fine. When I was a child, the wires that carried TV signals from our roof-top antenna to our TV were unshielded. This means that when Mom was in the kitchen using the cake-mixer, the powerful electromagnetic waves from the mixer's motor would invade the TV wires and the TV became so disturbed it was unwatchable.
(We did get a cake out of it.)

Nowadays, the wires that bring TV signals to your TV are called co-axial cables (co-AX for short). The signal travels down a central wire, which is surrounded by insulation, which is then covered by a metal mesh (which shields the central wire from any external disturbance), which is finally covered with another layer of insulation.

If you cut open your cable-TV cable, it looks something like this.

The same shielding helps to protect passengers in cars or airplanes from lightning strikes. (Even though there are windows, the metal body often does an excellent job of shielding the interior from the very strong electric field of the lightning.)

Metal structures such as bridges have a very coarse mesh, but they are still pretty good at foiling up your car’s AM radio reception when you drive underneath—another example of shielding.

OMIT Section 18.9
Example

An electric field of magnitude 100,000 N/C directed towards the right causes the 5.0 g ball in the figure to hang at a 20 degree angle. Determine the charge on the ball.

Solution: Draw a free-body diagram:
The net force on the ball is zero, as the ball is permanently at rest. Write Newton's second law of motion for each coordinate direction in the free-body diagram:

\[
T \cos 20^\circ - mg = 0 \quad (1)
\]
\[
q_0 E - T \sin 20^\circ = 0 \quad (2)
\]

We have two independent equations for two unknowns; eliminate \( T \) and solve for \( q_0 \):

\[
(1) \rightarrow T = \frac{mg}{\cos 20^\circ}
\]
\[
(2) \rightarrow q_0 E = \left( \frac{mg}{\cos 20^\circ} \right) \sin 20^\circ
\]

\[
q_0 = \frac{mg \tan 20^\circ}{E}
\]
\[
q_0 = \frac{(5 \times 10^{-3} \text{ kg})(9.8 \text{ m/s}^2) \tan 20^\circ}{100,000 \text{ N/C}}
\]
\[
q_0 = 17.8 \text{ nC}
\]

Problem

How many of the Earth's electrons would have to be transferred to the Sun so that the resulting electrostatic force of attraction between the Earth and
The mass of the Earth is about $10^{27}$ g, and Avogadro's number is about $10^{23}$, so this means that there are about $10^{50}$ atoms (very approximately), and so there are at least that many electrons in the Earth. You can see that the fraction of the Earth's electrons that would have to be transferred is extremely small as a percentage of the total number of electrons in the Earth.

You can do the calculation precisely; I'd be interested to see your solution.

Selected problems and solutions:

Question: What is alike when we say "two like charges?"
Do they look, feel, or smell alike?

"Like" charges are either both $+$ or both $-$.  
"Unlike" charges — one is $+$ and one is $-$.  

Question: Plastic and glass rods that have been charged by rubbing with wool and silk, respectively, hang by threads. (a) An object repels the plastic rod. Can you
predict what it will do to the glass rod? Explain. (b) Repeat part (a) for an object that attracts the plastic rod.

(a) The object must be negatively charged. If the object were neutral, there would be no electric force. If the object were positive, it would attract the plastic rod. Therefore, the object is negatively charged—therefore the object attracts the glass rod.

(b) Could the object be \( \Theta \) ? No, because then it would repel the plastic rod.

2. Could the object be \( \Theta \)? Yes.

3. Could the object be neutral? Yes.

Polarization
If we subsequently move the neutral object to the other side of the charged object, the polarization of the neutral object flips.

Thus, the polarization of an object is temporary—if the charged object causing the polarization is moved away, then the neutral object will no longer be polarized.

There was a question in class about whether the polarization effect weakens for points in the neutral object farther from the charged object. It does in this case, because the electric field produced by the charged rod is not constant, but weakens with distance from the charged rod. For a constant electric field, the polarization in the neutral rod would be constant. (We are assuming that the dielectric properties of
the neutral object are homogeneous and isotropic—but now we are getting WAY beyond the level of this course, and you can safely ignore this sentence.)

