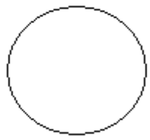
Pretest: Basics of Charging Conductors and Insulators

In answering all of the following questions, the following information will be useful:

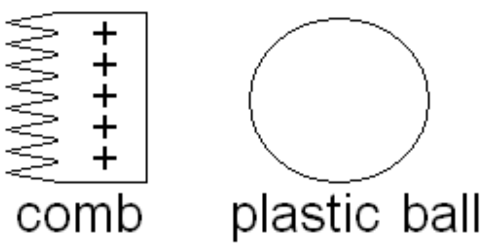
- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing. For example, a neutral sphere with no charges nearby can be shown as the follows:



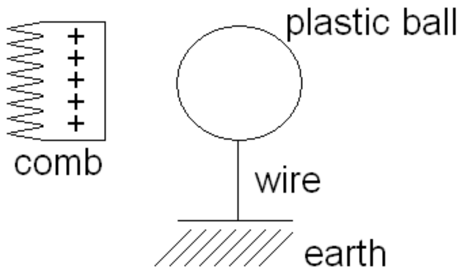
- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge you put on a conductor can rearrange itself. Core electrons in conductors do not move.
- For a conductor, excess charges only reside on its outer surface in equilibrium. Electrostatic equilibrium is established when there is no net force (including all forces) on the free electrons (conduction electrons). For example, excess positive or negative charge on an isolated metal sphere will distribute uniformly on the outer surface in equilibrium:

- Insulators (e.g., wood, wool, plastic, glass) are materials in which there are no conduction electrons and electrons can only move locally within the atoms or molecules when they feel a force, e.g., due to the presence of external charges.

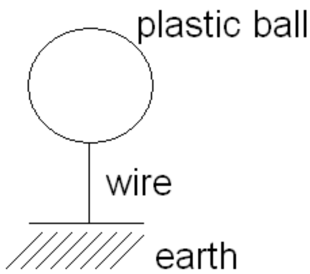
1.a) Draw the charge configuration of a neutral plastic ball while a charged comb is held nearby. You may draw atoms if necessary.



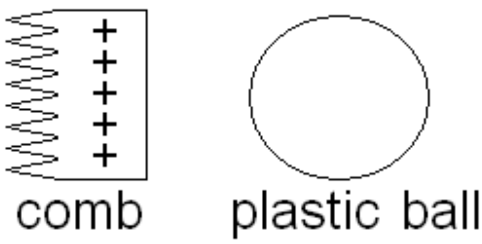
1.b) While holding a charged comb near a plastic ball, you connect the plastic ball to Earth by a thin metal wire (this process is called grounding). Draw the charge configuration in the plastic ball after it has been grounded. You may draw atoms if necessary. (Hint: The Earth is a conductor.)



1.c) Draw the charge configuration of the plastic ball if the comb is removed while the ball remains grounded. You may draw atoms if necessary.

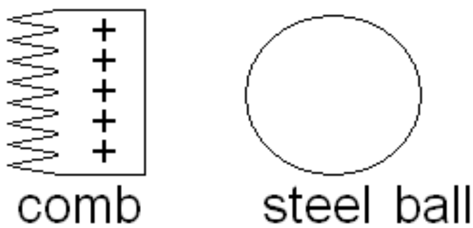


Draw the charge configuration of the plastic ball if the grounding wire is removed while the comb remains near the ball.

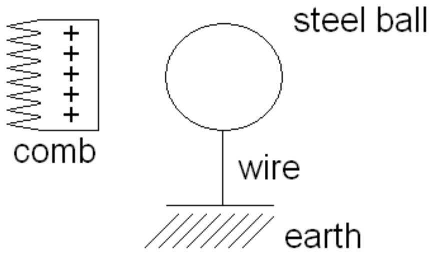


Is there a difference in the charge configuration of the plastic ball in the previous situations described in this part? Justify your answer.

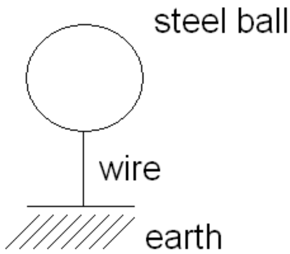
2.a) Draw the charge configuration of a neutral steel ball while a charged comb is held nearby.



