# Electric Charges, Forces and Fields

Chapter 17

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- Forces of Nature
- Electric Charge
- Coulomb's Law
- Electric Field
- Electric Field Lines
- Flux of an Electric Field

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## Part 1

Forces of nature
or
A short journey …
back to Physics 111

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**Physics 111: Analysis of motion - 3 key ideas**

Newton's laws of motion

Conservation of Energy

Conservation of Momentum

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## Newton's laws of motion

**Newton's First Law**: If no force acts on a body, then the body's velocity cannot change

**Newton's Second Law**: $\vec{F} = m\vec{a}$

Newton's laws of motion allow us to analyze many kinds of motion.

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## Newton's laws of motion (applications)

**Special case:** motion with **constant** acceleration (1D, 2D or 3D motion)

$\vec{F} = m\vec{a}$

↓

$$x = x_0 + v_0 t + \frac{at^2}{2}$$

$$v = v_0 + at$$

**Observables:**

| | |
|---|---|
| time | force |
| position | |
| velocity | |
| acceleration | |

Examples of problems: projectile motion, …

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## Conservation of energy

The total energy of an isolated system cannot change

In an isolated system where only conservative forces cause energy changes, the kinetic energy and potential energy can change, but their sum cannot change

$$K_i + U_i = K_f + U_f$$

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## Conservation of momentum

Conservation of linear momentum

If no net external force acts on a system of particles, the total linear momentum of the system cannot change

$$\vec{P} = m_1\vec{v}_1 + m_2\vec{v}_2 + ... + m_n\vec{v}_n = const$$

Conservation of angular momentum

If the net external torque acting on a system is zero, the angular momentum of the system remains constant, no matter what changes take place within the system

$$\vec{L}_i = \vec{L}_f$$

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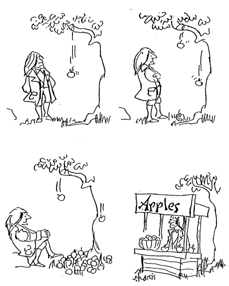
## What forces do we know from our experience and Physics 111?

Gravitational Force
Frictional Force
Spring Force (Hook's Law)
Normal Force
Tension force in a string
Aerodynamic Drag Force
……

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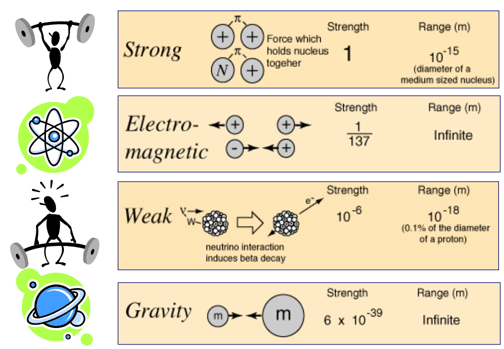
## There are ONLY four fundamental forces of nature

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## FOUR or ONE?

Many scientists think that all four of the fundamental forces are, the manifestations of a single force which has yet to be discovered.

Just as electricity, magnetism, and the weak force were unified into the electroweak interaction, they work to unify all of the fundamental forces.

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## Gravitational and electro-magnetic forces: this what we experience!!!

Frictional force, spring force, normal force, tension force in a string, aerodynamic force … are results of electromagnetic force

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# Part 2

## Electric Charge

## Electric charge

**Electric Charge** is an intrinsic characteristic of the fundamental particles making up objects around us (including us).

The ordinary matter consists of three (only!) particles:

| | electron (e) | proton (p) | neutron (n) |
|---|---|---|---|
| mass | $9.11\times10^{-31}$ kg | $1.67\times10^{-27}$ kg | $1.67\times10^{-27}$ kg |
| charge | $-1.60\times10^{-19}$ C | $1.60\times10^{-19}$ C | 0.00 |

The SI unit of electric charge is the Coulomb

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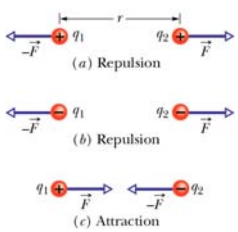
## Important characteristic of electric charge

**An electric charge has a magnitude and sign.**
It is either positive or negative.
Electron has negative electric charge
Proton has positive electric charge

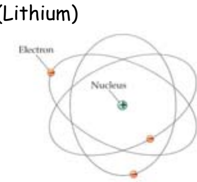



If the charges have the same sign, the forces between them are repulsive

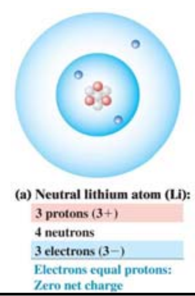
Charges of opposite sign experience attractive forces

## Atoms and molecules are made up from electrons, protons and neutrons!

A classical (solar system) model of an atom (Lithium)




A quantum model of an atom (Lithium)




Atoms are combinations of equal amounts of electrons and protons.

