B1 · Charge and charging

Completed notes

Explain charge, draw charge separation, and predict the result of contact or grounding.

Slide 1 of 8 · Charge is carried by electrons

A rubbed balloon sticks to a wall. Unit B explains why. We start with what carries charge.

Atoms have **protons** (+) in the nucleus and **electrons** (−) around it. One electron has charge size e = **1.60×10^{-19} C**. C is the **coulomb**, the unit of charge.

Neutral: **equal** protons and electrons, so the charges cancel. Only **electrons** move; protons stay in the nucleus.

Gain electrons: **negative**. Lose electrons: **positive**. Charge is **conserved**: it moves, and is never made or lost.

Charge comes in whole electrons: Q = **ne**. n is a count, with no sign. Find the size, then add the **sign**.

Example. A neutral plastic rod is rubbed with wool and gains 2.5×10^{13} electrons from the cloth. What is the charge on the rod, with its sign? Use e = 1.60×10^{-19} C.

1. The rod gained electrons, so its charge is negative.

2. Q = ne = $(2.5 \times 10^{13})(1.60 \times 10^{-19}\ \text{C}) = 4.00 \times 10^{-6}$ C

3. Charge on the rod: −4.00 µC (1 µC = 10^{-6} C).

Try it. A glass rod is rubbed with silk and ends with a charge of +3.2 µC. How many electrons did the glass rod lose, and where did they go?

1. The glass is positive, so it lost electrons. They went to the silk, which has a charge of −3.2 µC.

2. Change µC to C first: 3.2 µC = 3.2×10^{-6} C.

3. n = Q/e = $(3.2 \times 10^{-6}\ \text{C}) \div (1.60 \times 10^{-19}\ \text{C}) = 2.0 \times 10^{13}$ electrons.

Slide 2 of 8 · Conductors, insulators and rubbing

On slide 1, only electrons moved. Where they can move depends on the material.

In a metal, some outer electrons are **free** and roam the whole object. Metals are **conductors**. In plastic, glass, rubber and wool, electrons stay with their atoms. These are **insulators**.

Extra electrons repel each other. On a metal they **spread out**. On plastic they stay **where you put them**.

Rubbing moves electrons, because materials hold electrons with different strengths. The weaker holder loses electrons and turns **positive**. The other turns **negative** by the **same amount**.

On the diploma, explain a result by saying which way the **electrons** moved.

Example. A plastic ruler is rubbed with a wool cloth and the ruler becomes negative. No protons moved. What is the sign of the charge on the wool, how do the two sizes compare, and which material holds electrons more strongly?

1. The ruler gained electrons and they came from the cloth, so the wool is positive.

2. The two charges have equal size and opposite sign, so the total stays zero (charge is conserved).

3. The plastic holds electrons more strongly, because the electrons moved to it.

Try it. A student rubs a metal rod with a cloth while holding the rod in a bare hand. Brought near bits of paper, it does nothing. Explain why, and say what could be changed so the rod keeps its charge.

1. The metal rod, hand, body and floor all conduct, so the extra electrons flow away to the ground and the rod stays neutral.

2. An insulating handle breaks the path, so the rod keeps its charge.

Slide 3 of 8 · Why a neutral object is attracted

A charged rod also pulls on objects that have no charge. Slide 2 helps explain why.

A negative rod near a neutral metal sphere: like charges repel, so free electrons move to the **far** side. The near side is short of electrons, so it is **positive**.

This shift is charge **separation**. It ends when the rod leaves. The sphere is still **neutral**. No electrons left it.

Unlike charges attract, and the near side is **closer**, so attraction is **stronger**. The sphere is pulled toward the rod.

Attraction alone **does not** prove an object is charged. Only **repulsion** proves it.

Example. A negative rod is held near, but not touching, a neutral metal sphere on an insulating stand. What is the sign of the charge on the side nearest the rod, what is the total charge of the sphere, and does the sphere move toward or away from the rod?

1. The electrons are pushed to the far side, so the near side is positive.

2. The total charge is still zero.

3. The sphere is pulled toward the rod, because the positive side is closer.

Try it. A charged rod attracts a small object hanging from a thread. Which statement must be true? A. The object has a charge opposite to the rod. B. The object is neutral. C. The object may be neutral or have a charge opposite to the rod. D. The object has the same charge as the rod.

1. Answer C.

2. A neutral object is also attracted, because its charges separate, so attraction does not prove an opposite charge.

3. Repulsion is the only test that proves the object is charged with the same sign as the rod.

Slide 4 of 8 · Charging by contact and sharing

So far the rod only came near an object. Now two metal spheres touch.

Touching conductors share charge. If the stands are **insulators**, no charge can enter or leave, so the **total** stays the same.

Identical spheres (same size and shape) end with **equal** charge: $q = \mathbf{(q_1 + q_2) \div 2}$.

Add the charges **with their signs** first, then divide by two. The final sign is the sign of **both spheres**.

Sketch the problem three times: **before**, **during** and **after**, with each charge written beside its sphere. Check that the total after equals the total **before**.

Example. Two identical metal spheres carry +7.0 µC and −3.0 µC. They touch and are then separated. What is the charge on each sphere after the separation?

1. Total = (+7.0 µC) + (−3.0 µC) = +4.00 µC.

2. Identical spheres share equally: each ends with +2.00 µC.

3. Check: +2.00 + 2.00 = +4.00 µC, the same as the total before.

Try it. Three identical spheres A, B and C carry +9.0 µC, 0 and −3.0 µC. A touches B and they separate. Then B touches C and they separate. What is the final charge on each of A, B and C?

1. First touch: A and B each have (9.0 + 0) ÷ 2 = +4.50 µC. C is untouched at −3.0 µC.

2. Second touch: B and C each have (4.5 + (−3.0)) ÷ 2 = +0.750 µC. A stays at +4.50 µC.

3. Check: 4.50 + 0.750 + 0.750 = +6.00 µC, the same as the start.

Slide 5 of 8 · Method: how to find the charge after spheres touch

These are the steps you used on slide 4.

Step 1: write each charge **with its sign**. Step 2: **add** the signed charges. Step 3: divide by the **number of identical spheres**.

Step 4: give **every sphere** that charge, with its sign. Step 5: check that the total after is **the same as** the total before.

Example. Two identical metal spheres carry +7.0 μC and −3.0 μC. They touch and are then separated. Use the five steps to find the charge on each sphere.

1. Steps 1 and 2: (+7.0) + (−3.0) = +4.00 μC.

2. Step 3: (+4.00) ÷ 2 = +2.00 μC.

3. Steps 4 and 5: each sphere has +2.00 μC, and +2.00 + 2.00 = +4.00 μC matches the total before.

Try it. NEW, for teacher review: Two identical spheres carry +5.0 μC and −9.0 μC. They touch and are separated. What is the charge on each sphere?

1. Steps 1 and 2: (+5.0) + (−9.0) = −4.00 μC.

2. Step 3: (−4.00) ÷ 2 = −2.00 μC.

3. Each sphere has −2.00 μC. Check: −2.00 + (−2.00) = −4.00 μC, the same as before.

Slide 6 of 8 · Grounding and induction

On slide 3 the shift ended when the rod left. A path to the Earth lets the sphere keep a charge.

The Earth is so large that it can give or take any number of electrons and stay neutral. A wire or conducting path to the Earth is called a **ground**.

Induction means charging an object **without touching it** with the charged object. Steps in order: 1. bring the rod **near**; 2. connect the **ground**; 3. remove the **ground** wire; 4. remove the **rod**.

A negative rod pushes electrons away, so they leave through the ground and the sphere ends **positive**. A positive rod pulls electrons up from the ground and the sphere ends **negative**.

Contact gives the **same** sign as the rod. Induction gives the **opposite** sign. The shift while the rod is near is charge **separation**; the charge left is **induced** charge. Remove the ground wire first so the charge is trapped; if the rod leaves first, electrons **flow back**.

Example. A positive rod is brought near, but never touches, a neutral metal sphere on an insulating stand. The sphere is grounded with a wire. The ground wire is removed first, and then the rod. What is the sign of the charge left on the sphere, and where did the charge come from?

1. Electrons were attracted from the ground into the sphere and trapped there when the ground wire was removed.

2. The sphere is left negative, the sign opposite to the rod.

Try it. A neutral metal sphere on an insulating stand is to be given a positive charge using a negative rod. Which option does this? A. Touch the rod to the sphere, then remove the rod. B. Rod near, connect ground, remove rod, remove ground. C. Rod near, connect ground, remove ground, remove rod. D. Rod near, remove rod, connect ground.

1. Answer C. The negative rod pushes electrons from the sphere into the ground. The ground is removed first, so they cannot return, and the sphere stays positive when the rod is removed.

2. A charges the sphere negative by contact. B removes the rod while still grounded, so electrons return and the sphere is neutral. D grounds after the rod has gone, so the sphere is neutral.

Slide 7 of 8 · The electroscope

We cannot see electrons shift inside a metal. This tool shows it.

An electroscope is a metal **knob** joined by a metal rod to two thin metal **leaves**. Electrons can move between the knob and the leaves. When it is neutral the leaves hang **together**.

A negative rod near the knob pushes electrons **down** to the leaves. Both leaves are **negative**, so they **repel** and spread apart. A positive rod pulls electrons **up**, so both leaves are **positive** and they spread apart too.

A neutral electroscope shows that a charge is **near**. It cannot show the **sign**. Touch the knob with a charged rod and the leaves **stay apart**: charging by contact. Touch the knob with a finger and the leaves **fall**: it is grounded.

On a charged electroscope, an object with the **same** sign makes the leaves spread more. An object with the **opposite** sign makes them move closer together.

Example. An electroscope has been charged negative by contact, so its leaves stand apart. Charged object X is held near the knob, without touching it, and the leaves move farther apart. X is taken away. Charged object Y is held near the knob, without touching it, and the leaves move closer together. What is the sign of the charge on X, and on Y? Explain each answer with the movement of electrons.

1. X is negative. It repels electrons from the knob down to the leaves. The leaves become more negative, so they repel more and move farther apart.

2. Y is positive. It attracts electrons from the leaves up to the knob. The leaves become less negative, so they repel less and move closer together.