Question: A lightweight metal ball hangs by a thread. When a charged rod is brought near, the ball moves towards the rod, touches the rod, then quickly "flies away" from the rod. Explain.

When the ball touches the rod, some charge is transferred, so that the ball and rod have like charges. Thus they repel (I've drawn them with negative charges, but they might both have positive charges — they will still repel.)

Question: Metal sphere A has 4 units of negative charge, and metal sphere B has 2 units of positive charge. The two spheres are brought into contact. What is the final charge state of each sphere?

Each sphere ends up with a charge of -1.

We can pretend that it happens step-by-step:

A  
\[ - - \]  
P  
\[ + + \]
Problem: A plastic rod has been charged to $-20 \text{ nC}$ by rubbing.  
(a) Have electrons been added or protons been removed? Explain. 
(b) How many electrons have been added or protons removed?

What is a coulomb?

$|e| = 6.25 \times 10^{18} \text{ elementary charges}$

Similarly, the charge on one electron is

$-e = -1.60 \times 10^{-19} \text{ C}$

The charge on one proton is

$e = 1.6 \times 10^{-19} \text{ C}$

Problem: A plastic rod has been charged to $-20 \text{ nC}$ by rubbing.  
(a) Have electrons been added or protons been removed? Explain. 
(b) How many electrons have been added or protons removed?

(a) electrons added 
(b) $20 \text{ nC} = 20 \times 10^{-9} \text{ C}$

$= 20 \times 10^{-9} \times 6.25 \times 10^{18} \text{ electrons}$

$= 1.25 \times 10^{11} \text{ electrons}$

Problem: A plastic rod that has been charged to $-15.0 \text{ nC}$ touches a metal sphere. Afterward, the charge on the rod
is $-10.0$ nC.
(a) What kind of charged particle was transferred between the rod and the sphere, and in which direction?
(b) How many charged particles were transferred?

(a) 1.0 \times 10^{12} electrons were transferred from the plastic rod to the metal sphere.

(b) $5.0$ nC of charge is transferred.

The number of electrons transferred is

$5 \text{ nC} = 5 \times 10^{-9} \times 6.25 \times 10^{18} \text{ electrons}$

$= 3.125 \times 10^{10} \text{ electrons}$

Problem: Two identical metal spheres A and B are connected by a metal rod. Both are initially neutral. Then $1.0 \times 10^{12}$ electrons are added to sphere A, then the connecting rod is removed. Afterward, what is the charge on each sphere?

Eventually, half of the charge is on the left sphere and half on the right sphere. That is, there are $5.0 \times 10^{11}$ electrons on each sphere.

(We are assuming that the connecting rod is very thin compared to the size of the spheres.)

Problem: A metal rod A and a metal sphere B, on insulating stands, touch each other. They are originally neutral. A positively charged rod is brought near, but not
Problem: A metal rod A and a metal sphere B, on insulating stands, touch each other. They are originally neutral. A positively charged rod is brought near (but not touching) the far end of A. While the charged rod is still close, A and B are separated. The charged rod is then withdrawn. Is the sphere then positively charged, negatively charged, or neutral? Explain.

Eventually:

\[ + \quad + \]

Question: Rank in order, from largest to smallest, noting any ties, the electric field strengths \( E_1 \) to \( E_4 \) at points 1 to 4 in the figure.

The electric field is strongest where the field lines are most concentrated. Thus:

\[ E_3 = E_4 > E_2 > E_1 \]

Connection between electric force and electric field:

\[ \vec{F} = q \vec{E} \]
\[ F = \frac{kQ_1Q_2}{r^2} = \left(\frac{kQ_1}{r^2}\right)Q_2 \]

Thus, \( F = EA_2 \); that is, the force of particle \( Q_1 \) on particle \( Q_2 \) is the product of the charge \( Q_2 \) and the strength of the electric field \( E \) (created by \( Q_1 \)) at the location of \( Q_2 \). This takes some of the mystery out of “action-at-a-distance.”