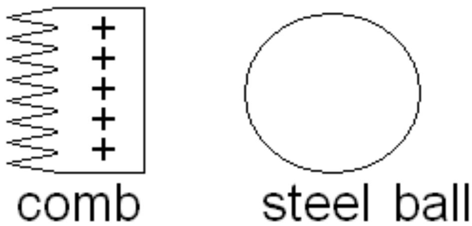
2.b) Draw the charge configuration of the steel ball after it has been grounded by a piece of metal wire as shown below.



2.c) Draw the charge configuration of the steel ball if the comb is removed while the ball remains grounded.



Draw the charge configuration of the steel ball if the grounding wire is removed while the comb remains near the ball.

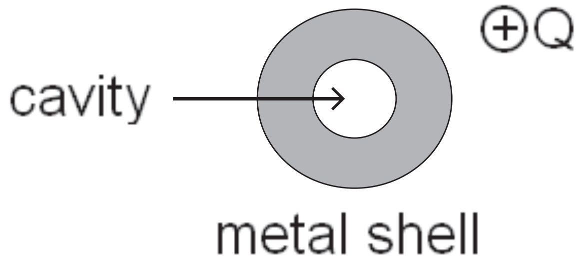


Is there a difference in the charge configuration of the metal ball between the previous situations described in this part? Justify your answer.

3) When you rub two identical neutral metal balls together, do they become charged? If so, why? If not, why not?

4) If a neutral piece of plastic is rubbed against a neutral piece of wool, will they become charged? If so, why? If not, why not?

5.a) A point charge, +Q, is located outside a neutral spherical metal shell with an empty cavity at the center. Does the point charge feel a force from the metal shell? If so, explain why there should be a force and if not, explain why not.



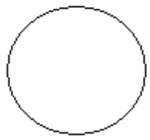
5.b) How would your answer to part a) change, if at all, if the spherical shell were made of plastic? Explain.

Tutorial: Basics of Charging Conductors and Insulators

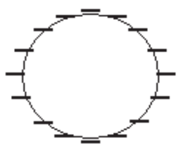
PART I: INDUCTION AND GROUNDING

In answering the following questions, the following information will be useful:

- For any question in which you are asked to predict the outcome, you will be provided with help in the questions following it to make sense of the situation.
- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally (i.e., in a specific place) in a material, there is no need to show those charges in a drawing. For example, a neutral sphere with no charges nearby can be shown as:



- Conductors (e.g., metals) are materials whose conduction electrons are free to move throughout the material. Therefore, any "excess" charge you put on a conductor can rearrange itself. Core electrons in conductors do not move.
- For a conductor, excess charges only reside on its outer surface in equilibrium. Electrostatic equilibrium is established when there is no net force (including confining forces) on the free or conduction electrons. Although we will not discuss confining forces in detail here, these forces are responsible, e.g., for why two like charges will remain in the material and not get separated infinitely apart due to the electrostatic repulsion between them.
- When discussing motion of electrons in conductors, it is implied that they are conduction (free) electrons.



- Insulators (e.g., wood, wool, plastic, glass) are materials in which there are no conduction electrons and electrons can only move locally within the atoms or molecules when they feel a force, e.g., due to the presence of external charges. We will refer to this LOCAL rearrangement of charges in insulators, polarization. In this tutorial, we will assume that this rearrangement is at the atomic level but it can also be at the molecular level depending upon the material.

Additional notes:

- For questions that refer to whether a *significant* amount of net charge is present on an object in a particular situation or whether *significant* force is exerted between two objects in a particular situation, the word *significant* refers to cases in which the consequences would be relatively easily measurable experimentally.

Section I: Basics

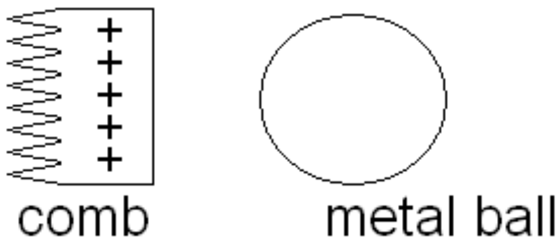
A. All macroscopic materials are made of a very large number of atoms/molecules. Typically, depending upon materials, at the level of atoms and molecules, materials have an equal number of protons and electrons. The charges on a proton and electron are equal in magnitude but opposite in sign. Based upon this, explain whether most materials should have an overall charge or be neutral.

B. Although the magnitude of the charges on protons and electrons is the same, the electron mass is approximately 2000 times smaller. Also, the protons are confined in a very small region, the nucleus, at the center whereas electrons occupy most of the space in an atom. Typically, which of these, protons or electrons, can be removed more easily to make a material charged?