Try it. NEW, for teacher review: An electroscope has been charged positive by contact, so its leaves stand apart. Charged object Z is held near the knob, without touching it, and the leaves move farther apart. What is the sign of the charge on Z? Explain with the movement of electrons.

1. Z is positive. It attracts electrons from the leaves up to the knob.

2. The leaves lose electrons, so they become more positive. They repel more and move farther apart.

Slide 8 of 8 · Method: how to explain a charging result in words

Use these steps for any “explain the charge” question in this lesson.

Step 1: name the object and say whether it is a **conductor**. Step 2: say which way the **electrons** move. Step 3: say what each object **gains or loses**.

Step 4: state the final sign. Gaining electrons gives **negative**; losing electrons gives **positive**. Step 5: say the total charge **did not change**.

Example. A positive rod is brought near a neutral metal sphere on an insulating stand. The sphere is grounded, the ground is removed, and then the rod is removed. Explain the final charge on the sphere.

1. 1: The sphere is metal, so electrons can move through it.

2. 2 and 3: The rod attracts electrons up from the ground, so the sphere gains electrons.

3. 4 and 5: The ground left first, so the sphere is negative, and the total charge did not change.

Try it. NEW, for teacher review: A neutral metal sphere on an insulating stand touches a negative rod. Explain the sign of the charge on the sphere.

1. 1: The sphere is metal, so electrons can move.

2. 2 and 3: Electrons move from the rod to the sphere, so the sphere gains electrons.

3. 4 and 5: The sphere is negative, and the total charge of rod and sphere did not change.

B1 · Worked practice

Charge and charging | Questions 1-2 of 12

Use $k = 8.99 \times 10^9$ N·m²/C² and $g = 9.81$ m/s² where needed. These values are from the Alberta Physics 30 data sheets, Constants section. All point-charge calculations approximate air as vacuum.

Easy · B1-P01. An object has 8 protons and 10 electrons, each with a charge of the same size. What is the object's total charge in units of e, and what electron change would make it neutral?

1. Count both kinds of charge: +8e + (−10e) = −2e. The object is negative because it has two extra electrons.

2. Remove two electrons. That leaves 8 protons and 8 electrons, so the charges balance. The protons do not need to move.

Easy · B1-P02. A neutral metal sphere loses electrons to another object. What is its final sign? Describe the change in the total charge of the two objects together.

1. Electrons carry negative charge. Losing them leaves an electron deficit, so the sphere becomes positive.

2. The other object gains the electrons. Its charge changes by the same amount with the opposite sign. The total charge of the two objects stays the same.

B1 · Worked practice

Charge and charging | Questions 3-4 of 12

Easy · B1-P03. Extra charge spreads across a metal object but stays near the rubbed spot on a plastic object. Which is the conductor and which is the insulator? Explain using charge motion.

1. The metal is the conductor: its free electrons can move through the material.

2. The plastic is the insulator: it resists charge flow through the object. This does not mean it cannot be charged or have its charges separated.

Easy · B1-P04. A known negative object repels a small charged object. What is the sign of the small object? If the observation were attraction instead, could you be certain it was positive? Explain.

1. Repulsion between the charged objects indicates like signs, so the small object is negative.

2. Attraction alone is not enough to decide. A positive object would be attracted, but a neutral object can also be attracted when its charges separate.

B1 · Worked practice

Medium · B1-P05. A positive rod approaches the left side of a neutral metal sphere on an insulating stand without contact. Draw the sphere’s near-side and far-side charge signs, the electron-motion arrow, and its total charge. Explain the attraction.

1. The positive rod attracts free electrons toward the left, nearer side. Draw an electron arrow left within the sphere; label the near side negative and far side positive.

2. No charge enters or leaves the sphere, so its total charge stays zero. The closer negative side is attracted more strongly than the distant positive side is repelled. The net force is toward the rod.

Medium · B1-P06. Two identical metal spheres on insulating supports have +8.0 µC and −2.0 µC. They touch and are separated far apart. No charge escapes. What is each final charge, and which way did electrons move?

1. Givens from the question: qA = +8.0 µC and qB = −2.0 µC; identical spheres on insulating stands. Conservation applies because no charge escapes.

2. Total = +8.0 + (−2.0) = +6.0 µC. In the case of identical spheres, each gets +6.0/2 = +3.0 µC.

3. Electrons move from B toward A. A becomes less positive while B loses electrons and becomes positive. Check: +3.0 + 3.0 = +6.0 µC.

B1 · Worked practice

Medium · B1-P07. A negative rod is held near a neutral metal sphere. The sphere is grounded, the ground is disconnected, and then the rod is removed. What is the final sign? Draw the electron path during grounding and explain the order.

1. The negative rod repels free electrons. Ground provides a conducting path, so electrons leave the sphere and enter Earth. Draw sphere → Earth and label it electron flow.

2. Disconnecting ground while the rod remains traps the electron deficit. Removing the rod then allows the remaining charge to redistribute. The final sphere is positive.

3. The rod never touches the sphere. This is charging by induction, with charge transferred through the ground connection.

Medium · B1-P08. A positive rod is brought near a neutral metal sphere on an insulating stand, then removed. There is no contact or grounding. What are the sphere’s total charge while the rod is near and after it leaves? Explain where the charges sit at both times.

1. While the rod is near, electrons move toward it: the near side is negative and the far side positive. The sphere’s total charge is zero because no charge enters or leaves.

2. After the rod leaves, the electrons redistribute without the rod’s influence. The sphere remains neutral. Separation within one object is different from moving charge on or off it.

B1 · Worked practice

Charge and charging | Questions 9-10 of 12

Challenging · B1-P09. Sphere A starts at +10.0 µC, sphere B at −4.0 µC and sphere C at 0 µC. All are identical metal spheres on insulating supports. A touches B, then they separate far apart. B then touches C and they separate far apart. No charge escapes. What is each final charge? Check the total.

1. For the first contact, A + B = +10.0 - 4.0 = +6.0 µC. Identical spheres share equally: A = +3.0 µC and B = +3.0 µC. C is still zero.

2. Only B and C participate in the second contact. Their total is +3.0 µC, so B = C = +1.5 µC. A stays +3.0 µC.

3. Final: A = +3.0 µC, B = +1.5 µC, C = +1.5 µC. The sum is +6.0 µC, equal to the initial total. Dividing the initial total among all three would ignore the contact sequence.

Challenging · B1-P10. A student charges a sphere using a negative rod and ground, but removes the rod while the ground wire is still attached. The rod is moved far away before the ground is disconnected. What is the final charge? Explain why this differs from the correct induction sequence.

1. With the negative rod nearby, electrons are driven from the sphere to Earth. The sphere has an electron deficit while influenced by the rod.

2. Removing the rod first removes that influence while the conducting Earth path remains open. Electrons can return from Earth, making the sphere neutral.

3. Disconnecting ground afterwards leaves a neutral sphere. To retain positive charge, disconnect ground before removing the negative rod.

B1 · Worked practice

Charge and charging | Questions 11-12 of 12

Challenging · B1-P11. A student says, “A neutral plastic comb cannot be attracted to a charged rod because electrons cannot move freely through plastic.” Identify the error. Draw or describe what the charges inside the comb do to explain the attraction without giving the comb a total charge.

1. The error is treating resistance to charge flow through the object as the inability of any charge to shift. The charges inside an insulator’s atoms or molecules can shift slightly.

2. Draw a negative rod beside several neutral particles. In each particle, show the negative charge shifted slightly away from the rod and the positive side nearer the rod. Each particle and the whole comb remain neutral.

3. The nearer opposite charge is attracted more strongly than the more distant like charge is repelled. This charge separation can attract the comb without giving it a total charge.

Challenging · B1-P12. Two metal objects of different sizes with charges +8.0 µC and −2.0 µC touch, and no charge can enter or leave. A student predicts +3.0 µC on each. Which part of the prediction is guaranteed, which is not, and what extra condition would justify equal sharing?

1. Charge conservation guarantees a final combined total of +6.0 µC. Adding the signed initial charges is valid even when the objects differ.

2. Equal final charges are not guaranteed for unequal conductors. Their shapes affect how the charge is shared.

3. The +3.0 µC-each result is justified for identical conducting spheres, separated far apart afterwards. Conservation alone does not justify dividing by two.

B2 · Coulomb’s law

Completed notes

Calculate a pair force, predict changes, and interpret an inverse-square graph.

Slide 1 of 7 · How the force changes

In B1, like charges repelled and unlike charges attracted. This lesson finds how strong that force is.

Symbols: q_1 and q_2 are the two charges in **coulombs (C)**; r is the distance between them in **metres (m)**; F is the size of the force in **newtons (N)**.

Each charge is its own factor. Double one charge: force × **2**. Double both charges: force × 2 × 2 = × **4**.

Distance: F ∝ **1/r²**. The symbol ∝ means **“is proportional to”**. Double r: force × **1/4**. Triple r: force × **1/9**.

Rule: write each change as a **factor**, then **multiply**. For distance, **flip** the change, then **square** it. A graph of F against $1/r^2$ is a **straight line through the origin**.

Example. Two charges exert a force of 0.800 N on each other. Both charges are doubled in size and the distance between them is tripled. What is the new force?

1. Each charge doubles, so the charges give a factor of 2 × 2 = 4.

2. The distance triples: flip to 1/3, then square it: $(1/3)^2 = 1/9$.

3. New force = 0.800 N × 4 ÷ 9 = 0.356 N. The overall factor 4/9 is less than 1, so the force gets smaller.

Try it. Two charges exert a force of 0.150 N on each other. One charge becomes three times larger and the distance is cut in half. What is the new force?

1. One charge triples, so its factor is 3.

2. The distance is cut in half: flip ½ to 2, then square it: $2^2 = 4$, so the distance factor is 4.

3. New force = 0.150 N × 3 × 4 = 1.80 N. A smaller distance gives a stronger force, so a bigger answer is expected.

Slide 2 of 7 · Coulomb’s law

Slide 1 showed how the force changes. One equation holds all of those rules.

Coulomb’s law gives the size of the force between two **point charges**. A point charge is a **tiny dot**. Formula: $F = \mathbf{k|q_1||q_2|/r^2}$, with $k = \mathbf{8.99 \times 10^9\ N{\cdot}m^2/C^2}$. F is in **newtons (N)**.

