

PHYS12 CH18: The Invisible Forces Between Charges

Coulomb's Law, Fields, Potential, and Capacitors

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December 2025

Outline

- 1 Introduction
- 2 Coulomb's Law
- 3 Electric Field
- 4 Electric Potential
- 5 Capacitors
- 6 Summary

The Mystery of the Invisible

What if forces could act
without touching?

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From lightning bolts to the neurons in your brain...

The Mystery of the Invisible

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From lightning bolts to the neurons in your brain...

Electric forces shape reality.

Learning Objectives

By the end of this section, you will be able to:

- 18.2: Describe Coulomb's law verbally and mathematically

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- **18.2:** Describe Coulomb's law verbally and mathematically
- **18.2:** Solve problems involving Coulomb's law

18.2 The Force Between Charges

The Mental Model

Like gravity pulls masses together, electric force acts between charges. But there's a twist: charges can attract OR repel.

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Two types of charge:

- Positive (+) and Negative (-)

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Two types of charge:

- Positive (+) and Negative (-)
- Like charges repel
- Unlike charges attract

18.2 Coulomb's Discovery



18.2 Coulomb's Discovery



Charles-Augustin de Coulomb (1780s) used a torsion balance to measure forces between charged spheres.

18.2 The Source Code of Electric Force

Universal Law: Coulomb's Law

$$F = \frac{kq_1q_2}{r^2}$$

Force between charges equals Coulomb's constant times the product of charges divided by distance squared.

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Force between charges equals Coulomb's constant times the product of charges divided by distance squared.

Where: $k = 8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$

18.2 Reading the Signs

The Paradox

If both charges are positive OR both negative: $F > 0$ (repulsive)

If charges have opposite signs: $F < 0$ (attractive)

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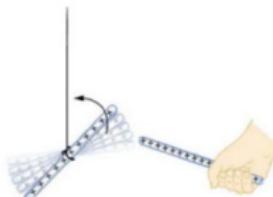
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(a)



(b)



(c)

18.2 Inverse-Square Law

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The Mental Model

Bring **charges** twice as close: **force** quadruples. Move them twice as far: **force** drops to one-fourth.

18.2 Coulomb vs Gravity

Similarities:

- Both are inverse-square laws

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Differences:

- k is MUCH larger than G (electric forces are stronger)
- Gravity only attracts; electric forces attract OR repel

Civilian vs Reality

Civilian: "Gravity holds everything together."

Physicist: "Electric forces hold atoms and molecules together. Gravity holds planets and galaxies."

Attempt: Decoding Electric Force

The Challenge (3 min, silent)

Two charges $q_1 = +3 \times 10^{-9}$ C and $q_2 = -4 \times 10^{-9}$ C are separated by 3.0 cm.

Given:

- $q_1 = +3 \times 10^{-9}$ C
- $q_2 = -4 \times 10^{-9}$ C
- $r = 3.0$ cm = 0.030 m

Find: Magnitude and direction of force

Can you calculate the force? Work silently.

Compare: Force Calculation

Turn and talk (2 min):

- ① What did you substitute for q_1 and q_2 ?
- ② Did you convert cm to m?
- ③ Is the force attractive or repulsive? How do you know?

Compare: Force Calculation

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Name wheel: One pair share your approach (not your answer).

Reveal: The Electric Interaction

Self-correct in a different color:

Step 1: $F = \frac{kq_1q_2}{r^2}$

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Check: Opposite charges attract. Negative force confirms this!

Learning Objectives

By the end of this section, you will be able to:

- **18.3:** Calculate the strength of an electric field

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- 18.3: Calculate the strength of an electric field
 - 18.3: Create and interpret drawings of electric fields

18.3 Force Fields in Physics

What if space itself could push on charges?

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The Mental Model

An electric field is an invisible map showing which way a positive charge would be pushed at every point in space.

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What if space itself could push on charges?

The Mental Model

An electric field is an invisible map showing which way a positive charge would be pushed at every point in space.

