

# PHYS12 CH18: The Invisible Forces Between Charges

## Coulomb's Law, Fields, Potential, and Capacitors

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# Outline

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

# The Mystery of the Invisible

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*without touching?*

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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:** 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 (-)
- Like charges repel
- Unlike charges attract

## 18.2 Coulomb's Discovery



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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

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

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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)



## 18.2 Reading the Signs

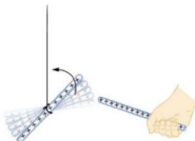
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(a)



(b)



(c)

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### The Mental Model

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

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

### Given:

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

**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?

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

# Reveal: The Electric Interaction

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

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

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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

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### The Mental Model

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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

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Electric field equals force per unit charge.

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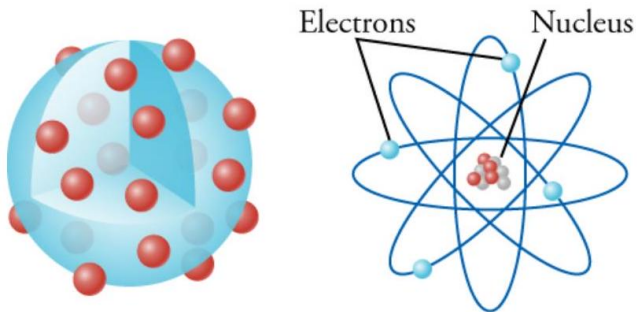
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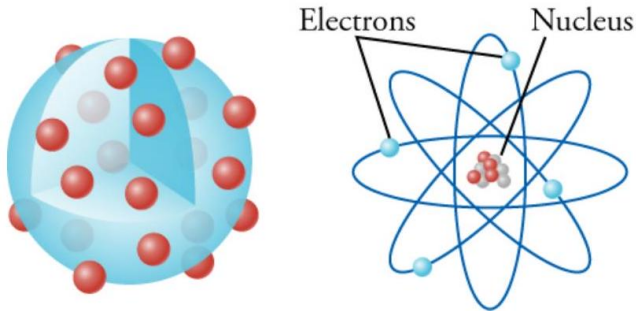
$$E = \frac{k|Q|}{r^2}$$

Units: N/C (newtons per coulomb)

## 18.3 Visualizing the Invisible



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### Field lines show:

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

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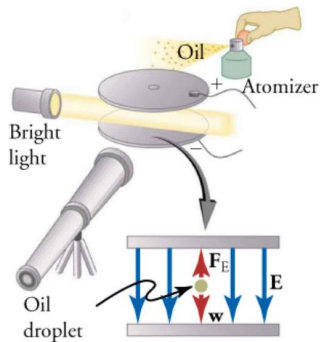
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### The Paradox

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

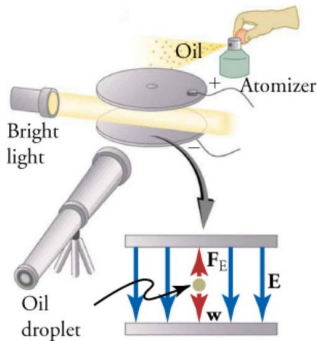
**Reality:** Field lines show force direction, but moving charges have inertia - they curve gradually.

## 18.3 Field Patterns

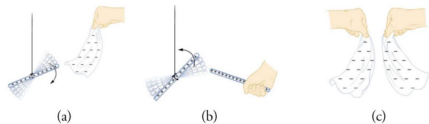


Positive and negative

## 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):

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- Count field lines touching each charge

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### 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

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

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

- **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

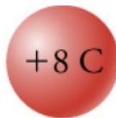
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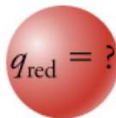
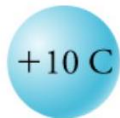
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Before  
interaction



After  
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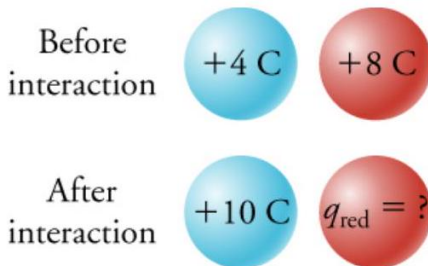


## 18.4 The Universe's Pressure Gauge

### The Mental Model

Gravitational potential: height in a gravitational field

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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

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

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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

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### 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  $Q = +5 \times 10^{-9} \text{ C}$  creates an electric potential.

### Given:

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

**Find:** Electric potential at distance  $r = 0.10 \text{ m}$

*Can you calculate the voltage? Work silently.*

# Compare: Voltage Calculation

## Turn and talk (2 min):

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# Reveal: The Electric Pressure

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

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



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

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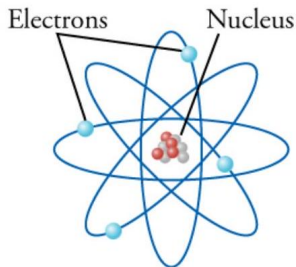
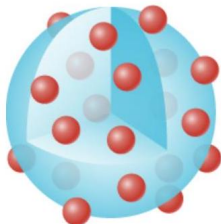
- **18.5:** Calculate energy stored in a capacitor and capacitance
- **18.5:** Explain properties of capacitors and dielectrics

## 18.5 Energy Storage Devices

What if you could bottle electric fields?

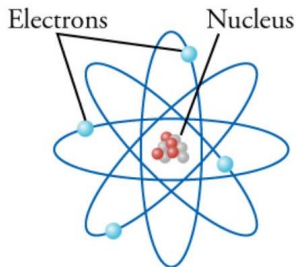
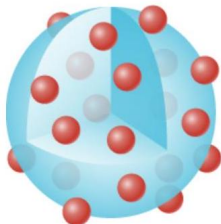
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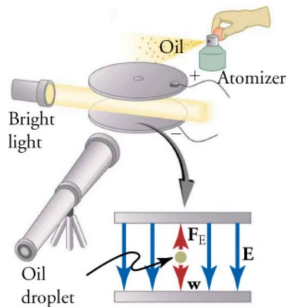
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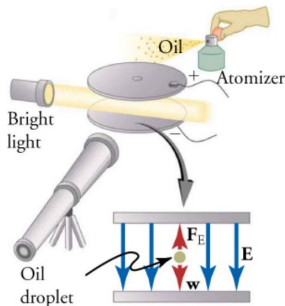


Capacitors store energy in electric fields between charged plates.

## 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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For parallel plates:

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

where  $\epsilon_0 = 8.85 \times 10^{-12}$  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.

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- 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  $C = 1.0 \times 10^{-9} \text{ F}$ .

### Given:

- $C = 1.0 \times 10^{-9} \text{ F}$  (1.0 nF)
- Plate area  $A = 0.010 \text{ m}^2$
- $\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$

**Find:** Required plate separation  $d$

*Can you find the spacing? Work silently.*

# Compare: Design Strategy

## Turn and talk (2 min):

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- 2 How did you rearrange to solve for  $d$ ?
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# Reveal: The Design Solution

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

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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

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- 4 Capacitance:  $C = \frac{Q}{V}$  - charge storage capacity



# Key Equations

$$F = \frac{kq_1q_2}{r^2} \quad (\text{Coulomb's law}) \quad (1)$$

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

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

$$U_E = \frac{kq_1q_2}{r} \quad (\text{Electric potential energy}) \quad (4)$$

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

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

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

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

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

These appear in every calculation!

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- How computer memory works (capacitor charge storage)



Complete the assigned problems  
posted on the LMS