Bars | | mean **size only**: drop any minus sign. Convert µC to C by multiplying by $\mathbf{10^{-6}}$. The distance r is in **metres**, measured from **centre to centre**.

The signs give the direction: like charges **repel**, unlike charges **attract**. Choose each arrow from the **signs of the charges**, not from a minus sign in the answer.

Newton’s third law: each charge feels the **same size** of force. To find r, rearrange first: multiply both sides by r^2, divide by F, then take the **square root**: $r = \mathbf{\sqrt{(k|q_1||q_2|/F)}}$.

Example. A +3.0 µC sphere and a −5.0 µC sphere are 0.30 m apart. Use $k = 8.99 \times 10^9\ N{\cdot}m^2/C^2$. What is the size of the force on each sphere, and does the force attract or repel?

1. The charges have opposite signs, so the force is attraction.

2. $F = (8.99 \times 10^9\ N{\cdot}m^2/C^2)(3.0 \times 10^{-6}\ C)(5.0 \times 10^{-6}\ C) \div (0.30\ m)^2 = 1.50\ N$.

3. Each sphere feels 1.50 N. Swapping the sphere positions changes only the arrow, never the size.

Try it. A +2.0 µC sphere and a +4.0 µC sphere repel each other with a force of 0.500 N. What is the distance between them?

1. Rearrange: $r^2 = k|q_1||q_2|/F$, so $r = \sqrt{(k|q_1||q_2|/F)}$.

2. Convert first: $2.0\ \mu C = 2.0 \times 10^{-6}\ C$ and $4.0\ \mu C = 4.0 \times 10^{-6}\ C$.

3. $r = \sqrt{[(8.99 \times 10^9)(2.0 \times 10^{-6})(4.0 \times 10^{-6}) \div 0.500]} = 0.379\ m$. Take the square root at the end, or you get r^2 instead of r.

Slide 3 of 7 · Method: what happens to the force

These are the steps you used on slide 1.

Step 1: write the formula **$F = k|q_1||q_2|/r^2$**. The constant k never changes, so it **drops out**.

Step 2: list the **changes** in words, such as “q_1 doubles” or “r triples”.

Step 3: make one **factor** for each change. A charge that changes by n gives a factor of **n**. A distance that changes by n gives **$1/n^2$**: flip it, then square it.

Step 4: **multiply** the factors. Keep the total as a **fraction**, such as $2 \times 2 \times 1/9 = 4/9$.
Step 5: new force = old force × the **total factor**. Check: a bigger charge or a smaller distance must make the force **bigger**.

Example. Two charges exert a force of 0.800 N on each other. Both charges are doubled in size and the distance between them is tripled. What is the new force?

1. Steps 1 and 2: $F = k|q_1||q_2|/r^2$. q_1 doubles, q_2 doubles, r triples.

2. Step 3: the charges give 2 and 2. The distance: flip 3 to 1/3, then square it to get 1/9.

3. Steps 4 and 5: $2 \times 2 \times 1/9 = 4/9$, so the new force is $0.800\ \text{N} \times 4/9 = 0.356\ \text{N}$. The total factor is less than 1, so the force is weaker.

Try it. Two charges exert a force of 0.500 N on each other. The distance is doubled and one charge is tripled. What is the new force? Write each step number beside your work.

1. The distance doubles: flip 2 to 1/2, then square it to get 1/4. One charge triples: factor 3.

2. Total factor = $3 \times 1/4 = 3/4$.

3. New force = $0.500\ \text{N} \times 3/4 = 0.375\ \text{N}$. The total factor is less than 1, so the force is weaker. This matches a longer distance winning over a bigger charge.

Slide 4 of 7 · Method: force between two charges

These are the steps you used on slide 2.

Step 1: list the givens in **coulombs** (μC × 10^{-6}) and **metres**.

Step 2: use the **sizes** of the charges. Drop any minus sign, because the size of a force is never **negative**.

Step 3: put the numbers into $F = \mathbf{k|q_1||q_2|/r^2}$, with $k = \mathbf{8.99 \times 10^9\ N{\cdot}m^2/C^2}$. Square the **distance**.

Step 4: use the signs for the direction. Like charges **repel**; unlike charges **attract**. Each charge feels the **same size** of force. Check: the unit is **newtons** and the power of ten fits the picture.

Example. A +3.0 μC sphere and a −5.0 μC sphere are 0.30 m apart. Use $k = 8.99 \times 10^9$ N·m²/C². What is the size of the force on each sphere, and does the force attract or repel?

1. Step 1: 3.0×10^{-6} C, 5.0×10^{-6} C and 0.30 m.

2. Steps 2 and 3: $F = (8.99 \times 10^9)(3.0 \times 10^{-6})(5.0 \times 10^{-6}) \div (0.30)^2 = 1.498\ldots$ N, which is 1.50 N.

3. Step 4: the signs are opposite, so the force is attraction, 1.50 N on each sphere. Check: newtons, and near 1 N for microcoulombs 0.30 m apart.

Try it. Two +4.0 μC spheres are 0.20 m apart. Use $k = 8.99 \times 10^9$ N·m²/C². What is the size of the force on each sphere, and does the force attract or repel? Write each step number beside your work.

1. Step 1: 4.0×10^{-6} C for each charge and 0.20 m.

2. Steps 2 and 3: $F = (8.99 \times 10^9)(4.0 \times 10^{-6})(4.0 \times 10^{-6}) \div (0.20)^2 = 3.596$ N, which is 3.60 N.

3. Step 4: both charges are positive, so the force is repulsion, 3.60 N on each sphere.

Slide 5 of 7 · How was Coulomb’s law found?

Slide 2 gave Coulomb’s law. How did Coulomb find it, long before modern meters?

In **1785** Coulomb measured the force between two small charged balls with a **torsion balance**. A thin **fibre** holds a light rod. A force on the rod **twists** the fibre.

The twist angle is **proportional** to the force. A scale around the rod shows the **angle**. A thin fibre twists even for a very **small** force.

Coulomb could not measure charge directly. He touched a charged sphere to an **identical** uncharged sphere. The charge is shared **equally**, so each has **q ÷ 2**.

Cavendish used the same kind of twisting balance to measure the **gravitational** force between heavy **lead** masses. Both balances turn a tiny force into a twist **angle**.

Example. A metal sphere carries +8.0 µC. It touches an identical metal sphere that is uncharged. They are then separated. What is the charge on each sphere?

1. Total charge = +8.0 µC + 0 = +8.0 µC.

2. The spheres are identical, so the charge is shared equally. Each sphere gets +8.0 ÷ 2 = +4.0 µC.

Try it. NEW, for teacher review. Say what the scale reading of a torsion balance tells you, and why Coulomb used a very thin fibre.

1. The twist angle is proportional to the force, so a bigger angle means a bigger force.

2. A thin fibre twists a measurable amount even for the very small force between two charged balls.

Slide 6 of 7 · Electric force and gravity

In Physics 20, gravity also had a law with $1/r^2$. Compare it with Coulomb's law from slide 2.

Newton's law of gravitation: $F_g = \mathbf{Gm_1m_2/r^2}$, where $G = \mathbf{6.67 \times 10^{-11}\ N{\cdot}m^2/kg^2}$ and m is mass in **kg**. Coulomb's law: $F_e = \mathbf{k|q_1||q_2|/r^2}$. The two laws have the **same form**.

Both forces depend on a **product** and fall as $\mathbf{1/r^2}$. Both come in **equal and opposite** pairs.

Gravity only **attracts**: there is one kind of mass. The electric force can **attract or repel**: there are two kinds of charge. For an electron and a proton the electric force is about $\mathbf{10^{39}}$ times bigger.

Most large objects are **neutral**: their electric forces cancel, so **gravity** wins. A ratio is one force **divided by** the other. When both use the same r, the $\mathbf{r^2}$ cancels.

Example. An electron and a proton are the same distance r apart. Find the ratio $F_e \div F_g$. Use $k = 8.99 \times 10^9$, $G = 6.67 \times 10^{-11}$, $e = 1.60 \times 10^{-19}$ C, m(proton) $= 1.67 \times 10^{-27}$ kg and m(electron) $= 9.11 \times 10^{-31}$ kg.

1. $F_e = ke^2/r^2$ and $F_g = G\ m_p\ m_e/r^2$. Divide: the distance cancels, so the ratio is the same at any distance.

2. $F_e \div F_g = ke^2 \div (G\ m_p\ m_e)$.

3. $= (8.99 \times 10^9)(1.60 \times 10^{-19})^2 \div [(6.67 \times 10^{-11})(1.67 \times 10^{-27})(9.11 \times 10^{-31})] = 2.27 \times 10^{39}$.

Try it. Check the exponent: in the ratio above, which constants are in the top and which in the bottom? Write the ratio as a formula, then say why the answer is so large.

1. Top: k and e^2 (electric). Bottom: G, m_p and m_e (gravity).

2. The ratio is $ke^2 \div (G\ m_p\ m_e) = 2.27 \times 10^{39}$.

3. It is huge because G and the masses are tiny, so gravity between particles is extremely weak. Check that the exponent is +39, not −39.

Slide 7 of 7 · Two-step problems

B1 shared charge between spheres that touch. Slide 2 found the force. This slide joins the two.

Two events, two steps. The force uses the charges **after touching**, not the ones the spheres started with. So the **charge** comes first and the **force** second.

Step one: share the charge. Identical spheres share the total **equally**. **Add** the signed charges, then divide by **two**. A negative value takes away from a positive one.

Step two: use the new charges in $F = \mathbf{k|q_1||q_2|/r^2}$. Convert µC to **C** and use **metres**. Both charges the same sign give **repulsion**; one of each sign gives **attraction**.

Factor questions: decide which way each change pushes the force. Half the distance: factor **more than 1**. Half one charge: factor **less than 1**. Write both factors, **multiply** them, then multiply by the old force.

Example. Two identical metal spheres carry +6.0 µC and −2.0 µC. They touch and are separated, and then they are placed 0.10 m apart. What is the size of the force on each sphere, and does it attract or repel?