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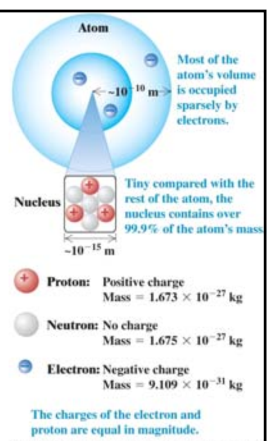
## Sizes and masses

Atoms are combinations of equal amounts of electrons and protons. The neutrons provide the glue to stick together the protons in the nucleus.
The proton and the neutron are about 2000 times heavier than the electron, so the vast majority of an atom's mass resides in the nucleus.
Atoms are mostly … empty. We live in almost empty space

Example: tennis ball and a grain of sand






## Net electric charge for a system of n particles

$$q_{net} = q_1 + q_2 + q_3 + \ldots q_n$$

The total (net) electric charge of an isolated system is conserved. The only way to change it is to add or remove charged particles.

The total electric charge of the universe is constant.

- ✓ the net electric charge of atoms and molecules is zero (equal amounts of electrons and protons)
- ✓ removing an electron from a neutral atom creates a positive ion
- ✓ negative ions?

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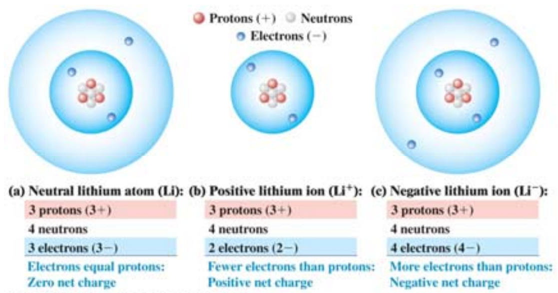
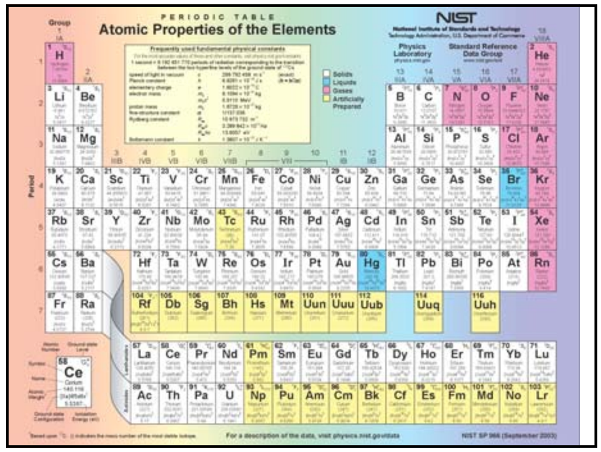
## Example:





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To make an uncharged object have a negative charge we must:

A) add some atoms
B) add some protons
C) add some electrons
D) add some neutrons
E) write down a negative sign



## Macro objects (many atoms or molecules)

Materials – two extreme models

**Insulators** – a material in which charges do not move freely though the interior of the sample. Examples: Glass, wood, rubber, plastics, stone, brick, etc

**Conductors** – material where free charges can move through the material. Examples: Ionized gases (plasmas), metals, ionic solutions if salts in water

**Semi-conductors** – a material intermediate between the two extreme models – GaAs, Ge, Si, are the classic examples.



## Macro objects can be charged by charge transfer or charge separation

- ✓ Charge transfer happens when electric charges (usually electrons) transfer from one object to another
- ✓ Charge separation occurs when two material are rubbed together or when objects collide



## Charge is quantized

Experiments show that any positive or negative charge q that can be detected can be written as

$$q = n \cdot e, \quad n = \pm 1, \pm 2, \pm 3, \ldots$$
$$e = 1.60 \times 10^{-19} C$$

where e is the **elementary charge**.