Not science fiction - this is how physicists think about forces at a distance.

18.3 The Source Code of Fields

Universal Law: Electric Field

$$\vec{E} = \frac{\vec{F}}{q_{\text{test}}}$$

Electric field equals force per unit charge.

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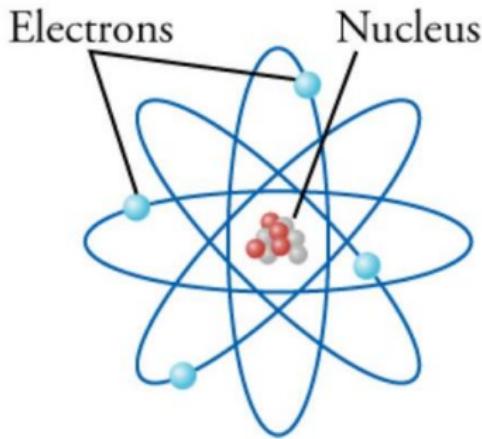
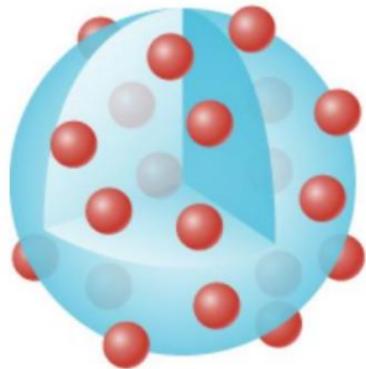
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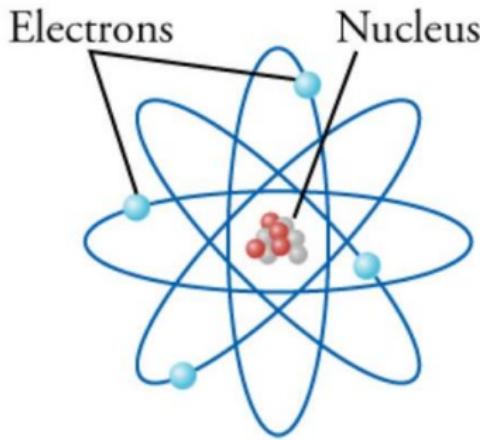
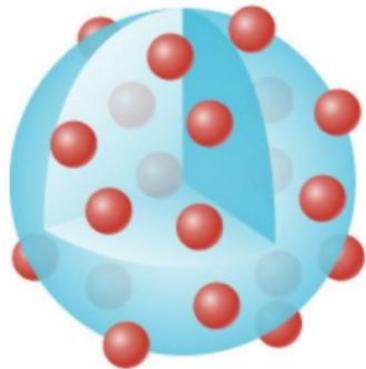
$$E = \frac{k|Q|}{r^2}$$

Units: N/C (newtons per coulomb)

18.3 Visualizing the Invisible



18.3 Visualizing the Invisible



Field lines show:

- Direction of **force** on positive **charge**
- Strength (closer lines = stronger **field**)

18.3 Field Line Rules

- ① Lines point **away** from positive **charges**

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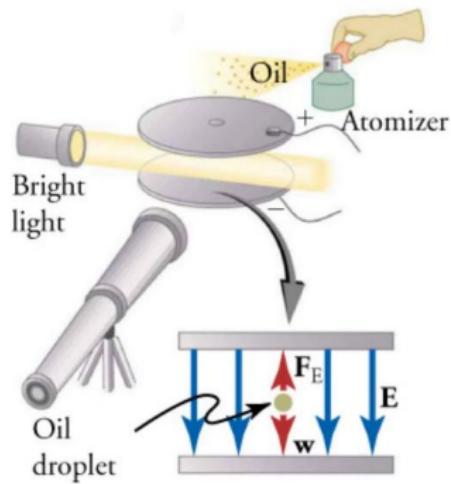
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The Paradox

Misconception: "Field lines are paths **charges** follow."