1. After touching, each sphere has $(+6.0 + (-2.0)) \div 2 = +2.0$ µC.

2. $F = (8.99 \times 10^{9})(2.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.10)^2 = 3.60$ N.

3. Both charges are positive, so the force is repulsion.

Try it. Two small charged spheres 0.40 m apart exert a force of 2.4 N on each other. They are moved to 0.20 m apart, and the charge on one of them is replaced by half its original size. What is the new force? A. 1.2 N. B. 2.4 N. C. 4.8 N. D. 9.6 N.

1. Halving the distance multiplies the force by 4. Halving one charge multiplies it by 1/2.

2. New force = 2.4 N × 4 × 1/2 = 4.8 N.

3. Answer C.

B2 · Worked practice

Coulomb’s law | Questions 1-2 of 12

Use $k = 8.99 \times 10^9$ N·m²/C² and $g = 9.81$ m/s² where needed. These values are from the Alberta Physics 30 data sheets, Constants section. All point-charge calculations approximate air as vacuum.

Easy · B2-P01. Convert each value to SI units: (a) +4.50 µC, (b) −8.00 nC, (c) 25.0 cm. Keep the charge signs.

1. Micro means 10^{-6}, so +4.50 µC = $+4.50 \times 10^{-6}$ C. Nano means 10^{-9}, so −8.00 nC = -8.00×10^{-9} C.

2. There are 100 cm in 1 m, so 25.0 cm = 0.250 m. Convert before using Coulomb’s law because k is expressed in SI units.

Easy · B2-P02. A positive charge A is left of a negative charge B. Draw the electric-force arrow on each. If the force magnitude on B is 0.240 N, what is the force on A?

1. Unlike charges attract. Draw the arrow on B left, toward A; draw the arrow on A right, toward B.

2. The pair forces have equal magnitudes and opposite directions, so the force on A is 0.240 N right. They act on different objects and do not cancel on one object.

B2 · Worked practice

Easy · B2-P03. Two charges exert 0.720 N. Keep both charges fixed and triple their distance. What is the new force magnitude? Explain the factor.

1. Coulomb’s law gives F proportional to $1/r^2$ when charges are fixed. Tripling r divides the force by $3^2 = 9$.

2. Fnew = 0.720/9 = 0.0800 N. The smaller force is consistent with greater distance.

Easy · B2-P04. Keep the distance and q_2 fixed, but double $|q_1|$. What happens to the electric-force magnitude? Would doubling the distance instead give the same change? Explain.

1. The charge product is in the numerator to the first power, so doubling $|q_1|$ doubles the force.

2. Doubling distance instead makes the denominator four times larger and the force one quarter of its original value. These are different changes.

B2 · Worked practice

Medium · B2-P05. Two point charges in air are A = +3.00 μC on the left and B = +2.00 μC on the right, separated by 0.200 m. What is the force on B, including direction? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens from the prompt: $q_A = +3.00 \times 10^{-6}$ C, $q_B = +2.00 \times 10^{-6}$ C, r = 0.200 m. k is the stated data-booklet constant. Like charges repel, so B feels a force right.

2. Use the point-charge model: $F = k|q_A q_B|/r^2 = (8.99 \times 10^9)(3.00 \times 10^{-6})(2.00 \times 10^{-6})/(0.200)^2 = 1.3485$ N.

3. To three significant figures: 1.35 N right on B. The units reduce to N and the direction is away from A.

Medium · B2-P06. Two point charges in air are A = −5.00 nC on the left and B = +8.00 nC on the right, 4.00 cm apart. What is the force on B? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens: $|q_A| = 5.00 \times 10^{-9}$ C, $|q_B| = 8.00 \times 10^{-9}$ C, r = 0.0400 m from the prompt; k is given. Unlike signs attract, so B is pulled left.

2. $F = k|q_A q_B|/r^2 = (8.99 \times 10^9)(5.00 \times 10^{-9})(8.00 \times 10^{-9})/(0.0400)^2 = 2.2475 \times 10^{-4}$ N.

3. Answer: 2.25×10^{-4} N left. The minus sign on q_A identifies attraction; it does not make a force magnitude negative.

B2 · Worked practice

Medium · B2-P07. Two point charges have magnitudes 2.00 µC and 5.00 µC. Their force magnitude in air is 0.500 N. How far apart are they? Use $k = 8.99 \times 10^9$ N·m²/C². Can the force direction be determined from these data?

1. Givens: $|q_1| = 2.00 \times 10^{-6}$ C, $|q_2| = 5.00 \times 10^{-6}$ C and F = 0.500 N from the prompt. Use Coulomb’s law because it relates these charges, force and distance.

2. Rearrange before substitution: $Fr^2 = k|q_1||q_2|$, then $r = \sqrt{(k|q_1||q_2|/F)} = \sqrt{(0.0899/0.500)} = 0.424$ m.

3. A distance is positive. Signs and positions were not given, so neither attraction/repulsion nor an absolute force direction is determined.

Medium · B2-P08. With the charges fixed, doubling the distance changes an electric-force magnitude from 0.800 N to what value? Apply the same change to a gravitational force initially 0.120 N. Explain one similarity and one difference between the two forces.

1. Both laws have r^2 in the denominator. Doubling distance multiplies the denominator by four: electric force = 0.800/4 = 0.200 N; gravitational force = 0.120/4 = 0.0300 N.

2. Both are inverse-square relationships for the point-source models. Gravity between ordinary masses attracts; electric force may attract or repel depending on the charge signs. The same $1/r^2$ pattern does not mean the same strength.

B2 · Worked practice

Challenging · B2-P09. The initial force magnitude is 0.540 N. Then $|q_1|$ is doubled, $|q_2|$ is tripled, and distance is tripled. The signs stay the same. What is the new magnitude, and does the force change between attraction and repulsion?

1. The numerator changes by $2 \times 3 = 6$. The squared distance changes by $3^2 = 9$. Thus $F_{new}/F_{old} = 6/9 = 2/3$.

2. $F_{new} = 0.540 \times (2/3) = 0.360$ N. Combining the factors before calculating avoids confusing a charge factor with a distance-square factor.

3. The signs remain unchanged, so it is still the same kind of force. An absolute direction would also require the positions and the chosen object.

Challenging · B2-P10. Sample data for fixed charges are: at r = 0.100 m, F = 0.800 N; at 0.200 m, F = 0.200 N; at 0.400 m, F = 0.0500 N. Draw a straightened graph with labelled axes and units, plot all three points, find its slope, and predict F at 0.300 m.

1. An inverse-square model becomes linear when the horizontal variable is $1/r^2$. Plot x = 100, 25.0 and 6.25 m^{-2} against y = 0.800, 0.200 and 0.0500 N. Use numerical scales and draw the line through the origin.

2. Slope = $\Delta F/\Delta(1/r^2) = (0.800 - 0.200)/(100 - 25.0) = 0.00800$ N·m^2. The third point also fits this slope.

3. At r = 0.300 m, $1/r^2 = 11.111\ldots$ m^{-2}, so $F = (0.00800)(11.111\ldots) = 0.0889$ N. These are sample data, not independent experimental proof of the law.

B2 · Worked practice

Coulomb’s law | Questions 11-12 of 12

Challenging · B2-P11. A student uses $q_1 = +2.00\ \mu C$, $q_2 = -6.00\ \mu C$ and $r = 0.300$ m, then reports “$F = -1.20$ N, so the force on the right-hand charge points left.” Say which part is right and which part is wrong. What is the correct magnitude and force direction on each charge? Use $k = 8.99 \times 10^9\ N\cdot m^2/C^2$; q_1 is on the left.

1. Coulomb’s magnitude law uses $|q_1||q_2|$. $F = (8.99 \times 10^9)(2.00 \times 10^{-6})(6.00 \times 10^{-6})/(0.300)^2 = 1.1987\ N = 1.20\ N$.

2. Unlike signs attract: the right-hand charge q_2 feels 1.20 N left; the left-hand charge q_1 feels 1.20 N right. These conclusions require identifying the object and positions.

3. A negative charge product indicates unlike signs, not a universal left direction. If right is chosen positive, the signed x-component on q_2 is -1.20 N, while its magnitude remains $+1.20$ N.

Challenging · B2-P12. You can vary distance between two small charged spheres and measure force. What should remain fixed to test the distance relationship? Choose at least three distances, predict the force ratios for r, 2r and 3r, name a suitable graph, and explain one role shared by the Coulomb and Cavendish torsion balances.

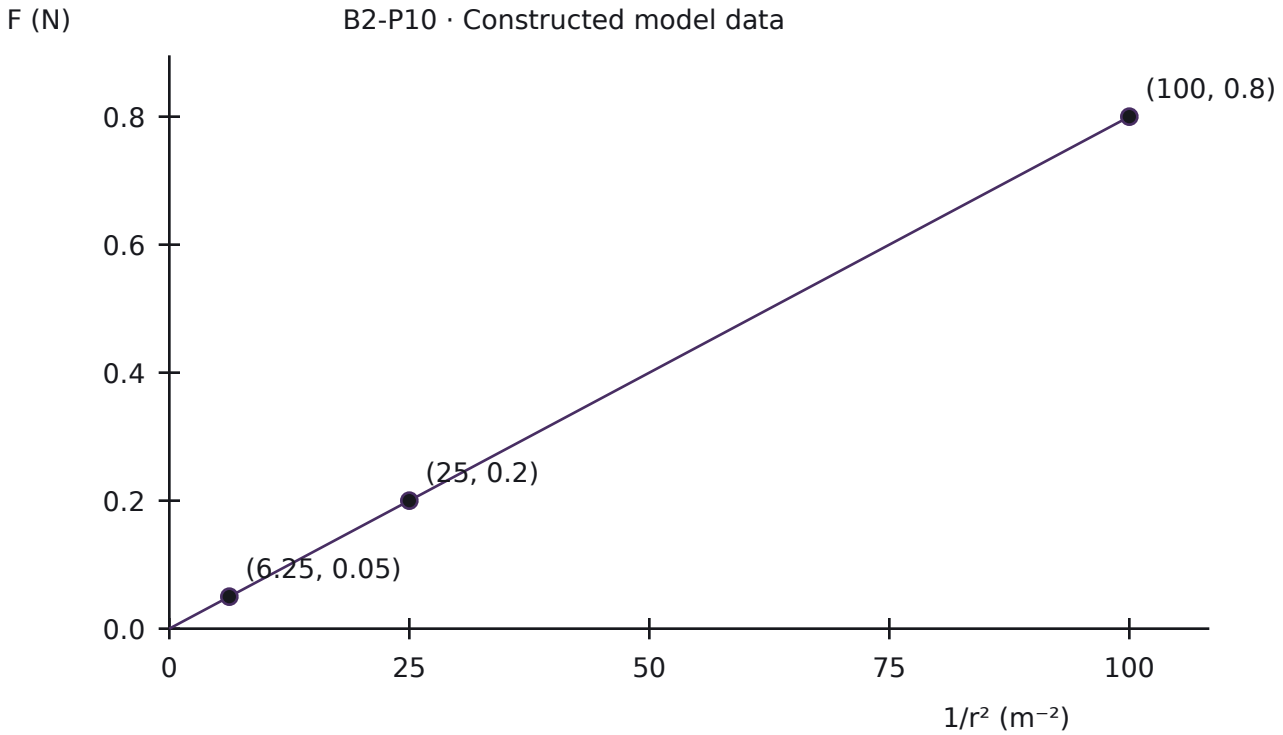
1. Keep both charges and the surrounding medium fixed; use distances large compared with sphere size for the point-charge approximation. A possible set is 0.100, 0.200 and 0.300 m.