## from a simple to complex

- Universe
- human beings
- cells
- condense matter, gases
- molecules
- atoms
- electrons, protons, neutrons
- fundamental particles: electrons, quarks, …

Note: ALL electrons are identical, as well as protons, neutrons …

# Part 3

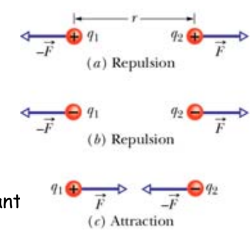
## A force between charges

## Coulomb's Law

The **electrostatic force** between two charges $q_1$ and $q_2$ separated by a distance r has the magnitude

$$F = k\frac{|q_1 q_2|}{r^2}$$

$$k = \frac{1}{4\pi\varepsilon_0} = 8.99\times10^9\ \mathrm{N\cdot m^2/C^2}$$




k is the electromagnetic constant
$\varepsilon_0$ is the permittivity constant

Where is the 3rd Newton's law?



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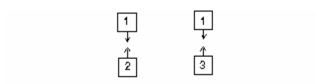
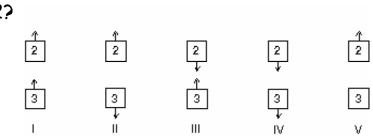
The diagram shows two pairs of heavily charged plastic cubes. Cubes 1 and 2 attract each other and so do cubes 1 and 3.



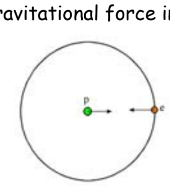

Which of the following illustrates the forces of 2 on 3 and 3 on 2?






## Comparing the gravitational and electrostatic forces

Let's calculate the ratio of the electrical to the gravitational force inside a hydrogen atoms.




$$F_g = \frac{GM_pM_e}{R^2}, F_e = \frac{k_e q_p q_e}{r^2}$$

$$\frac{F_e}{F_g} = \frac{\frac{k_e q_p q_e}{r^2}}{\frac{GM_pM_e}{r^2}} = \frac{k_e q_p q_e}{GM_pM_e}$$

$$\frac{F_e}{F_g} = \frac{(9\times10^9)(1.6\times10^{-19})^2}{(6.67\times10^{-11})(1.67\times10^{-27})(9.11\times10^{-31})} = 2.27\times10^{39}$$

So we can forget gravity as compared to electrostatic forces – at least on the atomic scale



## A contradiction to a simple observation?

If $F_e/F_{Gl} = 2.27\times10^{39}$ then, why the gravity force plays any observable role?

- ✓ The force of gravity play essentially NO role in atomic and molecular systems
- ✓ However macroscopic objects are neutral or almost neutral (the net electric charge is close to zero) Therefore the force of gravity play strong role for macroscopic objects

## An example with two coins?

Let's find an electrostatic force between two coins separated by a distance of 1 meter

a) force between 2 electrons — $2.30*10^{-28}$ N

b) force between electrons in the two coins — $2.30*10^{16}$ N

c) the net force between electrons and protons in the two coins — 0.0 N

$$F = k\frac{q_1 q_2}{r^2}$$

$k = 8.99\times10^{9}\ \mathrm{N{\cdot}m^2/C^2}$

$e = 1.60\times10^{-19}\ \mathrm{C}$

$N_{coin} \approx 10^{22}$ electrons

about 25 millions!!!



## Coulomb's law and the principle of superposition

The principle of superposition: the net effect is the sum of the individual effects

For n interacting particles the net force on particle 1 can be written as

$$\vec{F}_{1,net} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \ldots \vec{F}_{1n}$$

*being practical – see chapter 3 "Vectors in Physics" (adding vectors using components)*

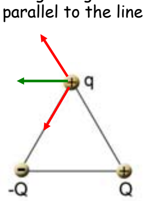


?

## Net Force and the superposition principle

Charges Q, -Q, and q are placed at the vertices of an equilateral triangle as shown. The total force exerted on the charge q is:

A) toward charge Q
B) toward charge -Q
C) away from charge Q
D) at right angles to the line joining Q and -Q
E) parallel to the line joining Q and -Q




Always draw a free body diagram!