Imagine hiking on a hillside. Sometimes the hill is steep, sometimes gently-sloped, sometimes there is a cliff. If the hill were invisible, this would be quite a mystery.

Now imagine that an electric field is analogous to a hilly landscape— but an invisible one, so it’s a bit mysterious.

In this chapter we describe an electric field in terms of “field lines” (what Faraday originally called “lines of force”), or (equivalently) as a collection of vectors, one for each point in space.

In the next chapter we’ll study an alternative description of an electric field, in terms of electric potential— this is closer to the landscape perspective.

Problem: Two small plastic spheres each have a mass of 2.0 g
and a charge of \(-50.0 \text{nC}\). They are placed 2.0 cm apart.

(a) What is the magnitude of the electric force between the two spheres?

(b) By what factor is the electric force on a sphere larger than its weight?

\[ F = \frac{kQ_1 Q_2}{r^2} \]

\[ F = \frac{(9 \times 10^9)(50 \text{nC})(50 \text{nC})}{(0.02)^2} \]

\[ F = \frac{(9 \times 10^9)(5 \times 10^{-9})(5 \times 10^{-9})}{(0.02)^2} \]

\[ F = 5.625 \times 10^2 \text{N} \]

\[ F = 0.056 \text{N} \]

(b) \[ W = mg \]

\[ W = (0.002 \text{kg})(9.8) \]

\[ W = 0.02 \text{N} \]

so the electric force is quite significant — it’s almost 3 times as large as the weight.

Problem: Determine the magnitude and direction of the force on charge A in the figure.
Superposition principle! Calculate (separately) the force that B exerts on A (\( \vec{F}_{BA} \)) and the force that C exerts on A (\( \vec{F}_{CA} \)). Then the total force on A is \( \vec{F}_{BA} + \vec{F}_{CA} \).

Since both forces \( \vec{F}_{BA} \) and \( \vec{F}_{CA} \) lie along the "x-axis," treating them as vectors means simply to use a \( \Theta \) sign for forces pointing to the right \( \rightarrow \), and to use a \( \Theta \) sign for forces pointing to the left \( \leftarrow \).

Use Coulomb's law to calculate each force:

\[
\vec{F}_{BA} = \frac{kQ_A Q_B}{r_{AB}^2} = \frac{(9 \times 10^9)(1 \times 10^9)(-1 \times 10^9)}{(0.01)^2}
\]

\[
\vec{F}_{BA} = -9 \times 10^{-5} \text{ N}
\]

and

\[
\vec{F}_{CA} = \frac{kQ_A Q_C}{r_{AC}^2} = \frac{(9 \times 10^9)(1 \times 10^9)(4 \times 10^9)}{(0.02)^2}
\]

\[
\vec{F}_{CA} = 9 \times 10^{-5} \text{ N}
\]

The total force on A is

\[
\vec{F}_{BA} + \vec{F}_{CA} = -9 \times 10^{-5} + 9 \times 10^{-5} = 0
\]

Problem: What magnitude charge creates a 1.0 N/C electric field at a point 1.0 m away?

\[
E = \frac{kQ}{r^2}
\]
Problem: A 30 nC charged particle and a 50 nC charged particle are near each other. There are no other charges nearby. The electric force on the 30 nC particle is 0.035 N. The 50 nC particle is then moved very far away. Afterward, what is the magnitude of the electric field at its original position?

\[
Q = \frac{E r^2}{k} = \frac{(1)(1)^2}{9 \times 10^9} = 1 \times 10^{-10} \text{ C} = 0.11 \text{ nC}
\]

\[
E = \frac{K Q}{r^2}
\]