- For all practical purposes and in this tutorial, we will assume that the protons (or nuclei/ions) are not removed from a material when a material becomes charged (has a net charge), instead, electrons either move to a material or from a material to make them negatively or positively charged.

Section II: Induced charges

Jim wants a neutral metal ball to become charged using a plastic comb that already has a positive charge. His experiment has several steps. He plans on holding the comb close to the metal ball, without touching as shown below.



Consider the following conversation between Jim and Mary:

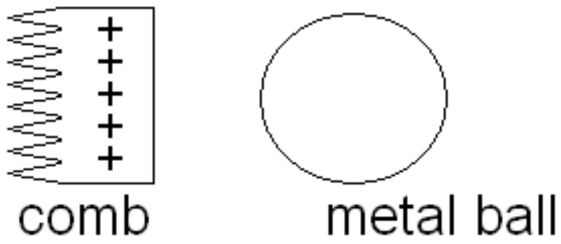
- Jim: This set up will lead to a charge separation on the metal ball because the ions will move away from the charged comb and cause a positive charge on the right side of the metal ball and a negative charge on the left side of the ball.
- Mary: I disagree; the ions in the metal ball cannot move on a large scale. I think that some free electrons in the metal ball will move towards the plastic comb and leave behind the positively charged ions on the opposite side of the ball. The effects of charge separation will only occur on the surface. Since the ball is a conductor and in equilibrium, the net force on all free electrons must be zero. The inside of the ball will still have equal amounts of uniformly distributed positive and negative charges (on a large scale).

Write down your prediction and explain why you would agree with Jim or Mary.

Let's examine the situation closely:

A. In the situation described above, the comb is being held close to the metal ball. Based on this, will the free electrons in the ball feel an attractive or repulsive force to the comb? Will the positive ions on the ball feel an attractive or repulsive force to the comb? Remember that the comb has a positive charge.

B. Since only the electrons are free to move in a metal, draw the equilibrium charge distribution on the surface of the metal ball as a result of the charged comb being held close to the ball. (Hint: In a conductor, in equilibrium, induced charges only reside on the surface of the conductor such that there is no net force on the free electrons.)



C. Although positive charges don't move, positive charge was left on the "right" surface of the metal ball. If the total positive charge on the "right" surface is $+Q$ when equilibrium is established, how much is the total negative charge on the "left" surface?

D. Is there any net charge on the metal ball as a whole?

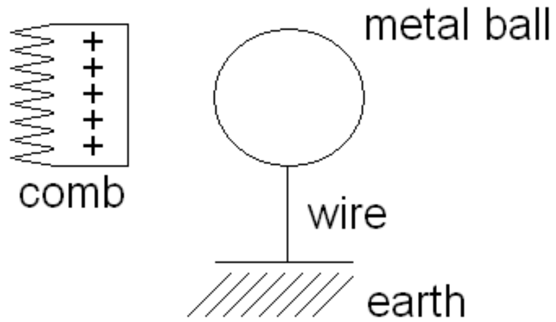
E. If the comb were removed and the free electrons in the metal ball return to an equilibrium state, would there be any net charge on the metal ball? What would happen to the charge separation in part C? Your answer should agree with part D.

- Summary: Charge separation in conductors due to the presence of an external charge (e.g., charged comb) that is close to the conductor (but not touching) is called <u>induction</u>. Induction alone cannot cause a conductor to have a net charge on it.

Section III: Creating a net charge on a conductor

Note: The earth is a huge conductor and acts as a reservoir of charge. This means that the free electrons can flow to and from the earth to another conductor in contact with the earth. For all practical purposes, any free electrons on the surface of the earth can be considered to be so far away that the repulsive force between them can be ignored.

A. Since a copper wire is a conductor, electrons can move freely through it. Draw your prediction for the charge distribution on the metal ball as a result of a wire being connected to the ball with a positively charged comb held close by (connecting a conductor to the earth via a wire is called grounding).



Let's think about the process systematically: **When the grounding wire was NOT present, there were charges induced on the surface of the metal ball via induction.**

B. Do the charges induced on (I) the closer and (II) the farther sides of the metal ball attract or repel the charged comb (no grounding wire present)?