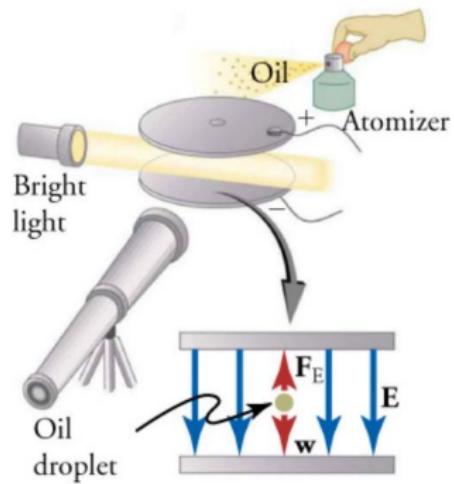
Reality: Field lines show **force** direction, but moving **charges** have inertia - they curve gradually.

18.3 Field Patterns

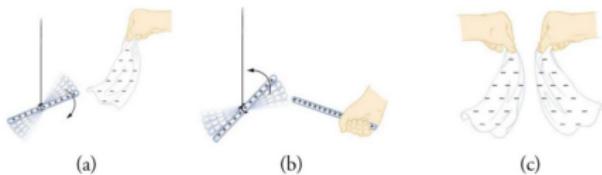


Positive and negative

18.3 Field Patterns



Positive and negative



Two negatives

Field lines connect opposite charges, repel from like charges.

Attempt: Reading Field Maps

The Challenge (2 min, silent)

Look at this field map. Three charges create these field lines.

Questions:

- ① Which **charges** are positive? Which are negative?
- ② Which **charge** has the largest magnitude?
- ③ Where is the **field** strongest?

Use field line density and direction to decode the charges.

Compare: Field Interpretation

Turn and talk (2 min):

- ① How did you identify positive vs negative **charges**?
- ② How did you compare **charge** magnitudes?
- ③ Where is the **field** strongest, and how do you know?

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Signs:

- Lines OUT = positive charge
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- Count field lines touching each charge

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- Lines OUT = positive charge
- Lines IN = negative charge

Magnitude:

- More lines = larger charge
- Count field lines touching each charge

Field Strength:

- Closest lines = strongest field
- Usually near charges

Learning Objectives

By the end of this section, you will be able to:

- **18.4:** Explain similarities and differences between electric and gravitational potential energy

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- **18.4:** Explain similarities and differences between electric and gravitational potential energy
- **18.4:** Calculate electric potential difference

18.4 The Universe's Pressure Gauge

The Mental Model

Gravitational potential: height in a gravitational field

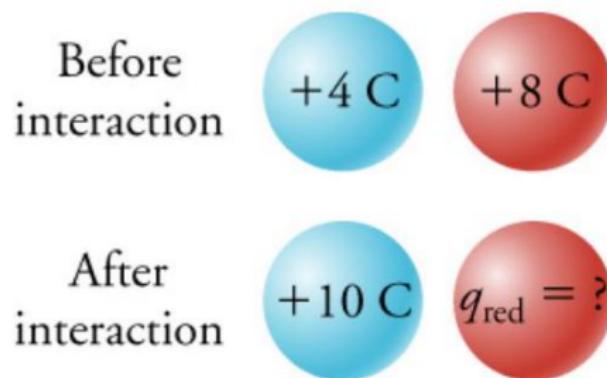
Electric potential: "height" in an electric field

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Gravitational potential: height in a gravitational field

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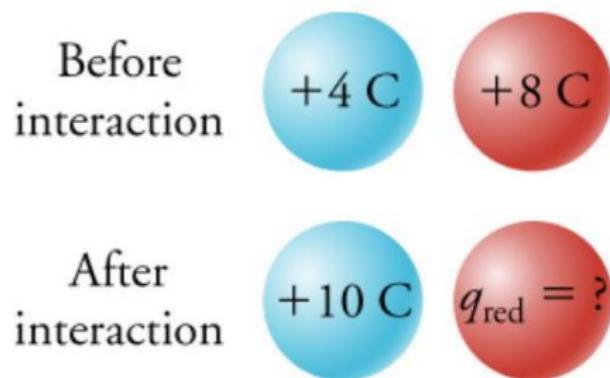


18.4 The Universe's Pressure Gauge

The Mental Model

Gravitational potential: height in a gravitational field

Electric potential: "height" in an electric field



Both store energy that can be released to do work.