**Step 1** Find \( r \)

\[
F = \frac{K Q_1 Q_2}{r^2} \rightarrow r^2 = \frac{K Q_1 Q_2}{F}
\]

\[
r^2 = \frac{9 \times 10^9 \left(3 \times 10^9\right) \left(5 \times 10^{-9}\right)}{0.035} = 4 \times 10^{-4} \text{ m}
\]

\[
r = 2 \times 10^{-2} \rightarrow r = 0.02 \text{ m}
\]

**Step 2**

\[
E = \frac{K Q}{r^2} = \frac{\left(9 \times 10^9\right) \left(3 \times 10^{-9}\right)}{(0.02)^2} = 6.8 \times 10^5 \text{ N}
\]

Problem: A +10 nC charge is located at the origin.

(a) What are
the strengths of the electric field vectors at the positions \((x, y) = (5.0 \text{ cm}, 0.0 \text{ cm}), (-5.0 \text{ cm}, 5.0 \text{ cm}), \text{ and } (-5.0 \text{ cm}, -5.0 \text{ cm})\)?

(b) Draw a diagram showing the electric field vectors at these points.

Solution:

\[
\vec{E} = \frac{kQ}{r^2}
\]

First find \(r\):

\[
r^2 = 0.05^2 + 0.05^2
\]

\[
r^2 = 0.0025 + 0.0025
\]

\[
r^2 = 0.005
\]

\[
|\vec{E}| = \frac{kQ}{r^2} = \frac{(9 \times 10^9) (10 \times 10^{-9})}{0.005}
\]

\[
|\vec{E}| = 1.8 \times 10^4 \text{ N/C}
\]

I'll let you calculate the electric field at the other two points.

Problem: What is the strength of an electric field that will balance the weight of a 1.0 g plastic sphere that has been charged to \(-3.0 \text{ nC}\)?

Solution:

We want the magnitude of the electric force to balance the gravitational force

Thus

\[
|\vec{F_E}| = |mg|
\]

Solving for \(E\), we get

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m = 1 \text{ g} = 0.001 \text{ kg})</td>
</tr>
<tr>
<td>(Q = 3 \text{ nC} = 3 \times 10^{-9} \text{ C})</td>
</tr>
</tbody>
</table>
Solving for \( E \), we get
\[
E = \frac{mg}{Q} = \frac{(0.001)(9.8)}{3 \times 10^{-6}} = 3.3 \times 10^6 \text{ N/C}
\]

Problem: A parallel-plate capacitor is formed from two 4.0 cm \( \times \) 4.0 cm electrodes spaced 2.0 mm apart. The electric field strength inside the capacitor is \( 1.0 \times 10^6 \) N/C. What is the charge in nC on each electrode?

Solution:
\[
E = \frac{Q}{\varepsilon_0 A} \rightarrow Q = \varepsilon_0 A E = 8.85 \times 10^{-12} \left( \frac{1}{\text{C}^2/(\text{N} \cdot \text{m}^2)} \right) \left( 1.0 \times 10^6 \right)
\]
\[
A = 4 \text{ cm} \times 4 \text{ cm} = 0.04 \text{ m} \times 0.04 \text{ m} = 1.6 \times 10^{-3} \text{ m}^2
\]
\[
Q = 1.4 \times 10^{-8} \text{ C} = 14 \text{ nC}
\]

Problem: A 2.0-mm-diameter copper ball is charged to +50 nC. What fraction of its electrons have been removed? Copper has density 8900 kg/m\(^3\), atomic mass 63.5 g/mole, and atomic number 29.

Solution:
First calculate the mass of the copper ball.
\[
\text{mass} = (\text{density}) \times (\text{volume})
\]
\[
m = \rho \cdot \frac{4}{3} \pi r^3 = \left( 8900 \text{ kg/m}^3 \right) \left( 2.0 \times 10^{-3} \text{ m} \right)^3 = 9.8 \times 10^{-3} \text{ kg}
\]
\[
\text{diameter} = 2.0 \text{ mm}
\]
\[
\text{radius} = 1.0 \times 10^{-3} \text{ m}
\]
Problem: Two protons are 2.0 fm apart. Determine the magnitude of the (a) electric force and (b) gravitational force of one proton on the other.
(c) Calculate the ratio of the electric force to the gravitational force and comment.