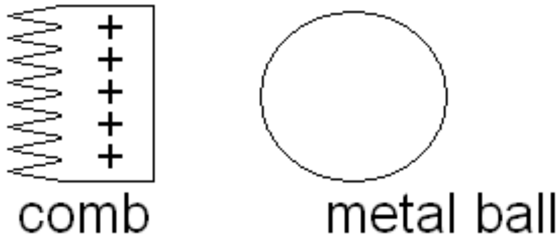
C. Since the negative charges induced on the ball via induction are closer to the comb than the positive charges induced, is there a net attraction between the comb and the metal ball on the whole?

Note: There is a net attraction between the comb and the ball due to charge separation on the conductor's surface. In this case, in addition to the confining force, for the metal ball, there is:

- Attraction between the comb and the negative charges induced on the nearer surface (left) of the ball.
- Repulsion between the comb and the positive charges induced on the farther surface (right) of the ball.
- Repulsion among the electrons themselves on the left surface.
- Repulsion among positive charges on the right surface.
- Attraction between the positive and negative charges induced on the two surfaces via induction.

D. If the distance between the comb and the ball were reduced, what would happen to the strength of attraction between the two?

E. If the positive charge on the comb were increased in magnitude, what would happen to the strength of attraction between the metal ball and the comb? Draw the charge configuration below. (Hint: Would more electrons accumulate on the left surface and leave behind positively charged ions on the farther surface of the metal ball as a result of this increase in charge?).



F. Without the grounding wire, the positive charges are stuck on the farther (right) surface. This occurs because some free electrons moved closer to the comb to take advantage of their attraction before equilibrium was established. Now, if you connect the ball to a grounding wire, can you predict a process via which the positive charges on the metal ball can neutralize? (Hint: Electrons are free to move from the earth through the conducting wire.)

G. As a result of the movement of electrons from earth, what will happen to the positive charges on the "right" surface of the metal ball?

H. The negative charges induced on the "left" surface of the metal ball feel an attractive force due to the comb and a repulsive force from each other (in addition to confining forces). Considering that the electrons do not leave the metal ball surface even when the grounding wire is connected and continue to take advantage of the attraction due to the comb, what can you conclude about these forces?

Section IV: Order of removing items

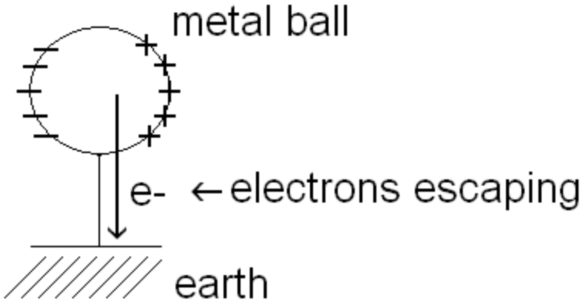
Consider the following statement from Jim:

- Jim: After grounding the conductor, you can first remove the comb and then the grounding wire. The metal ball will then have a net charge!

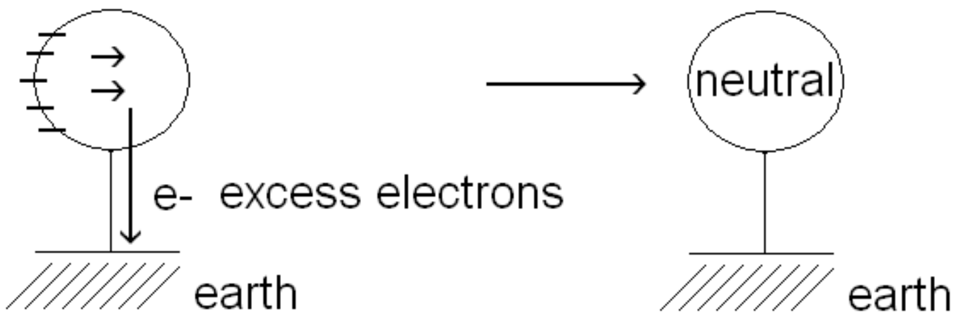
Write down your prediction about whether Jim is correct.

John, Mary, and Jim perform the experiment suggested by Jim. However, they are sorely disappointed when they finish because the metal ball is still overall neutral. They try to rationalize what went wrong.

- John: I think the metal ball is neutral overall because we took away the comb before we took away the grounding wire. The excess electrons that the metal ball acquired through the wire will go back to the ground. However, since the electrons from the ground went to the right surface to neutralize the positive charges, there will be a separation of charges when those electrons go back to the ground. Look, I drew a picture.



