ELECTRICAL PHENOMENA

OBJECTIVES

- To describe qualitatively the phenomena of electrification, electrostatic attraction and repulsion and to introduce the concepts of electric charge, insulators and conductors.
- To justify Coulomb's law and use it to calculate the force exerted by one or two charged particles on another.
- To justify field intensity and calculate its value in the case of one or two charged particles.
- To describe the electric field using force lines.
- To justify the concepts of potential electric energy and potential, as well as using them to calculate the work done when moving a particle in the electric field.
- To observe the relation between field intensity and potential.
- To carry out some predictions on the movement of charges in uniform fields.

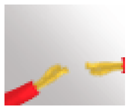
1.1 What we already know about electricity

At some time all of us have done the experiment of "electrifying" our pen by rubbing it on the sleeve of our jersey so that it attracts little pieces of paper. In previous years we have learned that the atoms of a material possess particles with the property we call an electric charge. We know that there are positive charges in the nucleus called protons, and negative charges outside the nucleus called electrons. Could you explain what type of charges have moved when we charge our pen?

The natural unit of electric charge should be the electron. But as it is too small for practical purposes we have adopted another unit called the **coulomb,** equivalent to the charge of some 6 trillion electrons. We will give the exact definition of this unit in the topic on electric current, in the section on electrolysis.

1.2 Differences between conductors and insulators

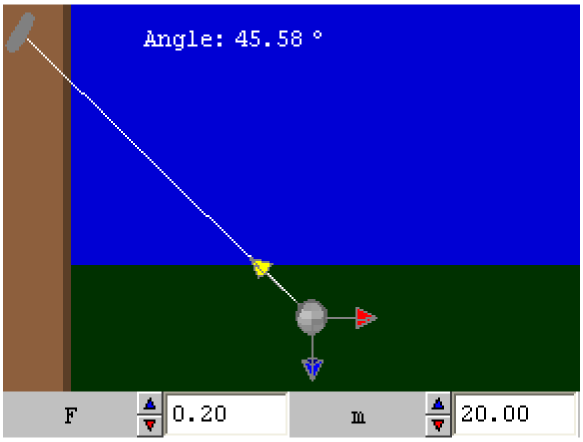
Your experience also tells you that if you had done the previous experiment with a metal pen, you would not have been able to charge it. This is due, you would say, to the fact that metal is a **conductor** and plastic is an **insulator**. Could you explain the difference between these two types of bodies? Of course, conductors can also be charged. Could you explain a way to do this? The image of the electric spark between charged bodies will perhaps help you.



In the following sections, unless stated otherwise, we are going to study the electric field created by charged bodies without taking into account whether they are conductors or insulators.

1.2 El péndulo electrostático

We will try to measure electric force with the help of an instrument which is easy to understand: the electrostatic pendulum. We shall see how this instrument lets us measure the force acting on a body. You can graduate the magnitude of the force acting on the pendulum on the right.



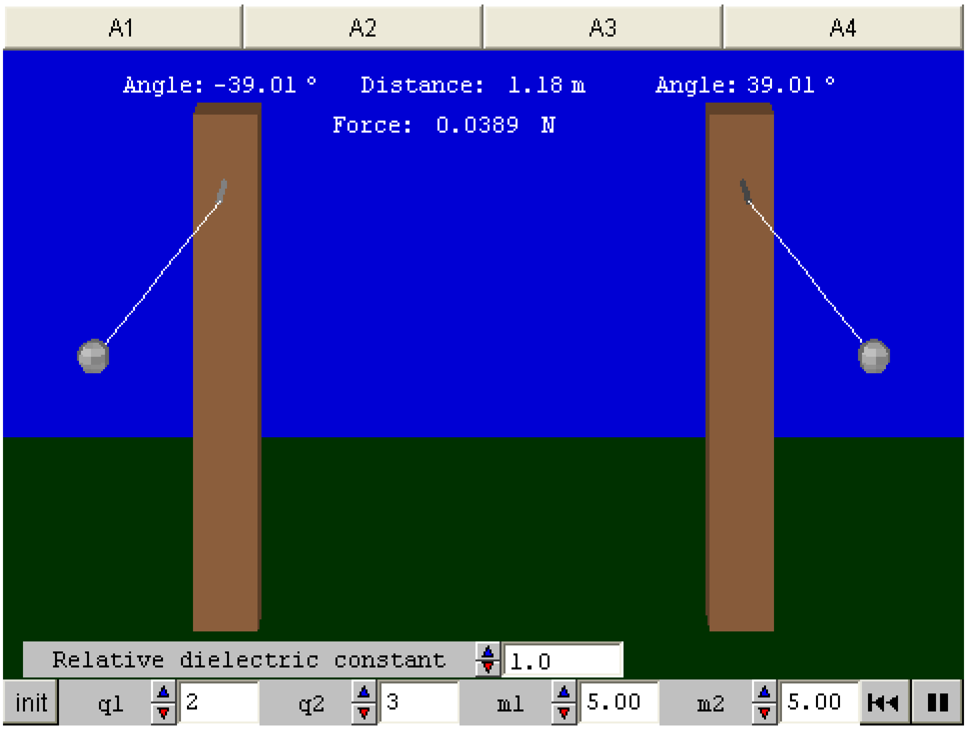
When you click on **next** you will see how to use this pendulum to measure the force between two charged bodies.

