PHYS12 CH18: The Invisible Forces Between Charges

Coulomb's Law, Fields, Potential, and Capacitors

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Outline

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

What if forces could act
without touching?

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

- **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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- Like charges repel

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The Mental Model

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

Two types of charge:

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

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

$$\boxed{F = \frac{kq_1 q_2}{r^2}}$$

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

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Universal Law: Coulomb's Law

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

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

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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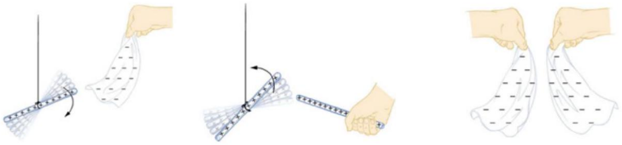

(a) (b) (c)

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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- 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

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?

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

Reveal: The Electric Interaction

Self-correct in a different color:

Step 1: $F = \frac{kq_1 q_2}{r^2}$

Reveal: The Electric Interaction

Self-correct in a different color:

Step 1: $F = \frac{kq_1 q_2}{r^2}$

Step 2: $F = \frac{(8.99\times10^9)(3\times10^{-9})(-4\times10^{-9})}{(0.030)^2}$

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Self-correct in a different color:

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Step 3: $F = -1.2 \times 10^{-4}$ N

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$$\boxed{|F| = 1.2 \times 10^{-4} \text{ N, attractive}}$$

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$$\boxed{|F| = 1.2 \times 10^{-4} \text{ N, attractive}}$$

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

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.

18.3 Force Fields in Physics

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.

Universal Law: Electric Field

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

Electric field equals force per unit charge.

18.3 The Source Code of Fields

Universal Law: Electric Field

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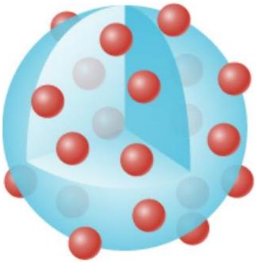
Electric field equals force per unit charge.

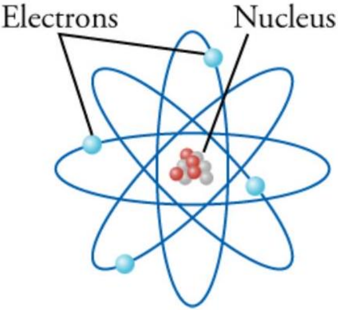
For a point charge Q:

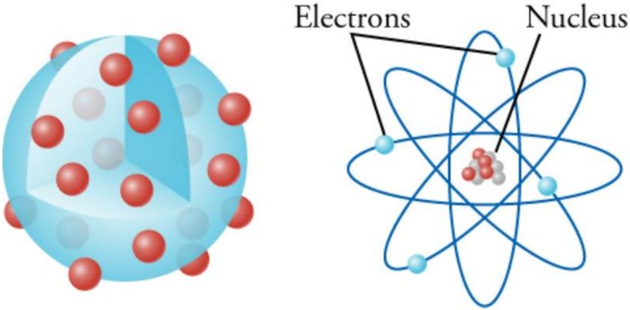
$$E = \frac{k|Q|}{r^2}$$

Units: N/C (newtons per coulomb)

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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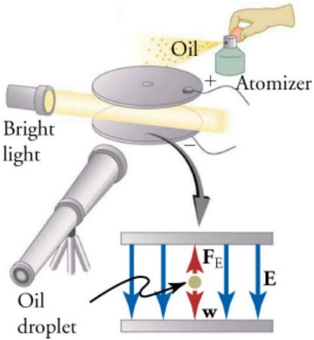
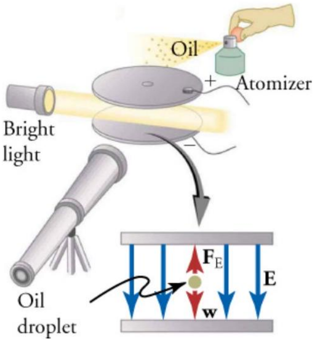
The Paradox

Misconception: "Field lines are paths charges follow."
Reality: Field lines show force direction, but moving charges have inertia - they curve gradually.

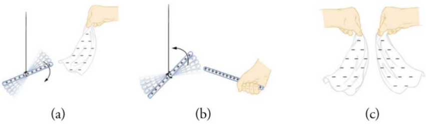


Positive and negative

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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Self-correct in a different color:

Signs:

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

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Magnitude:

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

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Self-correct in a different color:

Signs:

- 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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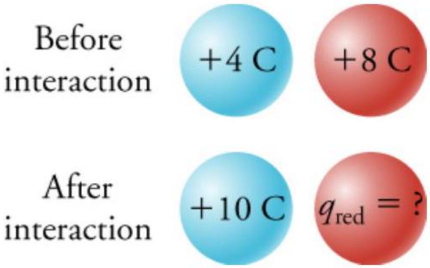
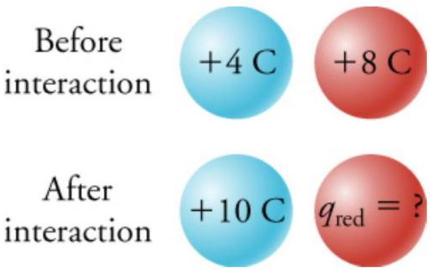
Electric potential: "height" in an electric field



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

$$\boxed{U_E = \frac{kq_1 q_2}{r}}$$

Energy stored in configuration of two charges.