2. Predicted ratios are 1 : 1/4 : 1/9. Plot force in N against $1/r^2$ in m^{-2}; an ideal inverse-square model gives a straight line through the origin.

3. Both balances use the twist of a suspended wire to make a small force measurable. Coulomb studied electric forces; Cavendish studied gravitational attraction. Charge leaking away or inaccurate centre-to-centre distances could distort the test.

B2-P10 · Graph key

Straightened force-distance data | all three points plotted



Slope = (0.800 - 0.200)/(100 - 25.0) = 0.00800 N·m². A horizontal value of 11.111... m⁻² corresponds to r = 0.300 m, giving F = 0.0889 N.

B3 · Net electric force

Completed notes

Add force vectors on one target and choose between a charge model and force balance.

Slide 1 of 5 · One target, several sources

B2 found the force between two charges. Most real cases have more than two. This lesson adds the forces on one charge.

Pick one charge as the **target**. Every other charge is a **source**. Find the force on the target from **each source**. The sum of the separate forces is the **net force**.

Coulomb's law $F = \mathbf{k|q_1||q_2| \div r^2}$ gives the **size** only, with $k = \mathbf{8.99 \times 10^9\ N{\cdot}m^2/C^2}$. The direction comes from the signs: **alike** charges push apart, **unlike** charges pull together.

Draw an arrow for each force first. Choose east as **positive**. An arrow east counts as **+** and an arrow west counts as **−**. Add the forces **with their signs**. The sign of the net force gives its direction.

The distance r always runs from the **source** to the **target**. If the target is outside the pair of sources, measure a **distance** for each source. Label every position in a sketch before you calculate.

Example. A is +4.0 µC at x = 0, the target B is +2.0 µC at x = 0.30 m, and C is +3.0 µC at x = 0.50 m. East is positive. What is the net force on B, with its direction?

1. A is west of B and alike, so A pushes B east: $F = (8.99 \times 10^9)(4.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.30)^2 = +0.799$ N. C is 0.20 m east of B and alike, so C pushes B west: $F = (8.99 \times 10^9)(3.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.20)^2 = -1.35$ N.

2. Net = +0.7991 − 1.3485 = −0.5494 N.

3. Net force on B: 0.549 N west (the minus sign means west).

Try it. Same positions, but C is now −3.0 µC. A is +4.0 µC at x = 0, the target B is +2.0 µC at x = 0.30 m, and C is at x = 0.50 m. What is the net force on B, with its direction?

1. A is positive and west of B, so it pushes B away, east: +0.799 N.

2. C is negative and east of B, so it pulls B toward it, also east: +1.35 N.

3. Net force = (+0.799 N) + (+1.35 N) = +2.15 N, so 2.15 N east. Two arrows the same way give a bigger answer.

Slide 2 of 5 · Forces at right angles

Slide 1 had forces on one line. Now two forces meet at a right angle.

A coordinate pair such as (0.30 m, 0) means **0.30 m east and 0 m north**. East is the positive x direction and **north** is the positive y direction.

Find each force with Coulomb's law, and decide each direction from the signs. Draw both arrows **from the target**. If the two forces are at **right angles**, draw a right triangle with the arrows as its sides.

The net force is the **hypotenuse**: $F = \sqrt{(F_1^2 + F_2^2)}$. The angle comes from $\tan\theta =$ **opposite ÷ adjacent**, so $\theta =$ **$\tan^{-1}$(opposite ÷ adjacent)**.

A direction needs an angle and a **reference**, such as "36.9° north of west". If the forces are at 90°, the net force is bigger than **either force** but smaller than their **sum**.

Example. The target (+2.0 µC) is at the origin (0, 0). A +3.0 µC charge is at (0.30 m, 0) and a −4.0 µC charge is at (0, 0.40 m). What is the net force on the target, with its direction?

1. The +3.0 µC charge is alike, so it pushes the target west: $F = (8.99 \times 10^9)(3.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.30)^2 = 0.599$ N. The −4.0 µC charge is unlike, so it pulls the target north: $F = (8.99 \times 10^9)(4.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.40)^2 = 0.450$ N.

2. The forces meet at a right angle: $F = \sqrt{(0.599^2 + 0.450^2)} = 0.749$ N.

3. $\tan\theta = 0.450 \div 0.599$, so $\theta = 36.9°$. Net force: 0.749 N at 36.9° north of west.

Try it. Same positions, but the charge at (0.30 m, 0) is −3.0 µC and the charge at (0, 0.40 m) is +4.0 µC. The target is still +2.0 µC. What is the net force on the target, with its direction?

1. The sizes do not change: 0.599 N and 0.450 N. Only the directions change.

2. The −3.0 µC charge is east of the target and unlike, so it attracts the target east. The +4.0 µC charge is north of the target and alike, so it repels the target south.

3. Net force = $\sqrt{(0.599^2 + 0.450^2)} = 0.749$ N at $\tan^{-1}(0.450 \div 0.599) = 36.9°$ south of east.

Slide 3 of 5 · Method: how to find the net force on one charge

These are the steps you used on slides 1 and 2, in one place.

Step 1, **draw**: sketch the target and every source. Label each charge and each **distance**.

Step 2, **size**: for each source, F = $\mathbf{k|q_1||q_2| \div r^2}$, using the **sizes** of the charges only. Step 3, **arrow**: alike charges push the target **away**; unlike charges pull it **toward** the source.

Step 4, **split**: write each force as an **x part** and a **y part**. East and north are **+**; west and south are **−**. Step 5, **add**: add all the x parts, then add all the **y parts**.

Step 6, **finish**: size = $\mathbf{\sqrt{x^2 + y^2}}$; angle = $\mathbf{\tan^{-1}(y \div x)}$. Name the direction from a **reference**, such as “north of west”.

Example. Use the six steps. The target (+2.0 µC) is at (0, 0). A +3.0 µC charge is at (0.30 m, 0) and a −4.0 µC charge is at (0, 0.40 m).

1. Steps 1 to 3: the +3.0 µC charge pushes west with 0.599 N. The −4.0 µC charge pulls north with 0.450 N.

2. Steps 4 and 5: x part = −0.599 N, y part = +0.450 N. One force on each axis, so the sums are the same.

3. Step 6: F = $\sqrt{(0.599^2 + 0.450^2)} = 0.749$ N. $\tan\theta = 0.450 \div 0.599$, so $\theta = 36.9°$ north of west.

Try it. Use the six steps. The target (+1.0 µC) is at (0, 0). A +2.0 µC charge is at (0.20 m, 0) and a +3.0 µC charge is at (0, 0.30 m). Find the net force, with its direction.

1. Steps 2 and 3: $F = (8.99 \times 10^9)(2.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.20)^2 = 0.4495$ N, pushing west. $F = (8.99 \times 10^9)(3.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.30)^2 = 0.2997$ N, pushing south.

2. Steps 4 and 5: x = −0.4495 N, y = −0.2997 N.

3. Step 6: $F = \sqrt{(0.4495^2 + 0.2997^2)} = 0.540$ N. $\tan\theta = 0.2997 \div 0.4495$, so $\theta = 33.7°$ south of west.

Slide 4 of 5 · A force along a diagonal

On slide 2 each force lay along an axis. Now a force points along a slant.

A source at (0.30 m, 0.40 m) is 0.30 m east and 0.40 m north of a target at the origin. The straight-line distance is r = **$\sqrt{(0.30^2 + 0.40^2)} = 0.50$ m**. The force acts along this **diagonal line**.

Find the size first with Coulomb's law. Alike charges push the target **away** from the source and unlike charges pull it toward the source. The target is pushed away, so a source to the north-east pushes the target **south-west**.

A **component** is one part of a force along one axis. The force triangle has the **same shape** as the distance triangle, so component = force × (**side** ÷ **slant side**). Each component is **smaller** than the force.

To add several forces, make two sums: one for **east-west** and one for **north-south**. East and north count as **+**; west and south count as **−**. Then use **$\sqrt{(x^2 + y^2)}$** for the size and tan θ for the angle.

Example. The target (+1.0 μC) is at the origin and a +5.0 μC source is at (0.30 m, 0.40 m). What is the force on the target, and what are its east-west and north-south parts, with directions?

1. $F = (8.99 \times 10^9)(5.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.50)^2 = 0.180$ N. The charges are alike, so the target is pushed south-west.

2. West part = 0.180 N × 0.30/0.50 = 0.108 N. South part = 0.180 N × 0.40/0.50 = 0.144 N.

3. Check: $\sqrt{(0.108^2 + 0.144^2)} = 0.180$ N.

Try it. The +1.0 μC target is at the origin and the +5.0 μC source is at (0.30 m, 0.40 m). A second source of −2.0 μC is added at (0, 0.20 m). What is the net force on the target, with its direction?

1. The −2.0 μC source is north of the target and unlike, so it attracts the target north: $F = (8.99 \times 10^9)(2.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.20)^2 = 0.450$ N.