Whether you modify the mass (and thus the weight) or you modify the horizontal force, the angle varies and equilibrium is reached among the three forces acting on the bob of the pendulum:

The **force applied F**, the **tension of the string T**, and the **weight of the body P**.

1.3 Coulomb's Law

The visual shows the interaction between two charged pendulums. Do the suggested activities.



A1: Give q1 and q2 different positive values and click on play. What happened? Which pendulum exerts a greater force on the other one? Exchange the values of the charges? Can you see any changes in the results? Repeat the experiment changing the sign of one of the charges. Does anything change?

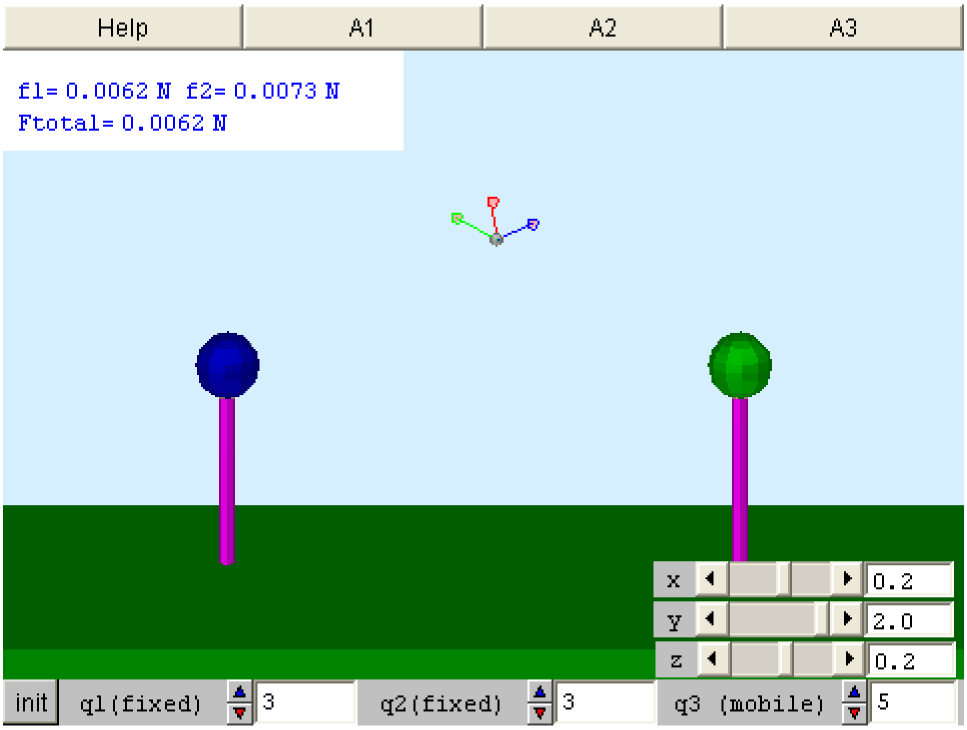
A2: Give q1 and q2 values different from 0 and change the mass of one of the pendulums to 10 grams. Then click on play. Is the movement of both pendulums the same? Explain why or why not.

A3: Give q1, q2, m1 and m2 the value 1. Click on play and note down the force observed and the distance between the two spheres. Change the value of m2 to 3 grams and click on play again. Note down the force observed and the distance. Repeat the experiment for m2=6 g and m2 = 9 g. Now multiply the force by the distance for every pair of values you have noted down. What can you observe? What is the mathematical significance of this observation?

A4: The relative dielectric constant is a property of the medium that surrounds the charged spheres. Change the value of the relative dielectric constant for fixed values of q1 and q2. How do the results change? Find the relation between the dielectric constant and the constant in Coulomb

1.3 The superposition of Coulomb's forces

In the following visual we see the effect, **superposition**, of two charged particles on a third one. The conclusions can be generalized to any number of particles.



Help: This visual allows you to change the values of the fixed charged particles q1 and q2, the mobile charged particle q3, and the position of the latter particle in space, given by x, y and z. The program will give you the value of the force exerted by q1 and q2 on q3, as well as the resulting force. You can change the point of view by clicking and dragging on the visual.

A1: Give q1 and q3 the value of 4 or 5 microcoulombs. Observe the value and direction of the force. Change the position of q3 with the x and z controls. Observe the changes in the force and its direction. What happens if we change the sign of q3? Click on init and repeat the experiment with q2 and q3.

A2: Give q1, q2 and q3 the value of 5 microcoulombs. Explain the value of the three vectors that appear. Observe the changes in these values when we change the value of the z coordinate of q3, for example. Move the space around if you need a better point of view to see the results.