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- $U_E > 0$: like charges (they want to fly apart)

Universal Law: Electric Potential Energy

$$\boxed{U_E = \frac{kq_1q_2}{r}}$$

Energy stored in configuration of two charges.

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

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

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."

What really matters: difference in potential

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In uniform field E:

$$\Delta V = -E(x_f - x_i)$$

What really matters: difference in potential

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Rearranged:

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

What really matters: difference in potential

In uniform field E:

$$\Delta V = -E(x_f - x_i)$$

Rearranged:

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

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

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

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

Substitute: $V = \frac{(8.99\times10^9)(5\times10^{-9})}{0.10}$

Reveal: The Electric Pressure

Self-correct in a different color:

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

Substitute: $V = \frac{(8.99\times10^{9})(5\times10^{-9})}{0.10}$

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

Reveal: The Electric Pressure

Self-correct in a different color:

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

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

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

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

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

What if you could bottle electric fields?

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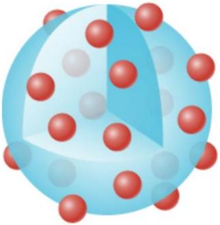

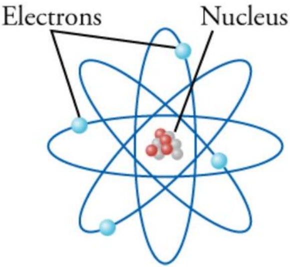

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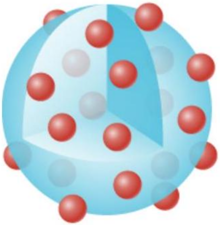
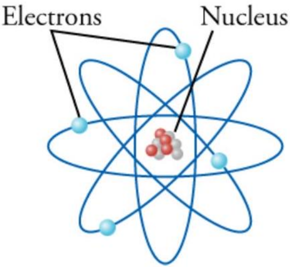
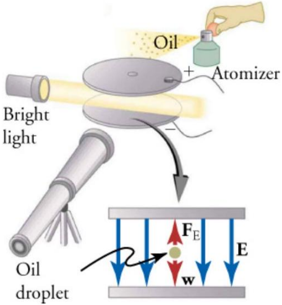
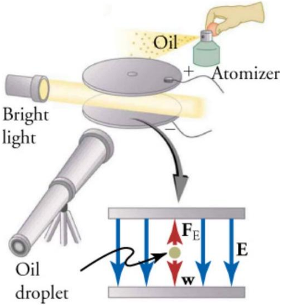




Capacitors store energy in electric fields between charged plates.

18.5 The Parallel-Plate Capacitor





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

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

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

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Universal Law: Capacitance

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

For parallel plates:

$$C_0 = \varepsilon_0 \frac{A}{d}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}\ \text{F/m}$

18.5 Energy Storage

Universal Law: Energy in Capacitor

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

Energy stored equals half capacitance times voltage squared.

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Universal Law: Energy in Capacitor

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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

What determines capacitance?

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- Increase plate area A: capacitance increases

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$$C_0 = \varepsilon_0 \frac{A}{d}$$

- 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.

Real-World Enhancement

Insert insulating material (dielectric) between plates:

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

18.5 Dielectrics

Real-World Enhancement

Insert insulating material (dielectric) between plates:

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

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 $A = 0.010$ m^2
- $\varepsilon_0 = 8.85 \times 10^{-12}$ 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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Turn and talk (2 min):

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Name wheel: One pair share your approach.

Reveal: The Design Solution

Self-correct in a different color:

Formula: $C_0 = \varepsilon_0 \frac{A}{d}$

Reveal: The Design Solution

Self-correct in a different color:

Formula: $C_0 = \varepsilon_0 \frac{A}{d}$

Rearrange: $d = \varepsilon_0 \frac{A}{C}$

Reveal: The Design Solution

Self-correct in a different color:

Formula: $C_0 = \varepsilon_0 \frac{A}{d}$

Rearrange: $d = \varepsilon_0 \frac{A}{C}$

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

Reveal: The Design Solution

Self-correct in a different color:

Formula: $C_0 = \varepsilon_0 \frac{A}{d}$

Rearrange: $d = \varepsilon_0 \frac{A}{C}$

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

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

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Self-correct in a different color:

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Rearrange: $d = \varepsilon_0 \frac{A}{C}$

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

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

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

What You Now Know

1. Coulomb's Law: $F = \frac{kq_1 q_2}{r^2}$ - forces between charges

The Four Revelations

What You Now Know

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2. Electric Field: $E = \frac{F}{q}$ - force per unit charge

The Four Revelations

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1. Coulomb's Law: $F = \frac{kq_1 q_2}{r^2}$ - 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: $F = \frac{kq_1 q_2}{r^2}$ - 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

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

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

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

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

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

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

$$C_0 = \varepsilon_0 \frac{A}{d} \quad \text{(Parallel-plate capacitor)} \tag{7}$$

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

Constants to Remember

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

These appear in every calculation!

From Theory to Reality

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- How computer memory works (capacitor charge storage)

Homework

Complete the assigned problems

posted on the LMS

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