Solution:
Problem: An electric dipole is formed from 1.0 nC point charges spaced 2.0 mm apart. The dipole is centred at the origin, oriented along the y-axis. Determine the electric field strengths at the points
(a) \((x, y) = (10 \text{ mm}, 0 \text{ mm})\) and
(b) \((x, y) = (0 \text{ mm}, 10 \text{ mm})\).

Solution:

\[
\text{By symmetry, these two distances are the same.}
\]

\[
\text{By symmetry, these two angles are the same.}
\]

Use Pythagoras to determine \(r^2\):

\[
r^2 = (0.01)^2 + (0.0001)^2
\]

\[
r^2 = 0.000101 \text{ m}^2
\]
Also notice that

$$r^2 = 0.000101 \text{ m}^2$$

$$r = 0.01005 \text{ m}$$

$$\cos \theta = \frac{0.01 \text{ m}}{0.01005 \text{ m}} = 0.99504$$

and

$$\sin \theta = \frac{0.001 \text{ m}}{0.01005 \text{ m}} = 0.099504$$

Now let's calculate the magnitudes of the electric field vectors, $|\vec{E}_1|$ and $|\vec{E}_2|:

$$|\vec{E}_1| = \frac{\varepsilon_0 Q_1}{r^2} = \frac{9 \times 10^9 (1 \times 10^9)}{0.000101} = 8.9 \times 10^4 \text{ N}$$

Similarly, $|\vec{E}_2| = 8.9 \times 10^4 \text{ N}$ also.

The components of $\vec{E}_1$ and $\vec{E}_2$ are

$$\vec{E}_1 = (|\vec{E}_1| \cos \theta, -|\vec{E}_1| \sin \theta) \quad \text{and} \quad \vec{E}_2 = (-|\vec{E}_2| \cos \theta, -|\vec{E}_2| \sin \theta)$$

Therefore, the net electric field at the indicated point is (superposition principle!)

$$\vec{E} = \vec{E}_1 + \vec{E}_2$$

$$= (|\vec{E}_1| \cos \theta - |\vec{E}_2| \cos \theta, -|\vec{E}_1| \sin \theta - |\vec{E}_2| \sin \theta)$$

$$= (0, -2(8.9 \times 10^4)(0.099504))$$

$$\vec{E} = (0, -18000 \text{ N/C})$$

The electric field strength at this point is

$$|\vec{E}| = 18000 \text{ N/C}$$

(b) Try this one yourself. The final result is

$$\vec{E} = (0, 37000 \text{ N/C})$$

So the field strength is $|\vec{E}| = 37000 \text{ N/C}$
Problem: The figure shows four charges at the corners of a square of side \( L \). Assume that \( q \) and \( Q \) are positive.

(a) Draw a diagram showing the three forces on charge \( q \) due to the other charges.

(b) Obtain an expression for the magnitude of the net force on \( q \).

Solution:

\[
|\vec{F}_1| = \frac{k|q||Q|}{L^2}
\]
\[ \vec{F}_1 = \left( -\frac{KQq_1}{L^2}, 0 \right) \]

Similarly,
\[ \vec{F}_2 = \left( 0, -\frac{KQq_2}{L^2} \right) \]

\[ |\vec{F}_3| = \frac{K|4Q|L}{r^2} = \frac{4KQq_1}{2L^2} \]
\[ |\vec{F}_3| = \frac{2KQq_2}{L^2} \]

\[ F_{3x} = |\vec{F}_3| \cos 45^\circ = \frac{2KQq_1}{\sqrt{2}L^2} = \frac{\sqrt{2}KQq_1}{L^2} \]
\[ F_{3y} = |\vec{F}_3| \sin 45^\circ = \frac{2KQq_2}{\sqrt{2}L^2} = \frac{\sqrt{2}KQq_2}{L^2} \]

\[ \vec{F}_3 = \left( \frac{\sqrt{2}KQq_1}{L^2}, \frac{\sqrt{2}KQq_2}{L^2} \right) \]