A3: Give q1 the value of 1 microcoulomb and q3 the value of 5 microcoulombs. Move q3 to the position (-0.7, 0, 0). Calculate the value of q2 in order to make the total force on q3 equal to zero. Check the result with the visual. Would you be able to find a similar value if q3 where at (-1, 1, 1)?

1.4 First conclusions about electric force

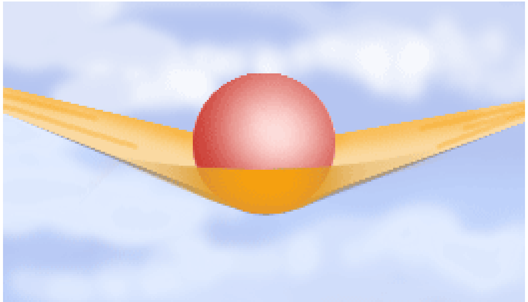
- The atoms of bodies possess **positively charged heavy particles, protons, and negatively charged light particles, electrons.** The excess of electrons means that the body is negatively charged and the deficit of electrons means that the body is positively charged.
- In some bodies the charge is forced to remain almost immobile, these are **insulators**, while in other bodies it can move freely, these are conductors.
- **Bodies with charges of the opposite sign attract each other, while bodies with charges of the same sign repel each other.**
- The value of the force of attraction or repulsion between two particles is explained by **Coulomb's Law:**

$$F = K\frac{Q_1 \cdot Q_2}{r^2}$$

where Q1 and Q2 are the values of the charges which are interacting, r is the distance between the particles, and K is the dielectric constant which depends on the medium. For a vacuum: $K = 9 \cdot 10^9\ N \cdot m^2/C^2$

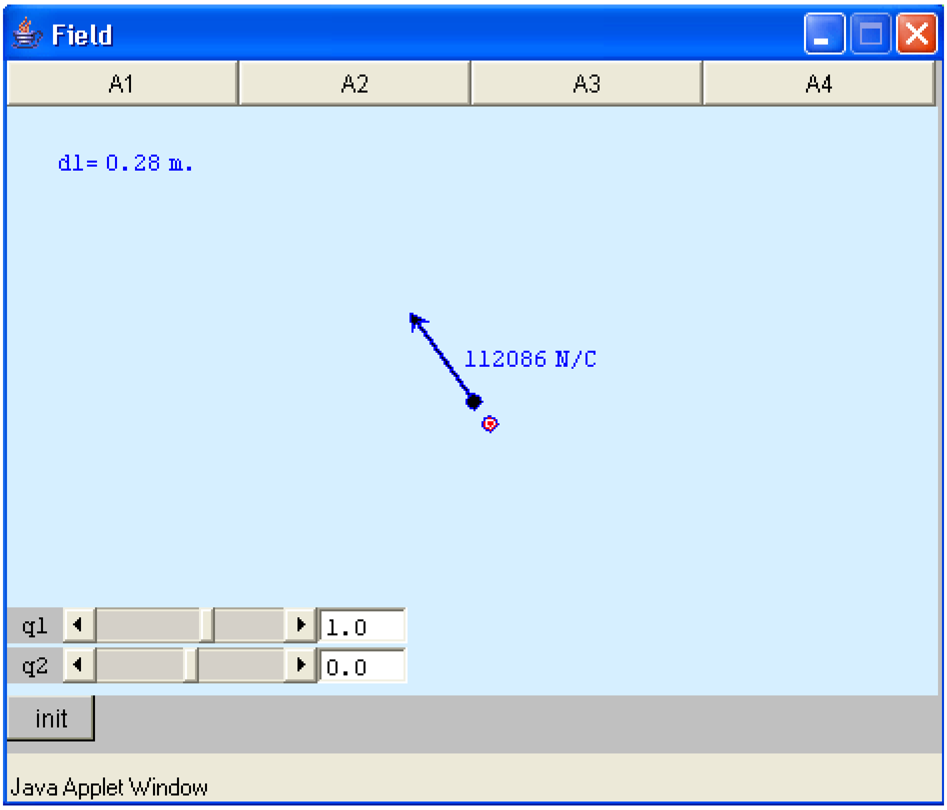
- When two or more charged particles act on another, the force exerted by each one is independent of that exerted by the others **(principle of superposition)**. The total force is obtained from the vectorial sum of each one of the particular forces.

2.1 Field intensity



To understand the idea of remote action, characteristic of force fields, we will choose the model of the elastic membrane. What would happen to a second ball which was put on the same surface? Wouldn't it be "pushed" by the deformation of the surface?

In a similar way, suppose that the electric charge of bodies alters the space around them. The magnitude which measures this change is **the intensity of the electric field**, the force exerted on a positively charged unit situated at a determined point. Click on **Field** to learn about some of its properties (do activities A.1, A.2, A3 and A.4 in the visual)



A1: Give the charged particle q1 a value greater than 0. Move the black dot around it. In which direction does the field intensity vector point? What if the particle is charged negatively?