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## Net Force

Two point charges are arranged as shown, where $Q_1$ = -2C, $Q_2$ = 1C. In which region could a third charge +1 C be placed so that the net electrostatic force on it is zero?

A) I only
B) I and II only
C) III only
D) I and III only
E) II only


What if the third charge is q=-1C?

What if the particles have charges Q and -Q?

What if the particles have charges Q and Q?



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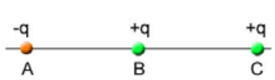
## Net Force

Consider the three electric charges shown in the figure. List the charges in order of the magnitude of the force they experience, starting with the smallest
(Note: the distance from A to B is the same as the distance from B to C.)



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## Net Force 2

Four identical point charges are placed at the corners of a square. A fifth point charge placed at the center of the square experiences zero net force.
Is this a stable equilibrium for the fifth charge

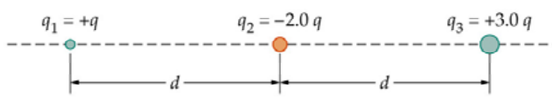
good to use PhET computer simulation as an illustration problem

## Example: 3 electric charges in a line

Given that $q$ = +12 mC and $d$ = 16 cm,

(a) find the direction and magnitude of the net electrostatic force exerted on the point charge $q_2$ in Figure below?

(b) How would your answers to part (a) change if the distance $d$ were tripled?

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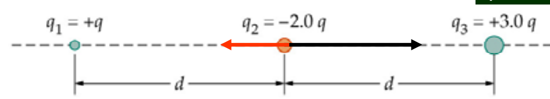
problem




$$F_{blue} = \frac{1}{4\pi\varepsilon_0}\frac{3.0q\times 2.0q}{d^2} = 9\times10^9\times\frac{3.0q\times 2.0q}{d^2}$$

$$F_{red} = \frac{1}{4\pi\varepsilon_0}\frac{1.0q\times 2.0q}{d^2} = 9\times10^9\times\frac{1.0q\times 2.0q}{d^2}$$

$$F_{\text{resultant}} = 9\times10^9\times\left[\frac{3.0q\times 2.0q}{d^2} - \frac{1.0q\times 2.0q}{d^2}\right] \text{ to the right}$$

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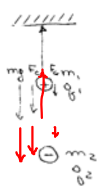
problem

**Problem 1.** (10 points)

A small object of mass 0.025 kg and charge 1.9 μC hangs from the ceiling by a thread. A second small object of mass 0.50 kg and charge -4.2 μC, is placed 52 cm vertically below the first charge.

(a) Find the tension in the thread

(b) Find the ratio of the electrical to the gravitational force between the objects.



a) $T = m_1 g + k\frac{q_1 q_2}{r^2} + G\frac{m_1 m_2}{r^2}$ (too small) $= 0.51\ N$

b) $R = \frac{F_c}{F_G} = \frac{k\frac{q_1 q_2}{r^2}}{G\frac{m_1 m_2}{r^2}} = \frac{k q_1 q_2}{G m_1 m_2} = 8.6\cdot10^{10}$

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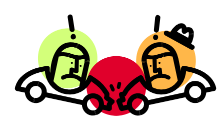
problem

## A tale of two particles

An electron and a proton are released from rest in space, far from any other object. The particles move toward each other, due to their mutual attraction. When they meet, is the kinetic energy of the electron greater than, less than, or the same as the kinetic energy of the proton?
Explain.



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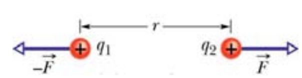
# Part 4

## Electric Field

## A couple "simple" questions

The Coulomb law

$$F = k\frac{q_1 q_2}{r^2}$$




How does $q_1$ "know" of the presence of $q_2$?

Since the charges do not touch, how can $q_1$ exert a force on $q_2$?

Action on a distance!

Other examples?

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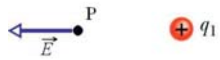
## Electric Fields or Action on a Distance




We can say that $q_1$ sets up an **electric field** in the space surrounding it.

1. At any given point P in that space the field has both magnitude and direction.
2. The magnitude depends on the magnitude of $q_1$ and the distance between P and $q_1$.
3. The direction depends on the direction from $q_1$ to P and the electrical sign of $q_1$.
4. Thus when we place $q_2$ at P, $q_1$ interacts with $q_2$ through the electric field at P.