Net force on \( q_2 \) is the sum \( \vec{F}_1 + \vec{F}_2 + \vec{F}_3 \)
\[ \vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = \left( -\frac{KQq_1}{L^2}, 0 \right) + \left( 0, -\frac{KQq_2}{L^2} \right) + \left( \frac{\sqrt{2}KQq_1}{L^2}, \frac{\sqrt{2}KQq_2}{L^2} \right) \]

\[ \vec{F} = \left( \frac{2z-1}{L^2}, \frac{2z-1}{L^2} \right) \]

\[ |\vec{F}| = \frac{KQq_2}{L^2} \sqrt{(2z-1)^2 + (2z-1)^2} \]
\[ = \frac{KQq_2}{L^2} \sqrt{2(2z-1)^2} \]
\[ = \frac{KQq_2}{L^2} \left( \sqrt{2} (2z-1) \right) \]
\[ |\vec{F}| = \frac{KQq_2}{L^2} \left( 2 - \sqrt{2} \right) \]
Problem: Two 2.0-cm-diameter disks face each other, 1.0 mm apart. They are charged to ±10 nC. (a) Determine the electric field strength between the disks. (b) A proton is shot from the negative disk towards the positive disk. What launch speed must the proton have to just barely reach the positive disk?

Solution:

\[
(a) |\vec{E}| = \frac{q}{\epsilon_0 A}
\]

\[
|\vec{E}| = \frac{10 \text{ nC}}{(8.85 \times 10^{-12}) \pi (10^{-4})}
\]

\[
A = \pi r^2 = \pi (0.01)^2
\]

\[
|\vec{E}| = \frac{10 \times 10^{-9}}{(8.85 \times 10^{-12}) \pi (10^{-4})}
\]

\[
|\vec{E}| = 3.6 \times 10^6 \text{ N/C}
\]

(b) Solution 1: Strategy - use the electric field strength from part (a) to determine the force on the proton, then use Newton’s second law to calculate its acceleration, finally, use kinematics equations to determine the initial speed \(v_1\) that results in a final speed of \(v_2 = 0\).

Now carry out the strategy:
\[ F = qE \]
\[ = (1.6 \times 10^{-19} \text{ C})(3.6 \times 10^6 \text{ N/C}) \]
\[ F = 5.76 \times 10^{-13} \text{ N} \]

By Newton's second law, \( a = F/m \), so the acceleration is
\[ a = \frac{F}{m} \]
\[ = -\frac{5.76 \times 10^{-13}}{1.67 \times 10^{-27}} \text{ N/kg} \]
\[ a = -3.45 \times 10^{14} \text{ m/s}^2 \]

The relevant kinematics equation is
\[ v_f^2 - v_i^2 = 2a \Delta x \]
\[ 0 - v_i^2 = 2(-3.45 \times 10^{14})(0.001) \]
\[ v_i^2 = 6.9 \times 10^{11} \]
\[ v_i = 8.3 \times 10^5 \text{ m/s} \]

**Solution 2:** If you would rather use the principle of conservation of energy, you need to also use the concept of potential from Ch 21. That is,
\[ U_i + K_i = U_2 + K_2 \]
\[ K_1 = (U_2 - U_1) + K_2 \]
\[ \frac{1}{2} m v_i^2 = (q V_2 - q V_1) + \frac{1}{2} m v_2^2 \]

But \( v_2 = 0 \),
\[ \frac{1}{2} m v_i^2 = q (V_2 - V_1) \]
\[ \frac{1}{2} m v_i^2 = q \Delta V \]