A2: Note down the value of the field intensity at fixed distances: 0.5, -1, -1.5,... Find a relation between these values. Now try with different values of q1. Search for the mathematical expression in your textbook that justifies this result.

A3: Without moving the black dot, give q1 the greatest possible value and gradually change the value of q2 from -5 to +5 microcoulombs. How does the field intensity change? Why?

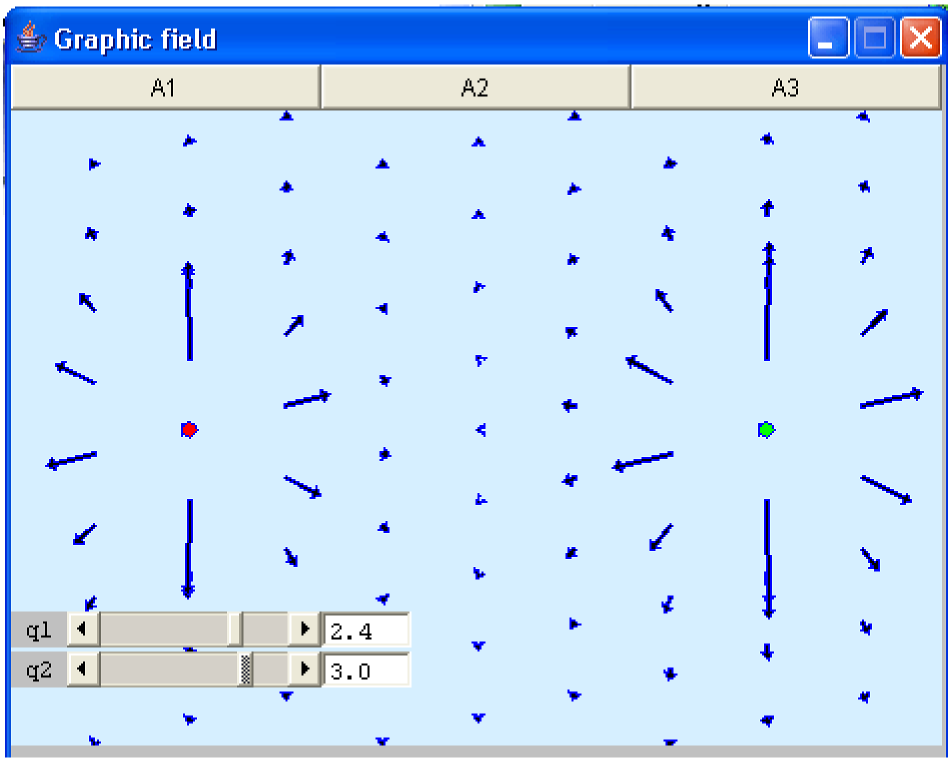
A4: Give q1 and q2 the values -5 and +5, respectively, and move the black dot 2 metres away from both charged particles. Gradually move q1 and q2 together in such a way that the distances d1 and d2 are approximately equal. What can you see in the measurement of the field intensity as the particles move closer together? Could you give an example of a natural dipole?

2.2 Lines of force in the electric field

In the visual **Graphic field** we can observe the intensity of the field created by one or two charges at different points in space.

In practice, to graphically represent the electric field, it is more convenient to use the concept of lines of force: lines which are tangent at every point to the field intensity vector at that point. The visual **Lines of force** shows us their characteristics. Study the field created by a positive charge, by a negative charge, and by pairs of charges with equal or different values. Trace at least 6 lines of force for every case.

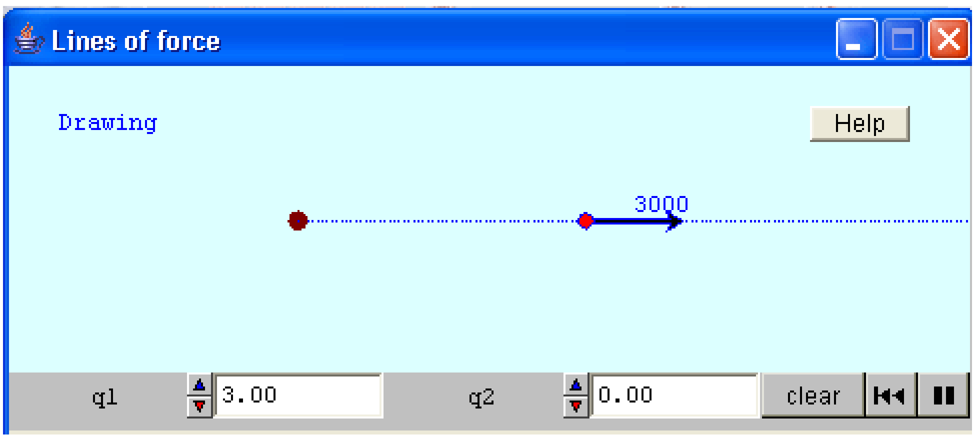
Then try to answer these questions: Do the lines of force intersect? Is field intensity related to the degree of approximation or separation of the lines?