2. East-west: only the diagonal source, 0.108 N west. North-south: +0.450 N − 0.144 N = 0.306 N north.

3. Net force = $\sqrt{(0.108^2 + 0.306^2)} = 0.324$ N, at $\tan^{-1}(0.306 \div 0.108) = 70.6°$ north of west.

Slide 5 of 5 · A charge hanging at rest

So far every force was electric. Now gravity and a thread pull as well.

Weight W = **mg**, with g = **9.81 m/s²**: each kilogram weighs 9.81 N. T is the **tension**, the pull of the thread. F_e is the **electric force**, which is horizontal.

At rest the net force is **zero**. The three force arrows close into a **right triangle**. Draw the weight straight **down**, the tension along the **thread** and the electric force **sideways**.

In the triangle, θ is the angle between the weight and the **thread**. F_e is **opposite** θ and mg is adjacent to θ: tan θ = **F_e ÷ mg**, so F_e = **mg tan θ**.

The angle θ is measured from the **vertical**. F_e is **opposite** the angle and mg is **adjacent** to it, so use **tan θ**, not sine or cosine. For two equal charges, Coulomb's law then gives q = **$\sqrt{(F_e r^2 \div k)}$**.

Example. A sphere of mass 0.0100 kg hangs from a thread at 20.0° from the vertical, pushed sideways by a fixed charge 0.15 m away. Find the electric force. If the two charges are equal, find each charge.

1. The sphere is at rest, so weight, tension and electric force form a closed right triangle, and tan θ = F_e ÷ mg.

2. F_e = (0.0100 kg)(9.81 m/s²)(tan 20.0°) = 0.0357 N. No charges were needed.

3. Equal charges: $q = \sqrt{[(0.0357)(0.15)^2 \div (8.99 \times 10^9)]} = 3.0 \times 10^{-7}$ C.

Try it. A sphere of mass 0.0200 kg hangs from a thread and is pushed sideways by a fixed charge so that the thread makes 30.0° with the vertical. The sphere is at rest. What is the size of the electric force on the sphere? Use g = 9.81 m/s².

1. The sphere is at rest, so the weight, tension and electric force form a closed right triangle. The angle is between the weight and the thread, so F_e is opposite it and mg is adjacent: tan θ = F_e ÷ mg.

2. F_e = mg tan θ = (0.0200 kg)(9.81 m/s²)(tan 30.0°) = 0.113 N.

B3 · Worked practice

Net electric force | Questions 1-2 of 12

Use $k = 8.99 \times 10^9$ N·m²/C² and $g = 9.81$ m/s² where needed. These values are from the Alberta Physics 30 data sheets, Constants section. All point-charge calculations approximate air as vacuum.

Easy · B3-P01. A is positive and left of a negative target B. C is negative and right of B. Draw the two force arrows on B. Do the forces add or partly cancel? Explain each arrow.

1. A attracts the negative B, so the force due to A points left, toward A.

2. C repels the negative B, so the force due to C also points left, away from C. Both arrows act on B and point the same way, so they add. Attraction and repulsion do not automatically mean opposite directions.

Easy · B3-P02. The forces on one charge are 0.600 N right and 0.250 N left. Choose right as positive. What are the signed components and the net force?

1. With right positive, the components are +0.600 N and −0.250 N. Use direction signs rather than charge signs when adding force components.

2. $F_{net,x} = +0.600 - 0.250 = +0.350$ N, so the net force is 0.350 N right. It points with the larger force.

B3 · Worked practice

Net electric force | Questions 3-4 of 12

Easy · B3-P03. A target feels 0.400 N east and 0.400 N west. What is its net force? Does that mean neither source exerts a force? Explain.

1. Choose east positive: $F_{net,x} = +0.400 - 0.400 = 0$ N.

2. Each force is still not zero. Their effects on the target's acceleration cancel. Zero net force is a statement about the vector sum, not that the forces are missing.

Easy · B3-P04. A charged sphere is at rest with its string tilted from vertical by a horizontal electric force. Describe the weight, tension and electric-force arrows. Why must the tension not be drawn vertically?

1. Weight points straight down. Electric force is horizontal. Tension points along the tilted string toward its support, with an upward component and a component opposing the electric force.

2. At rest, the horizontal forces must balance. A purely vertical tension could not oppose the horizontal electric force. The string's actual direction determines the tension arrow.

B3 · Worked practice

Net electric force | Questions 5-6 of 12

Medium · B3-P05. Point charges in air are A = +3.00 μC at x = 0, target B = −1.00 μC at x = 0.300 m and C = +1.00 μC at x = 0.600 m. What is the net force on B? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens are the charges and coordinates in the prompt; each source is 0.300 m from B. A attracts B left; C attracts B right. Choose right positive.

2. $F_{A\to B} = k|q_A q_B|/r^2 = (8.99 \times 10^9)(3.00 \times 10^{-6})(1.00 \times 10^{-6})/0.300^2 = 0.2997$ N left. $F_{C\to B} = 0.09989$ N right.

3. $F_{net,x} = -0.2997 + 0.09989 = -0.1998$ N. Answer: 0.200 N left. The stronger attraction wins; the net is less than either-force sum.

Medium · B3-P06. The calculated electric forces on a target are 0.500 N east and 0.200 N north. Draw a vector triangle. What are the size of the net force and its angle north of east?

1. Givens: $F_x = +0.500$ N and $F_y = +0.200$ N. Draw the east vector, then the north vector from its tip; the net force joins the start to the final tip.

2. The components are perpendicular, so $F = \sqrt{(0.500^2 + 0.200^2)} = 0.539$ N. $\theta = \tan^{-1}(0.200/0.500) = 21.8°$ north of east.

3. The result points northeast and is slightly larger than 0.500 N but smaller than 0.700 N. That is consistent with the triangle.

B3 · Worked practice

Net electric force | Questions 7-8 of 12

Medium · B3-P07. A 4.00×10^{-4} kg charged sphere hangs at rest. Its string is 25.0° from vertical and the electric force acts horizontally right. What are the electric-force magnitude and the tension? Use g = 9.81 m/s².

1. Givens: $m = 4.00 \times 10^{-4}$ kg and $\theta = 25.0°$ from the prompt; at rest means a = 0. g is the given data-booklet value. Draw mg down, F_e right and T up-left.

2. Vertical balance: $T \cos \theta = mg$. $T = (4.00 \times 10^{-4})(9.81)/\cos 25.0° = 4.33 \times 10^{-3}$ N.

3. Horizontal balance: $F_e = T \sin \theta = mg \tan \theta = 1.83 \times 10^{-3}$ N right. $F_e < mg < T$, as expected for an angle below 45° from vertical.

Medium · B3-P08. Case A gives two point charges and their distance. Case B gives a hanging sphere's mass and string angle from vertical, with a horizontal electric force. Choose a method to find electric force in each case. Explain why the other method cannot be used directly from the givens.

1. Case A: use Coulomb's law because the charge product and distance determine the force magnitude. Use signs and positions to get direction. No mass or tension data are required.

2. Case B: use force balance. Weight is mg; with angle θ from vertical, $T \cos \theta = mg$ and $F_e = T \sin \theta$, giving $F_e = mg \tan \theta$.

3. Coulomb's law cannot be substituted directly in B because the source charges and the distance are not given. The balance triangle in A would need extra force-balance information.

B3 · Worked practice

Net electric force | Questions 9-10 of 12

Challenging · B3-P09. Point charges in air are target P = +1.00 μC at (0,0), A = +2.00 μC at (−0.300 m,0), and C = +1.00 μC at (0,+0.300 m). What is the net electric force on P, as a magnitude and direction? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens are the charges and coordinates. A repels P right; C repels P down. Both source-target distances are 0.300 m. Calculate each force on P separately.

2. $F_x = +(8.99 \times 10^9)(2.00 \times 10^{-6})(1.00 \times 10^{-6})/0.300^2 = +0.1998$ N. $F_y = -(8.99 \times 10^9)(1.00 \times 10^{-6})^2/0.300^2 = -0.09989$ N.

3. $F = \sqrt{(F_x^2 + F_y^2)} = 0.223$ N. $\theta = \tan^{-1}(0.09989/0.1998) = 26.6°$ south of east. The down-right direction comes from the arrows, not from a calculator angle alone.

Challenging · B3-P10. A charged sphere hangs at rest in a horizontal electric force of 3.00×10^{-3} N. Its mass is 5.00×10^{-4} kg. What is the string's angle from vertical and what is the tension? Use g = 9.81 m/s².

1. Givens: $F_e = 3.00 \times 10^{-3}$ N and $m = 5.00 \times 10^{-4}$ kg from the prompt. At rest, acceleration is zero. Weight = mg = 4.905×10^{-3} N.

2. Force balance gives $\tan\theta = F_e/(mg)$, because the horizontal and vertical tension components balance F_e and mg. $\theta = \tan^{-1}(0.00300/0.004905) = 31.5°$ from vertical.

3. $T = \sqrt{(Fe^2 + (mg)^2)} = 5.75 \times 10^{-3}$ N. It is larger than either component, which fits: the tension balances the two together.

B3 · Worked practice

Net electric force | Questions 11-12 of 12

Challenging · B3-P11. Two sources exert electric forces of 0.600 N east and 0.800 N north on a target. A student reports 1.40 N northeast. Find the correct magnitude and direction. Explain exactly what the student’s addition assumes incorrectly.

1. The forces are perpendicular. Use the right triangle: $F = \sqrt{(0.600^2 + 0.800^2)} = 1.00$ N.

2. $\theta = \tan^{-1}(0.800/0.600) = 53.1°$ north of east. “Northeast” alone could suggest 45°, so give the angle.

3. Adding 0.600 + 0.800 treats the forces as parallel and in the same direction. Here the diagonal is smaller than that arithmetic sum and larger than either component.

Challenging · B3-P12. A = +2.00 µC is at x = 0 and C = +8.00 µC is at x = 0.900 m. A positive target charge is placed somewhere between them. Where is the net electric force zero? Give its distance from A and explain why the target’s charge magnitude is not needed.

1. Let x be distance from A, so distance from C is $0.900 - x$. Between like positive sources, A repels the target right and C repels it left. Zero net force requires equal magnitudes.