To find the potential difference \( \Delta V \), note that
\[ \frac{\Delta V}{d} = E \quad \Rightarrow \quad \Delta V = E \cdot d \]
\[ = (3.6 \times 10^6 \text{ N/C})(0.001 \text{ m}) \]
\[ = (3.6 \times 10^6 \text{ V/m})(0.001 \text{ m}) \]
\[ = 3.6 \times 10^3 \text{ V} \]
The question amounts to determining the location on the x-axis where the net force on the sliding bead is zero. Let’s call this position x:

\[
\begin{array}{cccc}
0 & \phantom{0} & x & \phantom{0} & 4 \\
q & \phantom{0} & \phantom{0} & \phantom{0} & 4q
\end{array}
\]

The net force on this charge is

\[
F_{\text{net}} = \frac{Kq^2}{x^2} - \frac{Kq(4q)}{(4-x)^2} = 0
\]

\[
\frac{Kq^2}{x^2} - \frac{4Kq^2}{(4-x)^2} = 0
\]

\[
\frac{1}{x^2} - \frac{4}{(4-x)^2} = 0
\]

\[
\frac{1}{x^2} = \frac{4}{(4-x)^2}
\]
(4-x)^2 = 4x^2
4 - x = \pm 2x

Thus, either 4 - x = 2x or 4 - x = -2x
4 = 3x or 4 = -x

x = \frac{4}{3} \text{ cm} or x = -4 \text{ cm}

Thus, the lead has a net force of zero on it at x \approx 13 \text{ cm}

Problem: An electric field \( \vec{E} = (200,000 \text{ N/C, right}) \) causes the 2.0 g ball in the figure to hang at an angle. Calculate the angle \( \theta \).

Solution:

Draw a free-body diagram:

Since the charge is at rest, the x-component and the y-component of the net force are both zero. Thus, we get:

\[-T \sin \theta + qE = 0 \rightarrow T \sin \theta = qE\]

\[T \cos \theta - mg = 0 \rightarrow T \cos \theta = mg\]
Problem 49: An electron is released from rest at the negative plate of a parallel plate capacitor. The magnitude of the charge per unit area on each plate is \(1.8 \times 10^{-7} \text{ C/m}^2\), and the plates are separated by a distance of \(1.5 \times 10^{-2} \text{ m}\). How fast is the electron moving just before it reaches the positive plate?

Solution: Assume that the electric field inside the capacitor is uniform (standard assumption for a parallel-plate capacitor). The force exerted by the capacitor's electric field on the electric field is therefore constant, and the electron moves in a straight line across the capacitor.

\[
\tan \theta = \frac{qE}{mg} = \frac{qE}{mg} = \frac{(2.5 \times 10^{-9} \text{ C})(2 \times 10^5 \text{ N/C})}{(2 \times 10^{-3} \text{ kg})(9.8 \text{ m/s}^2)} = 0.255
\]

\(\theta = 14.3^\circ\)

\[
\Delta x = 1.5 \times 10^{-2} \text{ m}
\]
The magnitude of the capacitor's uniform electric field is:

\[ E = \frac{\sigma}{\varepsilon_0} \]

By Newton's second law, the constant acceleration of the electron is:

\[ a = \frac{F}{m} \]
\[ a = \frac{q E}{m} \]
\[ a = \frac{q \sigma}{m \varepsilon_0} \]

Using the following kinematics equation, we can determine the speed of the electron just before it hits the positive plate.

\[ v^2 = v_0^2 + 2a \Delta x \]
\[ v^2 = 0^2 + 2 \left( \frac{q \sigma}{m \varepsilon_0} \right) \Delta x \]
Problem 50: Two particles are in a uniform electric field whose magnitude is 2500 N/C. The mass and charge of particle 1 are \( m_1 = 1.4 \times 10^{-5} \text{ kg} \) and \( q_1 = -7.0 \times 10^{-6} \text{ C} \), whereas the corresponding values for particle 2 are \( m_2 = 2.6 \times 10^{-5} \text{ kg} \) and \( q_2 = +18 \times 10^{-6} \text{ C} \).