A1: Give q1 a value greater than 0. What happens to the points in the space that surrounds q1? What if q1 is negative?

A2: Drag the charge around with your mouse. You will see that the unit charges at different points suffer important changes. What is the cause of this phenomenon?

A3: Give both charged particles a positive value and increase these values gradually up to 5 microcoulombs. How does the field change? Move the particles as close as possible to each other. ¿What happens to the direction of
the field vector? Repeat the experiment with opposite signs for the charges.



Help: This visual allows you to set the values of q1 and q2 and to observe the field intensity vector at the point marked by the red dot, which you can drag across the visual. If you click on play, the visual will draw a line of force through the red dot. If you change the value of q1 or q2, you should click on clear before drawing any new lines of force.

2.3 Conclusions about field intensity

- **We call the force experienced by the unit of positive charge situated at a point, the intensity of the electric field at that same point.** Its unit is N/C.
- The field intensity vector created by a charge at a point has the direction of a straight line which joins the charge and the point. The orientation is towards the charge if it is negative and away from it if it is positive.
- The module of field intensity created by a charge Q at a point which is r distance away is:

$$E=K\frac{Q}{r^2}.$$

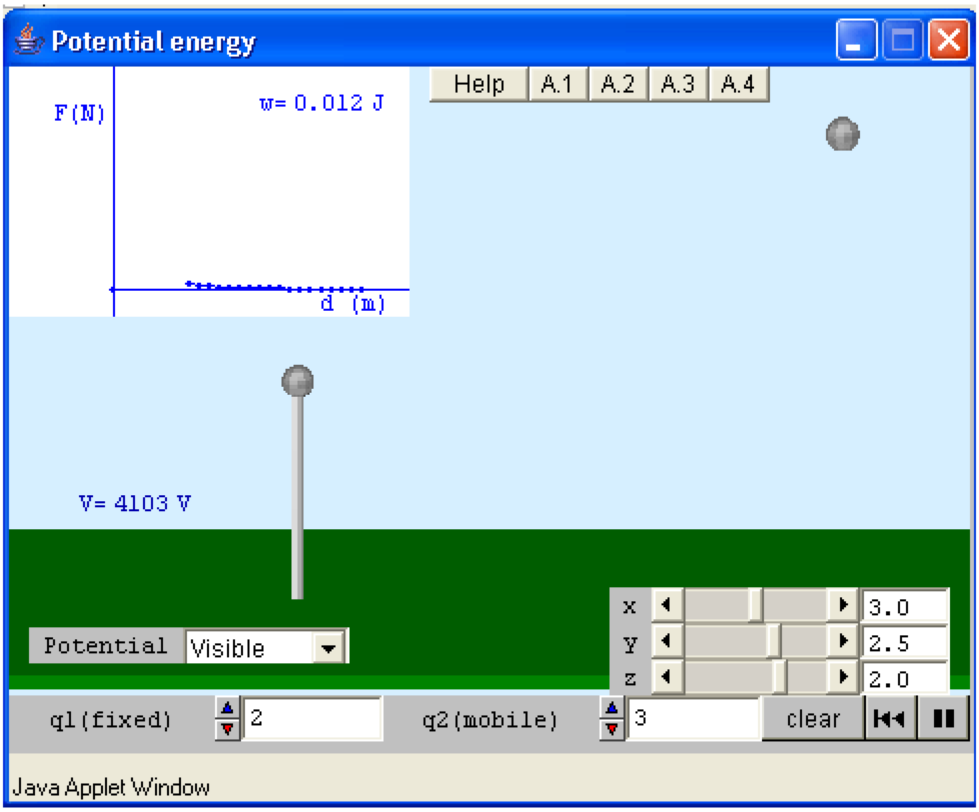
where K is Coulomb's constant, characteristic of the medium.

- When the electric field is created by more than one charge, the total field at a point is the vectorial sum of the field intensities which each charge creates at this point (**principle of superposition**).
- We call the tangent lines to the field intensity vector at each of its points **lines of force**. The direction of the line of force indicates that of the field. The lines of force "originate" in positive charges and "terminate" in negative ones.
- In the areas where the lines of force tend to be closer together the intensity of the electric field is greater.

3.1 Potential electric energy and potential

The flowerpot in the attached image has potential gravitational energy; that is, gravity can affect it because it is at a certain height above the ground. In the same way, the electric field created by a charged particle can affect another particle situated in its field.

We call the work carried out by the electric field when the particle travels from this point to infinity ***the potential energy* of a charged particle at a point in an electric field.** We call the potential energy of the unit of positive charge ***potential***. In the visual **Potential energy** you can study the characteristics of the potential energy of a particle in the field of another one and the potential created by a charged particle.