- Mary: I agree that the electrons from the metal ball will go to the ground after the comb is removed, but I disagree that there will be charge separation if the comb was removed before the grounding wire. Since conduction electrons are free to move in a metal, the negative charges on the left surface will combine with the positive charges on the right surface in your picture above. There is no incentive for the excess electrons to be close to each other in the metal when there is no positively charged comb nearby and there are positive charges on the right surface that can neutralize the electrons.

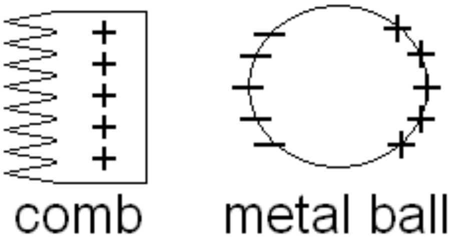


- Jim: John, don't be silly. The order in which the grounding wire and the comb are removed cannot matter. The earth is neutral, so there would be no forces pulling the electrons through the wire and back down to the ground.

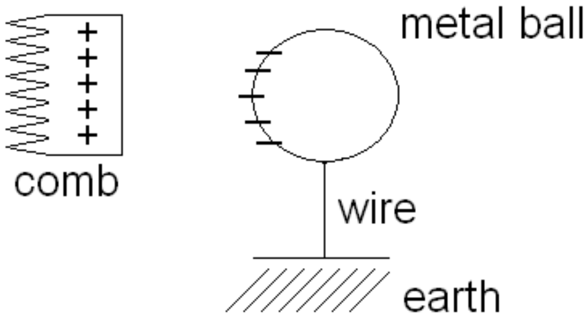
Predict which of these three is correct.

Let's look at the process that the three friends carried out step by step although in reality, these processes are extremely fast and we cannot separately observe these steps.

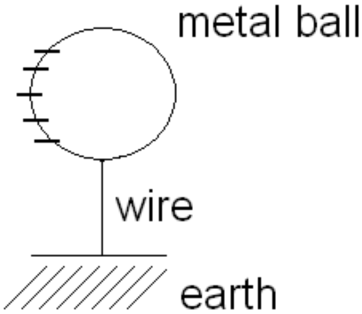
Step 1. Comb close to the metal ball without grounding (equilibrium situation shown).



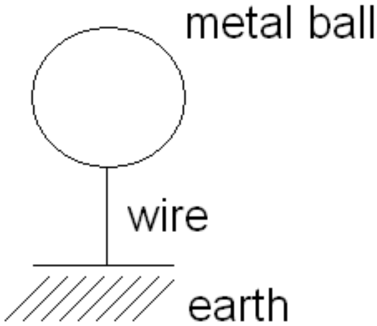
Step 2. Comb close to the metal ball with grounding (equilibrium situation shown).



Step 3. **For our thought experiment, immediately after the comb is removed, the non-equilibrium situation looks like that in the drawing below.** The metal ball will not stay in this configuration. Explain why this is the case. (Hint: Is there any incentive for the negative charges to be close to each other when the positively charged comb is removed? Earth is a charge reservoir where charges can be very far away from each other. Think of when a lightning bolt strikes a grounded metal object, where would the excess charge go?).



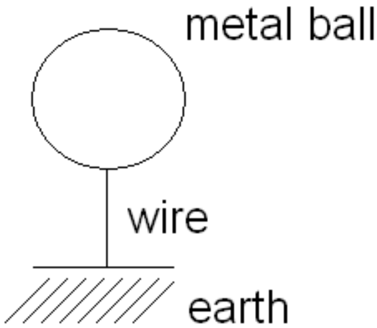
A. Since these excess electrons are free to move, draw the new charge configuration in the metal ball below after removing the comb when the charges have had a chance to equilibrate. If you think that the metal ball is neutral, you need not draw anything.



- Note: Once the electrons go to the earth, they move so far away from each other that they exert negligible forces on each other. That's why earth is a charge reservoir and charges can move freely to and from earth to the conductor connected to it through the grounding wire.

B. So who is correct? John, Mary, or Jim? Justify your response.

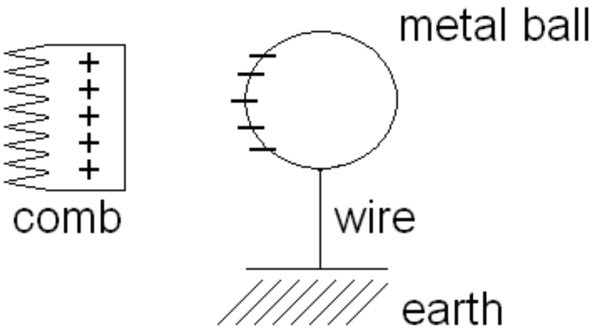
C. If the neutral metal ball was only grounded and not exposed to the charged comb, would the metal ball acquire an excess charge as a result of being grounded? (Hint: If the metal ball is neutral, are there any unbalanced forces pulling or pushing the free electrons in the metal ball or the ground?)