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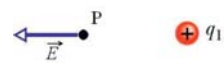
## The electric field is a vector field

The electric field consists of a distribution of vectors, one for each point in the region around a charged object.
A way to define the electric field at some point P

1. Place a positive charge $q_0$, called a test charge, at the point P
2. Measure the electrostatic force $\vec{F}$ that acts on the test charge
3. Define the electric field at the point P due to the charged object as

$$\vec{E} = \frac{\vec{F}}{q_0}$$




The SI unit for the electric field is the newton per coulomb (N/C)

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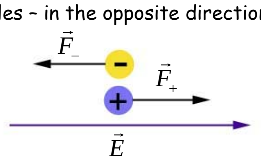
## A particle in an electric field

1. If we know the electric field vector at a given point, the force that a charge q experiences at that point is

$$\vec{F} = q\vec{E}$$

2. The direction of the force:
   positive particles – in the direction of the field
   negative particles – in the opposite direction of the field

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## The electric field due to a point electric charge

From Coulomb's law, the magnitude of the electrostatic force acting on $q_0$ is

$$F = k\frac{|q||q_0|}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{|q||q_0|}{r^2}$$

The direction of the force is directly away from the point charge if q is positive, and directly toward the point charge is q is negative. Then the magnitude of the electric field from a point charge is

$$E = k\frac{|q|}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

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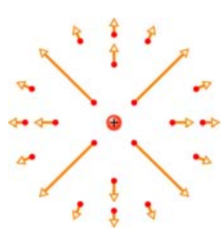
## Example



Electric field around a positive electric charge

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## The electric field due to more than one point electric charge

Using the superposition principle we can find the net force

$$\vec{F}_{0,net} = \vec{F}_{01} + \vec{F}_{02} + \vec{F}_{03} + \ldots \vec{F}_{0n}$$

Therefore the net electric field at the position of the test charge is

$$\vec{E} = \frac{\vec{F}_{0,net}}{q_0} = \frac{\vec{F}_{01}}{q_0} + \frac{\vec{F}_{02}}{q_0} + \frac{\vec{F}_{03}}{q_0} + \ldots \frac{\vec{F}_{0n}}{q_0}$$

$$\vec{E} = \vec{E}_{01} + \vec{E}_{02} + \vec{E}_{03} + \ldots \vec{E}_{0n}$$

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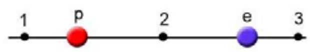
## Net Field

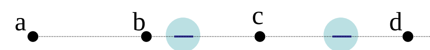
A proton p and an electron e are on the x axis. Find the directions of the electric field at points 1, 2, and 3 respectively




Go to PhET



Consider two identical negative charges as shown. At which lettered point is the magnitude of the electric field greatest? Least?






## Conceptual question

A proton moves in a region of constant electric field.

Does it follow that the proton's velocity is parallel to the electric field?

Does it follow that the proton's acceleration is parallel to the electric field?



## Conceptual question

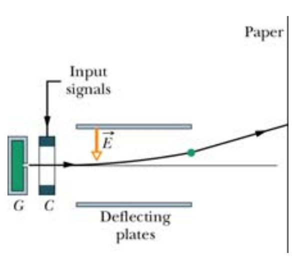
The force experienced by charge 1 at point A is different in direction and magnitude from the force experienced by charge 2 at point B.

Can we conclude that the electric fields at point A and point B are different?



## Example: a point charge in an electric field

The essential features of an ink-jet printer




$$\vec{F} = q\vec{E} = m\vec{a}$$

then … motion with constant acceleration (see physics 111)



## Tools (equations) to describe motion of electrons

| | | |
|---|---|---|
| atoms<br>molecules | quantum<br>mechanics | Schrodinger equation<br>Dirac equation |
| gases,<br>plasma, … | classical<br>mechanics | Second Newton's law |

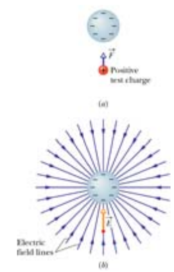
$$\vec{F} = q\vec{E} = m\vec{a}$$

# Part 5

## Electric Field Lines

Electric field **lines** provide a nice way to visualize patterns in electric fields

1. At any point, the direction of a straight field line gives the direction of the electric field at that point
2. Electric fields extend away from positive charge and toward negative charge
3. No field lines cross.
4. The field lines are drawn so that the number of lines per unit area is proportional to the *magnitude* of the electric field.