Help: This visual calculates the work done by the field created by the particle q1 (fixed) as q2 moves from the position defined by x, y and z to infinity. The graph represents the variation of force and work as the charge moves away. You can also see the value of the electric potential. By selecting the visible option in the drop down menu, you will see the potential created by q1 at the point (x, y, z).

A1: Give both q1 and q2 the value of 5 microcoulombs and click on play. Observe how the program calculates the work until the charge is so far away that the field can be neglected. Why does the work increase more quickly at the beginning? What would happen if we changed the sign of one of the charges? Why?

A2: Use the visual to calculate the potential energy for different values of q1 and q2. What is the relation between the potential energy and the charges?

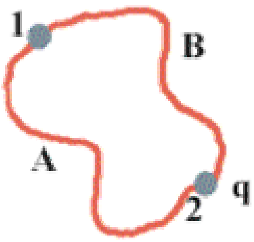
A3: Give both q1 and q2 the value of 5 microcoulombs. Use the visual to calculate the potential energy for different values of x. What is the relation between the potential energy and the distance? Would you be able to write an expression that relates the potential energy to the distance and the value of the charges? How would you calculate the proportionality factor?

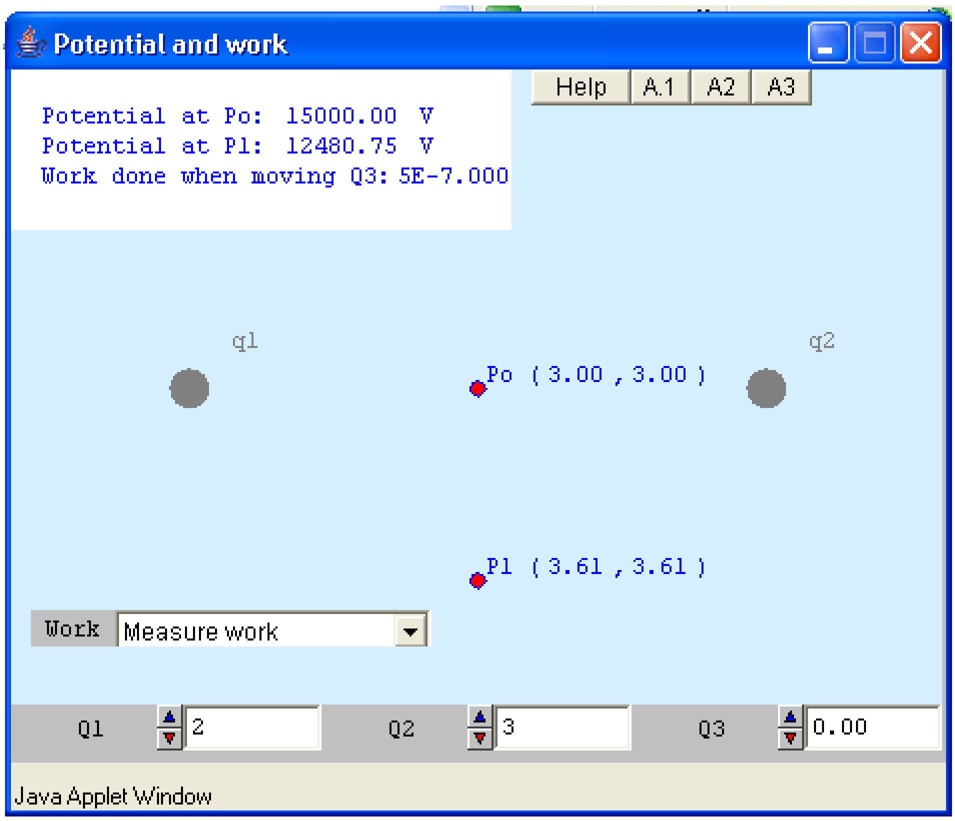
A4: Choose the visible option on the drop down menu. Give q1 different positive and negative values. What happens to the value of the potential? Does this value change if you change the values of q2? What if you alter the distance? Try to find a mathematical expression that relates the potential, q1 and the distance. What is the relation between this magnitude and the potential energy?

3.2 The sum of potentials. Work in the electric field

When there is more than one charge creating an electric field, the potential energy of a particle, or the potential at a point, is obtained by adding up all those created individually by each charge.

The potential has an interesting property: the work carried out by the field, when a charged particle q moves from one point to another, only depends on the potential at these two points and not the path taken. In the attached figure the work carried out to move q from 1 to 2 is the same whether it takes path A or path B. Find out all about it in **Potential and work**





Help: This visual lets you set the charge of the fixed particles Q1 and Q2, and the mobile particle Q3. Q3 will only be visible if you choose to measure the work carried out with the work drop down menu. The visual measures the potential created by Q1 and Q2 at Po. If you choose to measure the work carried out when moving Q3, the point P1 will also be visible (and you will be able to drag it around the visual). You will also see the work carried out when Q3 is moved from Po to P1.