2. Set $k(2.00\ \mu C)|q|/x^2 = k(8.00\ \mu C)|q|/(0.900 - x)^2$. k and the same |q| cancel. Thus $(0.900 - x)^2 = 4x^2$.

3. Both distances are positive: $0.900 - x = 2x$, so x = 0.300 m from A (0.600 m from C). The larger source is twice as far away, which makes up for its charge being four times as large. The cancelled target charge explains why its magnitude was unnecessary.

B4 · Electric fields

Completed notes

Distinguish field from force, map field directions and combine source fields.

Slide 1 of 6 · Field means force per charge

In B2 and B3, one charge pushed another across empty space. A field explains how.

A charge can push another charge across empty space. It does this with a **field**. A small test charge, **q_test**, feels a force F. Double q_test and F **doubles**.

So divide out the charge: E = **F/q_test**, the force per unit charge, in **N/C**.

E points the way a **positive** test charge is pushed. A negative charge is pushed the **opposite** way.

F = **|q|E**. The size of q gives the size of F. The **sign** gives the direction.

Convert μC to **C**: multiply by **10^{-6}**. Keep extra digits and round **once**, at the end.

Example. A +5.00 μC test charge feels a force of 0.0150 N south at a point. What are the size and direction of the electric field at the point?

1. Change to coulombs: 5.00 μC = 5.00×10^{-6} C.

2. E = F/q_test = (0.0150 N) ÷ (5.00×10^{-6} C) = 3.00×10^{3} N/C.

3. The test charge is positive, so the field points the same way as the force: south.

Try it. An electron (e = 1.60×10^{-19} C) is placed at a point where the electric field is 500 N/C north. What are the size and direction of the force on the electron?

1. Size: F = |q|E = (1.60×10^{-19} C)(500 N/C) = 8.00×10^{-17} N.

2. The electron is negative, so the force is opposite to the field: south.

Slide 2 of 6 · The field of a point charge

Slide 1 defined the field. Now find it for a point charge.

A point source **Q** makes a field. r is the distance from the **source**. Coulomb's law gives $F = k|Q|q_{test}/r^2$. Divide by q_{test} and it **cancels**.

$E = \mathbf{k|Q|/r^2}$, with $k = \mathbf{8.99 \times 10^9\ N{\cdot}m^2/C^2}$.

The field depends on the **source** and the **distance**, not on the test charge. Double r: the field is **one quarter**.

Positive source: the field points **away**. Negative source: **toward**. Use |Q| in the formula. The sign gives **direction** only.

Convert prefixes first: μ = $\mathbf{10^{-6}}$, n = $\mathbf{10^{-9}}$. The distance must be in **metres**.

Example. A source of +4.0 μC is 0.30 m from point P. Use $k = 8.99 \times 10^9\ N{\cdot}m^2/C^2$. What are the size and direction of the electric field at P?

1. The source is positive, so the field at P points away from it.

2. $E = k|Q|/r^2 = (8.99 \times 10^9\ N{\cdot}m^2/C^2)(4.0 \times 10^{-6}\ C) \div (0.30\ m)^2 = 4.00 \times 10^5\ N/C$.

Try it. A source of −2.0 nC (that is, -2.0×10^{-9} C) is 0.050 m from point P. What are the size and direction of the electric field at P?

1. The source is negative, so the field at P points toward it.

2. $E = (8.99 \times 10^9)(2.0 \times 10^{-9}) \div (0.050)^2 = 7.19 \times 10^3\ N/C$.

Slide 3 of 6 · From field to force to acceleration

Slides 1 and 2 gave the field. Now use it to find how a particle moves.

Field gives **force**, and force gives **acceleration**. Here q is the particle's **own** charge, not the test charge.

Force: F = **|q|E**. Only the electric force acts, so this is the net force.

Acceleration: a = **F/m**, so a = **|q|E/m**. Do the force on its own line first.

The force points **along** the field for a positive charge and **against** it for a negative charge. A uniform field has the **same size and direction** everywhere.

An electron has mass **9.11×10^{-31} kg**. Its weight is about 10^{13} times smaller than this force, so gravity is **ignored**.

Example. An electron ($q = -1.60 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg) is placed in a uniform electric field of 2.50×10^{3} N/C north. Only the electric force acts. What are the size and direction of the electron's acceleration?

1. Force: $F = |q|E = (1.60 \times 10^{-19}\ \text{C})(2.50 \times 10^{3}\ \text{N/C}) = 4.00 \times 10^{-16}$ N. The electron is negative, so the force is south.

2. Acceleration: $a = F/m = (4.00 \times 10^{-16}\ \text{N}) \div (9.11 \times 10^{-31}\ \text{kg}) = 4.39 \times 10^{14}\ \text{m/s}^2$, south.

Try it. A proton ($q = +1.60 \times 10^{-19}$ C, $m = 1.67 \times 10^{-27}$ kg) is placed in a uniform electric field of 2.50×10^{3} N/C north. Only the electric force acts. What are the size and direction of the proton's acceleration?

1. Force: $F = |q|E = (1.60 \times 10^{-19}\ \text{C})(2.50 \times 10^{3}\ \text{N/C}) = 4.00 \times 10^{-16}$ N. The proton is positive, so the force is north.

2. Acceleration: $a = F/m = (4.00 \times 10^{-16}\ \text{N}) \div (1.67 \times 10^{-27}\ \text{kg}) = 2.40 \times 10^{11}\ \text{m/s}^2$, north.

Slide 4 of 6 · Method: how to go from field to force to acceleration

These are the steps you used on slide 3.

Step 1: **find** the field E. Use the given field, or $E = \mathbf{k|Q|/r^2}$ for a point source, with the size of Q.

Step 2: name the **direction** of E: away from a **positive** source and toward a **negative** source.

Step 3: find the force with $F = \mathbf{|q|E}$. Here q is the charge placed in the field, not the test charge. Use its **size**.

Step 4: name the direction of F: the **same as** E if q is positive and **opposite to** E if q is negative.

Step 5: find the acceleration with $a = \mathbf{F \div m}$, in the direction of **F**.

Check: the answer has units of $\mathbf{m/s^2}$ and its direction matches the **sign** of q.

Example. An electron ($q = -1.60 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg) is placed in a uniform electric field of 2.50×10^3 N/C north. Only the electric force acts. What are the size and direction of the electron's acceleration?

1. Step 1 and 2: the field is $E = 2.50 \times 10^3$ N/C, north.

2. Step 3: $F = |q|E = (1.60 \times 10^{-19}\text{ C})(2.50 \times 10^3\text{ N/C}) = 4.00 \times 10^{-16}$ N.

3. Step 4: the electron is negative, so the force is opposite to the field: south.

4. Step 5: $a = F \div m = (4.00 \times 10^{-16}\text{ N}) \div (9.11 \times 10^{-31}\text{ kg}) = 4.39 \times 10^{14}$ m/s², south.

Try it. A source of +3.0 µC makes the field at a point 0.30 m away. A −2.0 µC charge of mass 0.0040 kg is placed there. What are the size and direction of its acceleration? Only the electric force acts.

1. Step 1: $E = k|Q|/r^2 = (8.99 \times 10^9)(3.0 \times 10^{-6}) \div (0.30)^2 = 2.9967 \times 10^5$ N/C.

2. Step 2: the source is positive, so E points away from the source.

3. Step 3: $F = |q|E = (2.0 \times 10^{-6})(2.9967 \times 10^5) = 0.5993$ N.

4. Step 4: the charge is negative, so F points toward the source.

5. Step 5: $a = F \div m = 0.5993 \div 0.0040 = 1.50 \times 10^2$ m/s², toward the source.

Slide 5 of 6 · Adding fields from several sources

So far one source made the field. Now there are two.

Two sources make two fields. Add them as **vectors**. The sum is the **net field**.

Find each field with $E = \mathbf{k|Q|/r^2}$. Mark each direction at the point. Then add. On a line, call one direction **positive**.

Arrows the same way: the sizes **add**. Opposite ways: the sizes **subtract**. At right angles: size = $\mathbf{\sqrt{(E_1^2 + E_2^2)}}$, tan θ = **opposite ÷ adjacent**.

Field lines: 1. draw the charges and mark their **signs**; 2. start on a **positive** charge, end on a **negative** one; 3. put lines **closer together** where the field is strong; 4. add an **arrow** on every line.

Lines never **cross**. Between large parallel plates the lines are straight and **evenly spaced**: a **uniform** field.

Example. Two sources, +2.0 μC at x = 0 and −2.0 μC at x = 0.40 m. Point P is midway between them, 0.20 m from each. Draw the field arrows at P, then find the size and direction of the net field at P.

1. The +2.0 μC source pushes a positive test charge east. The −2.0 μC source pulls it east.

2. Each field: $E = (8.99 \times 10^9)(2.0 \times 10^{-6}) \div (0.20)^2 = 4.50 \times 10^5$ N/C.

3. The fields point the same way, so $E = 9.00 \times 10^5$ N/C east.

Try it. Two equal positive point charges are placed on a horizontal line, and point P is midway between them. Which statement about the field at P is correct? A. It is zero. B. It is directed toward the left charge. C. It is directed toward the right charge. D. It is twice the field of one charge.

1. Each positive source makes a field at P pointing away from itself.

2. The two fields are equal in size and opposite in direction, so they cancel and the field at P is zero. Answer A.

Slide 6 of 6 · Method: how to add fields from several sources

These are the steps you used on slide 5.

Step 1: **draw** the point and every source, with each source's sign and its distance from the point.

Step 2: find the size of each field on its own with $E = \mathbf{k|Q|/r^2}$.

Step 3: draw each arrow starting at the point, **away from** a positive source and **toward** a negative source.

Step 4: **split** each arrow into x and y parts. Choose a positive direction for each axis and give each part a + or − sign.

Step 5: add all the **x** parts to get Ex and all the **y** parts to get Ey.

Step 6: $E = \sqrt{(E_x^2 + E_y^2)}$. Name the direction from a **reference**, such as east.

Check: the net arrow on the drawing points the **same way** as your answer.

Example. Two sources, +2.0 µC at x = 0 and −2.0 µC at x = 0.40 m. Point P is midway between them, 0.20 m from each. East is positive. Find the size and direction of the net field at P.