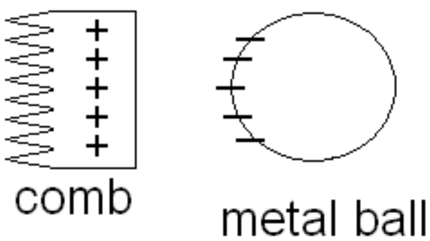
Section V: Charging a conductor by induction

Mary decides to experiment with removing the grounding wire first and the comb second. So lets look at the situation in which the grounding wire is removed before the comb carefully:

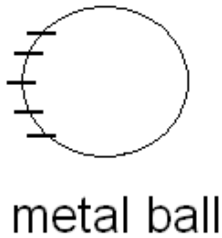
Step 1. Both the comb and grounding wire in place:



Step 2. Grounding wire is removed:

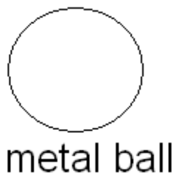


Step 3. Immediately after the comb is removed:



A. In step 3, will the charges remain in this configuration after the comb is removed (i.e., is this an equilibrium situation)? Explain. (Hint: Like charges repel.)

B. As a result of these repulsive forces between electrons, draw the charge configuration on the metal ball after the charged comb is removed and the free electrons have rearranged themselves to establish equilibrium. (Hint: Excess charges only reside on the surface of conductors in equilibrium).

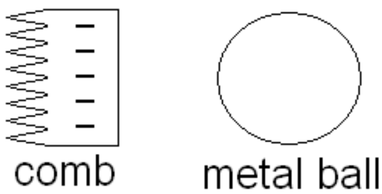


- Summary: For any isolated spherical conductor, excess charges will distribute uniformly on its outer surface in equilibrium. In a conductor, equilibrium is established very quickly (in a very small fraction of a second). Note that most of the conductor still has a very large number of positive and negative charges (on the order of 10^{23}) that neutralize each other locally on a certain scale.

Section VI: Charging a metal ball through induction with a negatively charged insulator

John, Mary, and Jim are now faced with a new challenge. They will charge the metal ball using the correct procedure (removing the grounding wire before the comb). However, the comb is now negatively charged.

A. Let's consider the situation when the negatively charged comb is held close to the metal ball and the ball is not grounded. Draw the charge configuration you would predict the metal ball to have under the influence of only the charged comb.

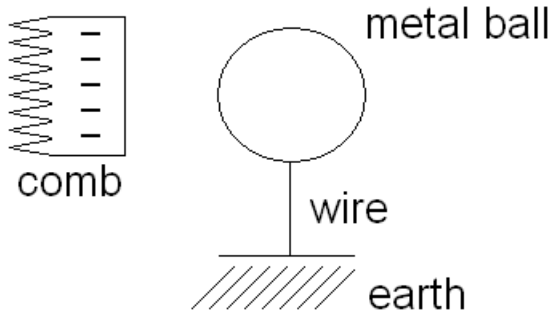


B. Will the free electrons in the metal ball feel an attractive or repulsive force from the comb? What will they do in response to this force?

C. Although positive charges don't move, will any excess positive charge develop on part of the surface of the metal ball? Is it the left side or the right side of the metal ball in the figure above?

D. If the total negative charge on the right side of the metal ball is -Q, how much is the total positive charge on the "left" surface? (Hint: The overall net charge is zero).

E. Let's consider the case in which we connect the metal ball to the earth with a grounding wire: The electrons feel a repulsive force from the comb as well as a repulsive force from each other. Predict the motion of the electrons after grounding the ball and draw the equilibrium charge configuration below. (Hint: The earth is a "charge" reservoir where electrons can get a very large distance away from each other).

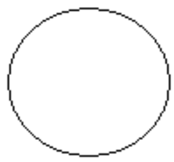


Consider the following statements from Mary and Jim about the type of charge on the metal ball after the grounding wire is removed first and then the comb.