A1: Give Q1 a non-zero value. The visual will show the potential at the point Po. If you give Q1 the value 0 and give Q2 a non-zero value, you will get the potential created by Q2 at Po. Change Q1 back to its previous value. Now you can see the potential created by both Q1 and Q2 at Po. If you drag Po around the screen, you will get the potential created by Q1 and Q2 at any point in the visual.

A2: We will now measure the work done when a charged particle is moved from one point to another in a field created by other charged particles. Give Q3 a non-zero value. The visual will show the potential created by Q1 and Q2 at the starting point Po and at the point you want to move Q3 to, P1. You will also see the work done when Q3 is moved from one to the other.

A3: Give Q1 the value of 5 microcoulombs, give Q2 the value -5 microcoulombs, and give Q3 the value -1. Find points Po and P1 such that the work W is positive. When will a charged particle move spontaneously from Po to P1? Would you be able to give a general answer? What if Q3 where positive?

3.3 Conclusions about potential electric energy

- We call the work carried out by the electric field when the charge Q2 moves from a point to infinity **potential energy of the charge Q2 at this point in the field created by Q1**. Its value is determined by:

$$E_p = K \frac{Q_1 \cdot Q_2}{r}$$

  where r is the distance between the charges.

- Potential energy is positive when it corresponds to repulsion and negative when it corresponds to attraction.
- When several charged particles interact with another one, the latter's potential energy is the sum of the potential energies due to each of the other charges (principle of **superposition**). *Click on **next** to continue*

3.3 Conclusions about potential and work in the electric field

- We call the potential energy that a positively charged unit situated at a certain point would have, the **potential** of a charge at that point. Its unit is the volt. The potential is positive if the charge is positive and negative in the opposite case. Its value is determined by:

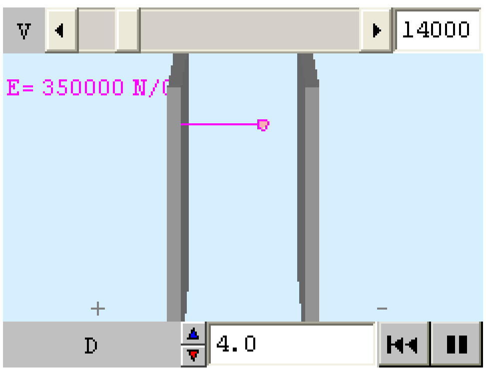
$$V=K\frac{Q}{r}$$

  where r is the distance between the charge and the point considered.
- The potential created by several charged particles is the sum of the potentials created by each one.
- The work carried out by the field when a charge q moves from one point to another (1 and 2) in a field is determined by the potential at these two points.:

$$W= q\cdot(V1-V2)$$

4.1 Relation between field intensity and potential

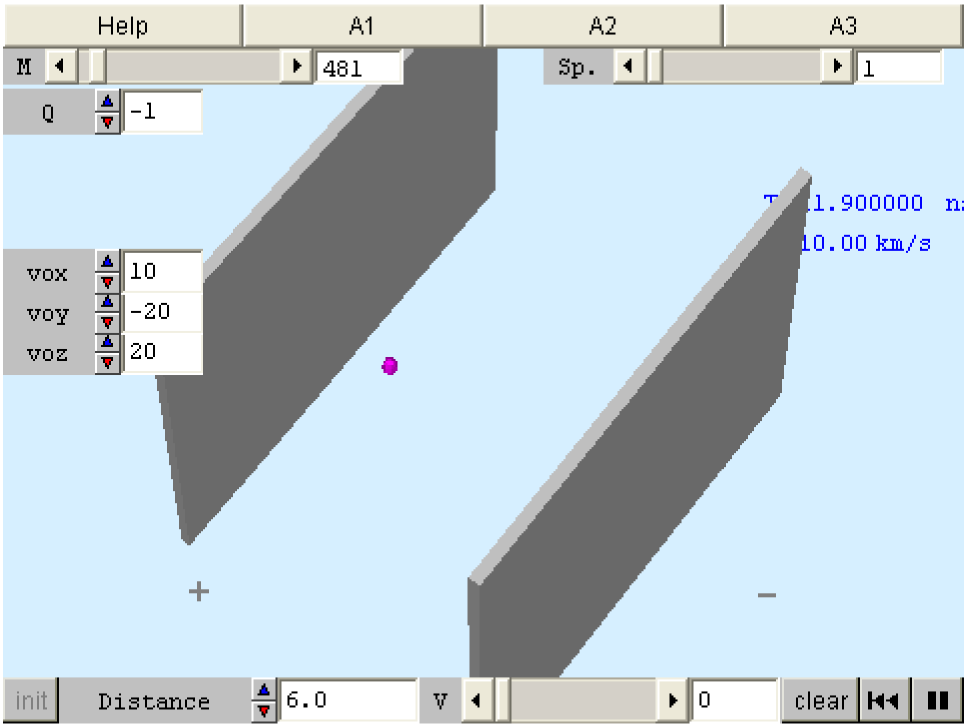
In the attached visual we can see a capacitator, a system formed by two conducting plates with equal charge, but different sign, separated by an insulator or a vacuum. The field intensity on the inside is approximately uniform, equal at all points. You can change the potential difference between the plates or the distance between them.