1. Step 1: draw P with +2.0 µC on the left and −2.0 µC on the right, each 0.20 m from P.

2. Step 2: each field is $E = (8.99 \times 10^9)(2.0 \times 10^{-6}) \div (0.20)^2 = 4.50 \times 10^5$ N/C.

3. Step 3: the + source gives east. The − source gives east.

4. Step 4: both x parts are positive. Each y part is zero.

5. Step 5: $E_x = 4.50 \times 10^5 + 4.50 \times 10^5 = 9.00 \times 10^5$ N/C. $E_y = 0$.

6. Step 6: $E = 9.00 \times 10^5$ N/C east.

Try it. Two sources, +4.0 µC at x = 0 and +1.0 µC at x = 0.60 m. East is positive. Point P is 0.20 m from the +4.0 µC source, on the line between the sources. Find the size and direction of the net field at P.

1. Step 1: P is 0.20 m from the +4.0 µC source and 0.40 m from the +1.0 µC source.

2. Step 2: $E_1 = (8.99 \times 10^9)(4.0 \times 10^{-6}) \div (0.20)^2 = 8.99 \times 10^5$ N/C. $E_2 = (8.99 \times 10^9)(1.0 \times 10^{-6}) \div (0.40)^2 = 5.619 \times 10^4$ N/C.

3. Step 3: both sources are positive, so each arrow points away from its source. E_1 points east. E_2 points west.

4. Step 4: x parts: $+8.99 \times 10^5$ and -5.619×10^4. Each y part is zero.

5. Step 5: $E_x = 8.99 \times 10^5 - 0.5619 \times 10^5 = 8.43 \times 10^5$ N/C.

6. Step 6: $E = 8.43 \times 10^5$ N/C east.

B4 · Worked practice

Electric fields | Questions 1-2 of 12

Use $k = 8.99 \times 10^9\ N \cdot m^2/C^2$ and $g = 9.81\ m/s^2$ where needed. These values are from the Alberta Physics 30 data sheets, Constants section. All point-charge calculations approximate air as vacuum.

Easy · B4-P01. A fixed source creates a field at P. A small positive test charge q_test is replaced by a test charge +2q_test and the source does not change. What happens to the field at P and to the force on the test charge? Explain using the definition of field.

1. The source arrangement and point have not changed, so E stays the same.

2. F = |q|E gives Fnew = 2|q|E = 2Fold. The force doubles, but F/q_test stays constant. Test charge changes the force, not the field of the source.

Easy · B4-P02. A point source is positive. At a point to its left, draw the electric-field arrow. Then draw the force arrow on a negative test charge placed there. Explain both directions.

1. The field points away from a positive source. At the point left of the source, draw E left.

2. A negative test charge feels force opposite E, so draw its force right, toward the positive source. The field direction always uses a positive test charge.

B4 · Worked practice

Electric fields | Questions 3-4 of 12

Easy · B4-P03. A +4.00 µC test charge feels 0.0800 N east in an electric field. What is the field strength and direction at that point?

1. Givens: $q_{test} = +4.00 \times 10^{-6}$ C and F = 0.0800 N east from the prompt. Field is force per unit positive test charge.

2. $E = F/q_{test} = 0.0800/(4.00 \times 10^{-6}) = 2.00 \times 10^{4}$ N/C east. The positive test charge's force and field directions agree.

Easy · B4-P04. Between large horizontal plates the electric field points up. Ignore the edges of the plates. Which plate is positive, which is negative, and which way is the electric force on an electron? Does the field strength change between two points inside?

1. Field arrows run from positive to negative. For an upward field, the lower plate is positive and the upper plate negative.

2. The electron is negative, so its electric force points down, opposite the field. In the uniform region between the plates, field strength stays constant from one point to another.

B4 · Worked practice

Electric fields | Questions 5-6 of 12

Medium · B4-P05. A point source Q = −4.00 μC is fixed in air. P is 0.200 m to its right. What is the electric field at P? Use k = 8.99 × 10^9 N·m^2/C^2.

1. Givens: |Q| = 4.00 × 10^{-6} C and r = 0.200 m from the prompt. k is given. Use E = k|Q|/r^2 because one point source creates the field.

2. E = (8.99 × 10^9)(4.00 × 10^{-6})/$(0.200)^2$ = 8.99 × 10^5 N/C.

3. A positive test charge at P would be attracted toward the negative source, which is left. Answer: 8.99 × 10^5 N/C left. P is a point; no second source charge is needed.

Medium · B4-P06. A charge q = −3.00 nC is placed in a field of 4.00 × 10^4 N/C west. What is the electric force on it? Does its negative sign reverse the field itself?

1. Givens: q = −3.00 × 10^{-9} C and E = 4.00 × 10^4 N/C west. Use F = |q|E because the field at the charge is already known.

2. |F| = |q|E = (3.00 × 10^{-9})(4.00 × 10^4) = 1.20 × 10^{-4} N. The negative charge feels force opposite west: east.

3. The field itself is not reversed by choosing a negative charge. The field of the source still points west.

B4 · Worked practice

Electric fields | Questions 7-8 of 12

Medium · B4-P07. At P, a +2.00 µC source is 0.300 m to the left and a −1.00 µC source is 0.300 m to the right. What is the net electric field at P? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens are the source charges and distances. The positive source's field points right, away from it. The negative source's field points right, toward it.

2. $E_{left} = (8.99 \times 10^9)(2.00 \times 10^{-6})/0.300^2 = 1.9978 \times 10^5$ N/C. $E_{right} = (8.99 \times 10^9)(1.00 \times 10^{-6})/0.300^2 = 9.9889 \times 10^4$ N/C.

3. The two fields point the same way, so add them: $E_{net} = 2.9967 \times 10^5 = 3.00 \times 10^5$ N/C right. Adding +2 and −1 µC before finding field directions would give the wrong field.

Medium · B4-P08. A source is at (0,0). A field map shows E at (0.200 m,0) pointing right with strength 4.00×10^5 N/C. The source stays fixed. What is its sign? Predict the field magnitude and direction at (0.400 m,0) and at (−0.200 m,0).

1. At the right-hand point, a field to the right points away from the source, so the source is positive.

2. At (0.400 m,0), distance doubles. E follows $1/r^2$ for a point source: $E = (4.00 \times 10^5)/4 = 1.00 \times 10^5$ N/C right.

3. At (−0.200 m,0), distance equals the original radius, so strength is 4.00×10^5 N/C, now left, away from the positive source. Equal distance gives equal magnitude, not necessarily equal direction.

B4 · Worked practice

Electric fields | Questions 9-10 of 12

Challenging · B4-P09. Point sources A = +1.00 μC at (−0.300 m,0) and C = −2.00 μC at (0,+0.300 m) create a field at P = (0,0). What are the net field magnitude and direction? Use $k = 8.99 \times 10^9$ N·m²/C².

1. Givens are the charges and coordinates. At P, the field from positive A points right; the field toward negative C points up. Each source is 0.300 m from P.

2. $E_x = (8.99 \times 10^9)(1.00 \times 10^{-6})/0.300^2 = 9.9889 \times 10^4$ N/C. $E_y = (8.99 \times 10^9)(2.00 \times 10^{-6})/0.300^2 = 1.9978 \times 10^5$ N/C.

3. $E = \sqrt{(E_x^2 + E_y^2)} = 2.23 \times 10^5$ N/C; $\theta = \tan^{-1}(E_y/E_x) = 63.4°$ north of east. Check: the net field is bigger than the larger component but is below their arithmetic sum.

Challenging · B4-P10. A point has an electric field of 6.00×10^4 N/C east. A small unknown charge feels 0.120 N west. What are the charge's magnitude and sign? Explain how the directions determine the sign.

1. Givens: |F| = 0.120 N and $E = 6.00 \times 10^4$ N/C. Force and field are opposite, so the charge must be negative.

2. $|q| = |F|/E = 0.120/(6.00 \times 10^4) = 2.00 \times 10^{-6}$ C. Thus q = −2.00 μC.

3. With east positive, $q = F_x/E_x = (-0.120)/(+6.00 \times 10^4)$, which gives the same negative sign. Units N/(N/C) reduce to C.

B4 · Worked practice

Electric fields | Questions 11-12 of 12

Challenging · B4-P11. Two equal sources are fixed on a horizontal line. Compare the field at the midpoint for (a) two positive sources and (b) a positive source on the left and an equal negative source on the right. Then describe field-line sketches for both pairs: add arrows and explain whether lines cross.

1. For two positives, the left source gives a midpoint field to the right and the right source gives an equal field to the left. Net E = 0 at the midpoint. Draw lines leaving both sources and bending away from the space between them; no line joins one positive source to the other.

2. For the opposite pair, both midpoint contributions point right: away from the positive and toward the negative. Net E is not zero and points right. Draw lines running from the positive source to the negative source, including curved paths above and below the pair.

3. Neither diagram has crossing lines. Crossing would assign two field directions to one point. At the zero-field point in case (a), the net field has no defined direction; do not draw an arrow through it.

Challenging · B4-P12. Mixed review: two identical metal spheres on insulating stands start with +6.00 µC and −2.00 µC, touch, then separate far apart. Afterwards one sphere is held fixed as a point source; the other is moved far enough away that its field at P is too small to matter. P is 0.300 m right of the fixed sphere. What field is at P, and what force acts on a −2.00 nC charge there? Use $k = 8.99 \times 10^9$ N·m²/C².

1. First conserve charge: total = +6.00 - 2.00 = +4.00 µC. Identical spheres share equally, so the fixed source has Q = +2.00 µC. Do not use its initial +6.00 µC charge.

2. Use the point-source field: $E = k|Q|/r^2 = (8.99 \times 10^9)(2.00 \times 10^{-6})/0.300^2 = 1.9978 \times 10^5$ N/C, which is 2.00×10^5 N/C to three digits. The field points right, away from the positive source. Keep the full value on your calculator.

3. Use the full field value for the force: $|F| = (2.00 \times 10^{-9})(1.9978 \times 10^5) = 4.00 \times 10^{-4}$ N. The charge is negative, so force is left. The question combines charge conservation, source field and force on a charge.