18.4 Potential Energy of Two Charges

Universal Law: Electric Potential Energy

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Energy stored in configuration of two charges.

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Sign tells the story:

- $U_E > 0$: like charges (they want to fly apart)
- $U_E < 0$: opposite charges (they want to come together)

18.4 Electric Potential (Voltage)

Universal Law: Electric Potential

$$V = \frac{U_E}{q} = \frac{kq}{r}$$

Potential energy per unit charge. Units: volts (V)

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Civilian vs Reality

Civilian: "Voltage is electricity flowing."

Physicist: "Voltage is electric pressure - potential energy per charge."

18.4 Potential Difference

What really matters: difference in potential

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Rearranged:

$$E = \frac{\Delta V}{d}$$

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In uniform field E :

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Rearranged:

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Electric field units: V/m (volts per meter)

18.4 The 9V Battery

Real-World: Battery Voltage

A 9V battery creates 9V **potential difference** between terminals.

This means: moving 1 coulomb from - to + terminal requires 9 joules of **work**.

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Battery converts chemical **energy** to electric potential energy.

Attempt: Calculating Voltage

The Challenge (3 min, silent)

A point charge $Q = +5 \times 10^{-9}$ C creates an electric potential.

Given:

- $Q = +5 \times 10^{-9}$ C
- $r = 0.10$ m

Find: Electric potential at distance $r = 0.10$ m

Can you calculate the voltage? Work silently.

Compare: Voltage Calculation

Turn and talk (2 min):

- ① What formula did you use?
- ② What did you substitute for each variable?
- ③ What are the units of your answer?

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Name wheel: One pair share your approach.

Reveal: The Electric Pressure

Self-correct in a different color:

Formula: $V = \frac{kQ}{r}$

Reveal: The Electric Pressure

Self-correct in a different color:

Formula: $V = \frac{kQ}{r}$

Substitute: $V = \frac{(8.99 \times 10^9)(5 \times 10^{-9})}{0.10}$

Reveal: The Electric Pressure

Self-correct in a different color:

Formula: $V = \frac{kQ}{r}$

Substitute: $V = \frac{(8.99 \times 10^9)(5 \times 10^{-9})}{0.10}$

$$V = 450 \text{ V}$$

Reveal: The Electric Pressure

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Substitute: $V = \frac{(8.99 \times 10^9)(5 \times 10^{-9})}{0.10}$

$$V = 450 \text{ V}$$

Check: 450 volts - much higher than a battery, but safe at this tiny charge!

Learning Objectives

By the end of this section, you will be able to:

- **18.5:** Calculate energy stored in a capacitor and capacitance

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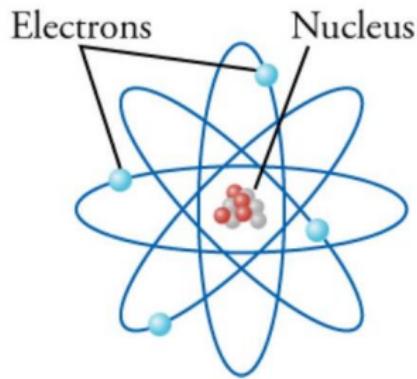
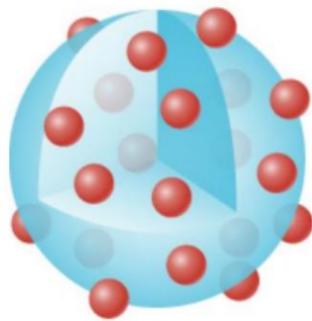
- **18.5:** Calculate energy stored in a capacitor and capacitance
- **18.5:** Explain properties of capacitors and dielectrics

18.5 Energy Storage Devices

What if you could bottle electric fields?