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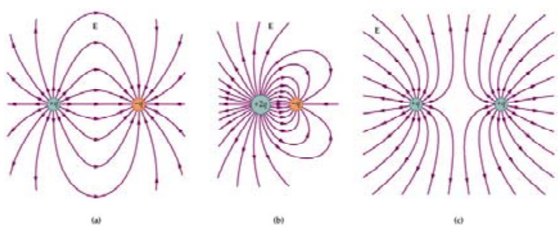
Examples




Note that twice as many field lines originate from the +2*q* charge than the +*q* or −*q* charges.

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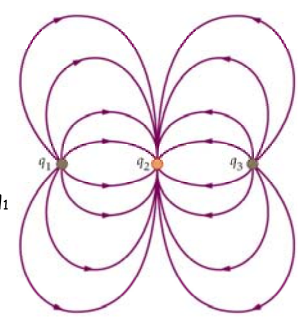
Problem

The electric field lines surrounding three charges are shown in the Figure. The center charge is $q_2$ = -10.0 mC.

(a) What are the signs of $q_1$ and $q_3$?

(b) Find $q_1$.

(c) Find $q_3$.

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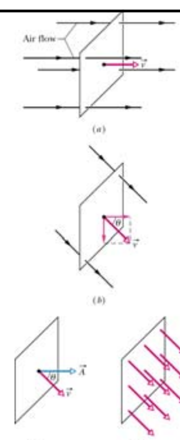
# Part 6

## Flux of an Electric Field

**Flux**

Example: a wide air stream of <u>uniform velocity</u> at a small square loop of area A.
Let Φ represents the *volume flow rate* (volume per unit time) at which air flows through the loop.
The rate depends on the angle between the velocity and the plane of the loop.

$$\Phi = (v\cos\theta)A = vA\cos\theta$$



## Flux of an Electric Field

$$\Phi = EA\cos\theta$$

$\theta$ is the angle between the electric field and the line perpendicular to the surface.

SI units: $N{\cdot}m^2/C$

*For a non-uniform fields we have to integrate over a surface*

*The electric flux through a surface is proportional to the net number of electric field lines passing through that surface.*

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## Gauss' Law

Gauss' law relates the net flux $\Phi$ of an electric field through a closed surface to the net charge $q_{enc}$ that is enclosed by that surface

$$\varepsilon_0 \Phi = q_{enc}$$

Gauss' law and Coulomb's law

*Demonstration for a point charge*

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} \qquad \Phi = EA = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}4\pi r^2 = \frac{q}{\varepsilon_0}$$

$$A = 4\pi r^2$$

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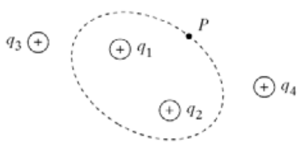
## Example

In the following figure, the dashed line denotes a Gaussian surface enclosing part of a distribution of four positive charges.

(a) Which charges contribute to the electric field at P?

(b) Is the value of the flux through the surface, calculated using only the electric field due to q1 and q2, greater than, equal to, or less than that obtained using the field due to all four charges?

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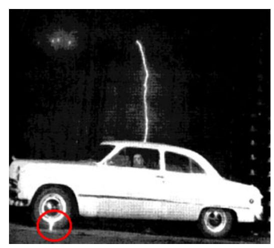
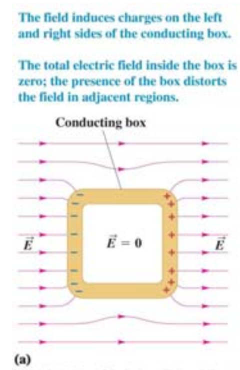
## A practical conclusion from the Gauss's Law – Faraday's cage



During a thunderstorm – stay in your car!!!




# Epilogue

## Interactive Computer Simulation

A very good collection of interactive simulations to learn physics from the Physics Education Technology project at the University of Colorado http://www.colorado.edu/physics/phet/