- Jim: I think that the metal ball will have an overall negative charge because electrons will come up from the ground and neutralize the excess positive charge on the "left" surface of the metal ball.
- Mary: Electrons will not come up from the earth to neutralize the ions because then there won't be a net attraction between the metal ball and the comb. I think that the metal ball will have an overall positive charge because the electrons on the "right" surface of the metal ball will escape through the copper wire into the ground.

Who is correct? Jim or Mary? Justify your response.

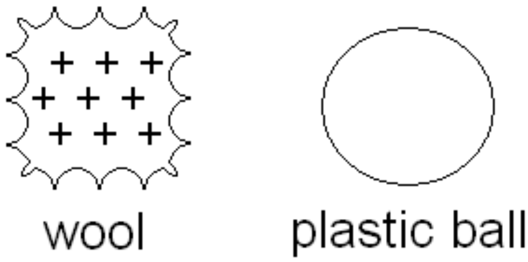
F. Draw the charge configuration on the metal ball after the grounding wire is removed first and then the charged comb is also removed. (Hint: Although we have an excess positive charge on the metal ball, ions are not free to move. However, the free electrons can move).



- Summary: The situation described above will result in a positive charge uniformly distributed on the surface of the metal ball in equilibrium. Electrons will go to the ground through the grounding wire when the comb is held close. When the grounding wire is removed, positive charges are trapped on the conductor. When the comb is removed, the free electrons on the surface of the metal ball will move to neutralize the positive charges that are close to each other while leaving excess charge elsewhere. This will uniformly redistribute the positive charges when equilibrium is established so that the positive charges can minimize repulsion between them under the constraints of confinement.

Section VII. Polarization in an insulator

Hermione is excited that the students at Hogwarts have to take a class in physics. During one of the labs, the students are asked to examine what happens when a positively charged piece of wool is held near a neutral plastic ball.

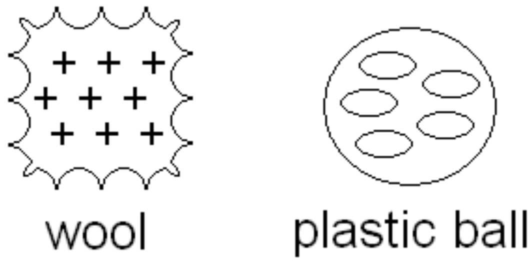


- Ron: If this is an insulator, and electrons are bound to atoms or molecules locally, nothing is going to happen to the plastic ball.
- Hermione: Ron, haven't you been studying? The positively charged wool will cause the electrons, e.g., inside each atom or molecule within the plastic ball to move towards the wool. This will polarize the plastic ball. In other words, there will be an induced distribution of charge due to polarization. This phenomena will lead to attraction between the wool and plastic ball even though overall the plastic ball is neutral.

A. Although Hermione is usually right, is she in this case? Explain why you agree with her or Ron.

B. Based on the situation described earlier, do the electrons inside the plastic ball feel an attractive force or a repulsive force by the charged wool?

C. Considering that electrons in an insulator like a plastic ball can only move locally (e.g., within the atoms or molecules) when they feel a force, e.g., due to charges on wool, draw the charge configuration of the plastic ball below. Some atoms have already been drawn for you (atoms are not drawn to scale and are strongly distorted).



D. Since the plastic ball does not lose or gain any electrons, what is the "net" charge on the ball as a result of the presence of the charged piece of wool?

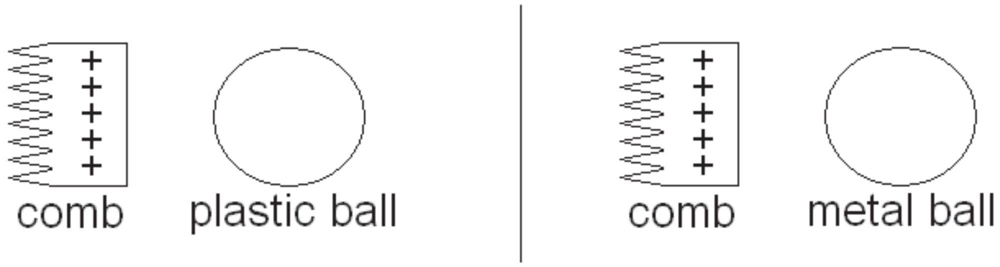
E. Is your drawing consistent with Ron or Hermione's comment earlier?

F. If the charged wool is removed, will the plastic ball remain polarized? (Hint: Consider the attractive force pulling the electrons within their atoms back towards the ions). Explain your answer.