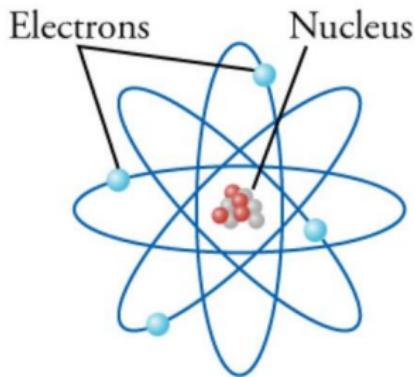
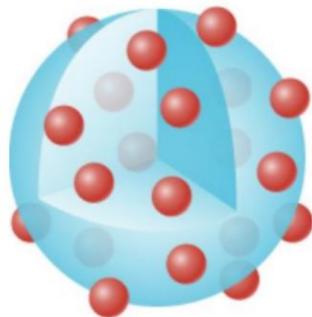
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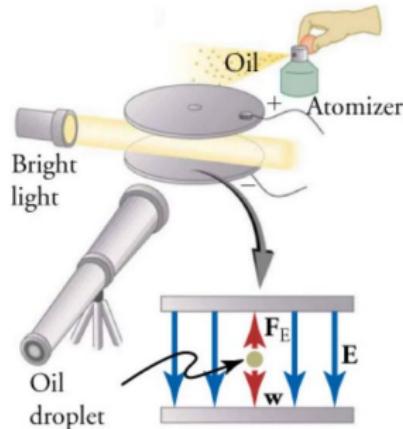
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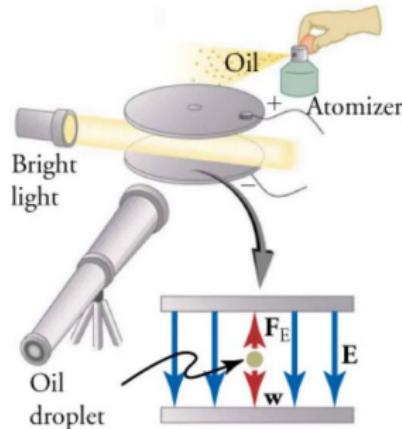


Capacitors store energy in **electric fields** between charged plates.

18.5 The Parallel-Plate Capacitor



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Design:

- Two metal plates separated by small **distance**
- One plate **charged +**, other **charged -**
- **Electric field between plates is uniform**

18.5 The Source Code of Capacitance

Universal Law: Capacitance

$$C = \frac{Q}{V}$$

Capacitance equals charge stored per volt applied. Units: farads (F)

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Universal Law: Capacitance

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For parallel plates:

$$C_0 = \epsilon_0 \frac{A}{d}$$

where $\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$

18.5 Energy Storage

Universal Law: Energy in Capacitor

$$U_E = \frac{1}{2} CV^2$$

Energy stored equals half capacitance times voltage squared.

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The Mental Model

Like kinetic energy $K = \frac{1}{2} mv^2$, but for electric fields instead of motion.

18.5 Capacitance Factors

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What determines capacitance?

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- Increase plate area A : capacitance increases
- Increase separation d : capacitance decreases
- Geometry only - not charge or voltage!

The Paradox

Misconception: "More charge means more capacitance."

Reality: Capacitance is constant for given geometry. More charge just means higher voltage.

18.5 Dielectrics

Real-World Enhancement

Insert insulating material (dielectric) between plates:

- Capacitance increases
- Can store more energy
- Prevents electrical breakdown

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Common dielectrics:

- Paper, plastic, ceramic, air

Attempt: Capacitor Design

The Challenge (3 min, silent)

Design a parallel-plate capacitor with capacitance $C = 1.0 \times 10^{-9}$ F.