Observe how the field intensity value changes when you alter these magnitudes. Can you express this relation mathematically? (A relation only valid in uniform fields). Also observe how, for determined values of intensity, the insulator becomes a conductor and the charge jumps between the plates like a spark.

4.2 Movement of a charged particle in an electric field

In the previous section we have seen that when the field intensity is high sparks can fly. These are charged particles which move in the field. To understand some of the characteristics of their movement use the following visual:



Help: This visual represents the movement of a charged particle Q, measured in the number of electron charges, with a mass M, measured in the number of electron masses, through a field created by a capacitor. You may assign different values to Q, M, the components of the speed of the particle, the potential difference between the plates of the capacitor and the distance between the plates. The visual also measures the time it takes a particle to hit the plate and its speed during the collision. You may change the point of view by dragging the plates around with your mouse. You may also increase the speed of the simulation with the Sp. control.

A1: Set Q to -1 and M to 1. Set the potential difference to 10 volts and click on play. Note down the time T and the speed. Repeat the experiment with V = 1000 V and d = 4 cm. What differences can you observe? What do you think the cause is? Set vox to

500 Km/s and repeat the experiment. What changes can you see now? What if we set voy and voz to 100 Km/s?

A2: Set Q to 1 and M to 1800 (approximate values for a proton). Set V to 1000 V and d to 4 cm. Click on play and compare this experiment to the case in which we have an electron (you may want to use the Sp. control) What are the differences?

A3: Using the values registered in the experiment with the proton in the previous exercise (V = 1000 V and d = 4 cm) find the minimum value of vox such that the proton reaches the positively charged plate. Check your answer with the visual.

4.3 Conclusions about the relation between field and potential

- **In a uniform field,** with the same value of field intensity at all points, the difference in potential between two points in the field, situated in the direction of the field is determined as follows :**$V_1 - V_2 = E \cdot d$** where E is the value of the field intensity and d the distance between the points.
- For this same reason it is normal to express field intensity in **volts/ m**, that is a measure of the variation of the potential with the distance, as well as in **N/C**.
- A charged particle which penetrates a uniform field at some speed moves within it with a parabolic movement, similar to that of a bullet in the earth's gravitational field.

EVALUATION

Qualitative knowledge of electricity

Fill in the blanks with the correct words

1 When a body is electrified, we can say that it has acquired a property called an ____ which may be of two types: ____.

2 Bodies with a charge with the same sign exert a ____ force on each other, whereas, if the signs are opposite, the force is ____.

3 A body is negatively charged if it has an ____ of electrons, and positively charged if there are less ____ than ____.

4. In an insulator, charges cannot ____ freely, whereas, in a conductor, the charge can ____ freely when there is an electric ____.

5 Coulomb's law measures the ____ exerted by one charged particle on another at a certain ____.

6 Field intensity at a ____ in an electric field measures the ____ exerted on a positive ____ situated there.

7 The ____ are tangential to the field intensity and cannot ____ each other.

8 The potential energy of a charged particle at a point measures the ____ carried out by the field when the charge is moved to ____.

9 The potential is the ____ per unit of positive charge at a ____ in the electric field. It is measured in ____.

10 The work carried out when a charged particle moves from one point of the electric field to another only depends on the ____ at those two points. Positively charged particles will spontaneously move towards points of

☐ potential and negatively charged particles will spontaneously move towards points of ☐ potential.

Choose the correct answer for each question.

1 The relative dielectric constant in a material medium is equal to 2. Accordingly, the interactive force between two charged particles in this medium is

- ☐ It depends on the sign of the charges.
- ☐ Twice that in a vacuum.
- ☐ Half that in a vacuum.
- ☐ 0,2 times that in a vacuum.
- ☐ Equal to that in a vacuum.

2 A particle A charged with 4 C is fixed in space and another one, 1 m away, charged with 2 C is displaced to a distance of 50 cm. How much work must be carried out to move the particle?

- ☐ -0,036 J
- ☐ 18 J
- ☐ 0,072 J
- ☐ -0,072 J
- ☐ 0,036 J

3 The relative dielectric constant in a material medium is equal to 2. Accordingly, the interactive force between two charged particles in this medium is

- [ ] It depends on the sign of the charges.
- [ ] Equal to that in a vacuum.
- [ ] 0,2 times that in a vacuum.
- [ ] Twice that in a vacuum.
- [ ] Half that in a vacuum.

4 The charge of A is 1 C, the charge of B, situated 80 cm from A is -2 C. At what point in space is the field intensity equal to zero?

- [ ] In the exact middle
- [ ] 16 cm from A
- [ ] 20 cm from A
- [ ] 20 cm from B
- [ ] 16 cm from B