Initially the particles are at rest. The particles are both located on the same electric field line but are separated from each other by a distance \( d \). When released, they accelerate, but always remain at this same distance from each other. Find \( d \).

Solution: Draw a free-body diagram for each particle. Then use the condition that the acceleration of each particle is the same, in conjunction with Newton's second law. You will be left with one equation with only one unknown, \( d \), which can be solved for \( d \).
\[
\begin{align*}
A_2 &= A_1 \\
F_2 &= \frac{F_1}{m_2} \\
\frac{q_2 E - Kq_1 q_2}{d^2} &= \frac{Kq_1 q_2}{d^2} - \frac{q_1 E}{m_1} \\

m_1 q_2 E - m_1 Kq_1 q_2 &= m_2 Kq_1 q_2 - m_2 q_1 E \\
m_1 q_2 E + m_2 q_1 E &= \frac{m_1 Kq_1 q_2}{d^2} + \frac{m_2 Kq_1 q_2}{d^2} \\
(m_1 q_2 + m_2 q_1) E &= \frac{Kq_1 q_2}{d^2} (m_1 + m_2) \\
d^2 &= \frac{Kq_1 q_2 (m_1 + m_2)}{(m_1 q_2 + m_2 q_1) E} \\
d &= \sqrt{\frac{Kq_1 q_2 (m_1 + m_2)}{(m_1 q_2 + m_2 q_1) E}}
\end{align*}
\]
Problem 52: The drawing shows an electron entering the lower left side of a parallel plate capacitor and exiting at the upper right side. The initial speed of the electron is $7.00 \times 10^6$ m/s. The capacitor is 2.00 cm long, and its plates are separated by 0.150 cm. Assume that the electric field between the plates is uniform everywhere and find its magnitude.

$$d = \sqrt{\frac{(8.99 \times 10^9)(7 \times 10^{-6})(18 \times 10^{-6})(1.4 + 2.6 \times 10^{-5})}{[(1.4)(18) + (2.6)(17)] \times 10^{-5} \times 10^{-6} \times 2500}}$$

$$d = 6.46 \text{ m}$$

(That's a very big capacitor!)

Do you understand why the values for the electric charges of the two particles were inserted into the equation as positive numbers, even though one of the charges was negative? Remember that when we draw free-body diagrams, we put the directions of the forces in "by hand" and then input the values into the resulting equations as magnitudes only.

Problem 52: The drawing shows an electron entering the lower left side of a parallel plate capacitor and exiting at the upper right side. The initial speed of the electron is $7.00 \times 10^6$ m/s. The capacitor is 2.00 cm long, and its plates are separated by 0.150 cm. Assume that the electric field between the plates is uniform everywhere and find its magnitude.
Solution: Doesn't this problem remind you of projectile motion? Yes! It's the same idea. The path of the electron, which is a curve, might be intimidating at first, but when you realize that you can treat the components of the motion of the electron separately, it is less intimidating.

Set up your coordinate system so that the positive $x$-axis is to the right and the positive $y$-axis is upward. Then the force in the $x$-direction is zero, which makes that component easy. The force in the $y$-direction is constant, so that component is also pretty easy.

Here's my strategy for solving the problem: Use the dimensions given and kinematics to determine the acceleration of the electron. Then use Newton's second law to determine the force acting on the electron, which can then be connected to the electric field.

\[
t = \frac{\Delta x}{v_x} = \frac{2 \times 10^{-2} \text{ m}}{7 \times 10^6 \text{ m/s}} = \frac{2}{7} \times 10^{-8} \text{ s}
\]

\[
\Delta y = v_{y0}^0 t + \frac{1}{2} a_y t^2
\]

\[
s = 2 \Delta y - 2 \left( 0.15 \times 10^{-2} \text{ m} \right) = 2 \times 10^{-14} \text{ m}^2
\]
The magnitude of the electric field is 2100 N/C. The direction of the electric field is downward (i.e., in the negative y-direction).