Given:

- $C = 1.0 \times 10^{-9}$ F (1.0 nF)
- Plate area $A = 0.010$ m²
- $\epsilon_0 = 8.85 \times 10^{-12}$ F/m

Find:

Required plate separation d

Can you find the spacing? Work silently.

Compare: Design Strategy

Turn and talk (2 min):

- ① What formula did you start with?
- ② How did you rearrange to solve for d ?
- ③ What units did you get for d ?

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Reveal: The Design Solution

Self-correct in a different color:

Formula: $C_0 = \epsilon_0 \frac{A}{d}$

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Rearrange: $d = \epsilon_0 \frac{A}{C}$

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Self-correct in a different color:

Formula: $C_0 = \epsilon_0 \frac{A}{d}$

Rearrange: $d = \epsilon_0 \frac{A}{C}$

Substitute: $d = (8.85 \times 10^{-12}) \frac{0.010}{1.0 \times 10^{-9}}$

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Formula: $C_0 = \epsilon_0 \frac{A}{d}$

Rearrange: $d = \epsilon_0 \frac{A}{C}$

Substitute: $d = (8.85 \times 10^{-12}) \frac{0.010}{1.0 \times 10^{-9}}$

$$d = 8.85 \times 10^{-5} \text{ m} = 0.089 \text{ mm}$$

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Self-correct in a different color:

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Rearrange: $d = \epsilon_0 \frac{A}{C}$

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$$d = 8.85 \times 10^{-5} \text{ m} = 0.089 \text{ mm}$$

Check: Less than a tenth of a millimeter - capacitors need very small spacing!

The Four Revelations

What You Now Know

- ① Coulomb's Law: $F = \frac{kq_1q_2}{r^2}$ - forces between charges

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- ① Coulomb's Law: $F = \frac{kq_1q_2}{r^2}$ - forces between charges
- ② Electric Field: $E = \frac{F}{q}$ - force per unit charge

The Four Revelations

What You Now Know

- ① Coulomb's Law: $F = \frac{kq_1q_2}{r^2}$ - forces between charges
- ② Electric Field: $E = \frac{F}{q}$ - force per unit charge
- ③ Electric Potential: $V = \frac{kq}{r}$ - energy per unit charge

The Four Revelations

What You Now Know

- ① Coulomb's Law: $F = \frac{kq_1q_2}{r^2}$ - forces between charges
- ② Electric Field: $E = \frac{F}{q}$ - force per unit charge
- ③ Electric Potential: $V = \frac{kq}{r}$ - energy per unit charge
- ④ Capacitance: $C = \frac{Q}{V}$ - charge storage capacity

Key Equations

$$F = \frac{kq_1 q_2}{r^2} \quad (\text{Coulomb's law}) \quad (1)$$

$$E = \frac{k|Q|}{r^2} \quad (\text{Electric field from point charge}) \quad (2)$$

$$\vec{E} = \frac{\vec{F}}{q} \quad (\text{Field definition}) \quad (3)$$

$$U_E = \frac{kq_1 q_2}{r} \quad (\text{Electric potential energy}) \quad (4)$$

$$V = \frac{kq}{r} \quad (\text{Electric potential from point charge}) \quad (5)$$

$$C = \frac{Q}{V} \quad (\text{Capacitance}) \quad (6)$$

$$C_0 = \epsilon_0 \frac{A}{d} \quad (\text{Parallel-plate capacitor}) \quad (7)$$

$$U_E = \frac{1}{2} C V^2 \quad (\text{Energy in capacitor}) \quad (8)$$

Constants to Remember

Constant	Value
Coulomb's constant k	$8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$
Elementary charge e	$1.602 \times 10^{-19} \text{ C}$
Permittivity ϵ_0	$8.85 \times 10^{-12} \text{ F/m}$

These appear in every calculation!

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- Why atoms bond (electric **forces**)
- How computer memory works (**capacitor charge** storage)

Homework

Complete the assigned problems
posted on the LMS