- Summary: Charge separation within the atoms (or molecules) of an insulator due to an external charge that is close by is called polarization.

Section VIII. Induction always causes attraction

In the lab, Ron, Harry Potter, and Hermione are given two setups. A positively charged comb is held near a neutral plastic ball and another positively charged comb is held near a neutral metal ball. Assume these setups are far away from each other so that they don't influence each other.



A. Predict whether or not the comb will be attracted to both the plastic and the metal balls? If so, why? If not, why not?

Consider the following statements from Ron and Hermione:

- Ron: Well, whether induction causes attraction or repulsion depends on the material.
- Hermione: No Ron! Due to induction, the negative charges induced on one surface will always be closer to the positive comb. Therefore, the attraction between the negative charges and the positive comb will be greater than the repulsion between the positive comb and the positive charges induced in the plastic or metal balls. Induction will always lead to attraction if one of the objects is neutral.

B. Who do you agree with?

C. Predict which set up above has a larger magnitude of attraction between the comb and the ball.

D. Considering that opposite charges attract and like charges repel and the strength of attraction and repulsion depends on the distance between charges, will the net attraction be more for the metal ball or the plastic ball?

- Summary: The charges on the metal ball "completely" separate while those on the plastic ball only separated on the atomic or molecular (local) scale when the positively charged comb is brought near by.

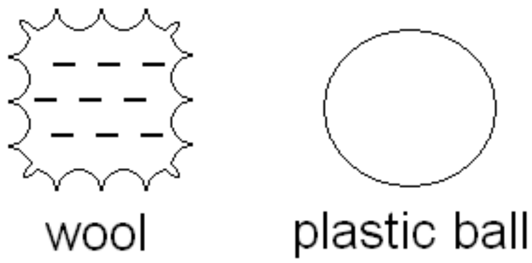
Section IX. Polarization in insulators with negatively charged objects

The Hogwarts students are now given a negatively charged piece of wool and are asked to predict what will happen when this wool is placed near a neutral plastic ball.

- Ron: Okay, Hermione, I think I know the answer. The electrons will move away from the wool within the bounds of their atoms and polarize the plastic ball.

A. Do you agree with Ron? Explain.

B. Draw the predicted charge configuration of the plastic ball. Draw a few atoms if necessary. (Hint: Do the electrons on the plastic ball feel an attractive or repulsive force from the wool?)

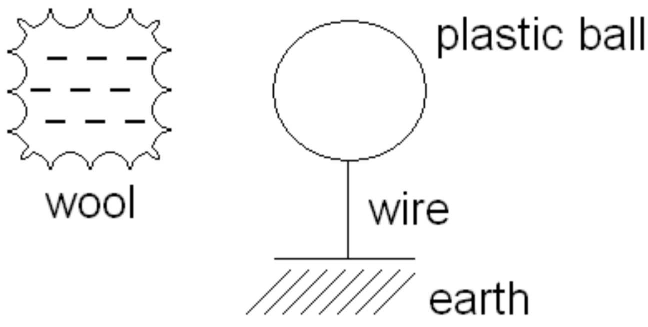


C. Is there a net attraction or repulsion between the wool and the plastic ball?

D. If the wool is removed, will the plastic ball remain polarized?

Section X: Grounding insulators

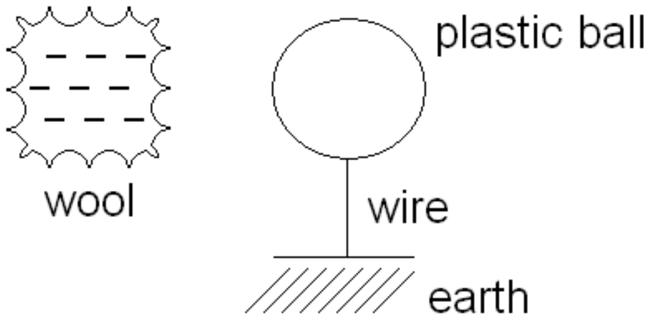
Hermione, being an over achiever, decides she wants to see what happens when the negatively charged wool is held near the plastic ball while the plastic ball is grounded with a copper wire (see figure below).



- Harry Potter: Hermione, I don't think that you can produce a net charge on an insulator through induction. The electrons cannot escape their atoms; therefore, they cannot leave the plastic ball through the wire and there will be no excess positive charge on the plastic ball overall!

A. Is Harry correct or not?

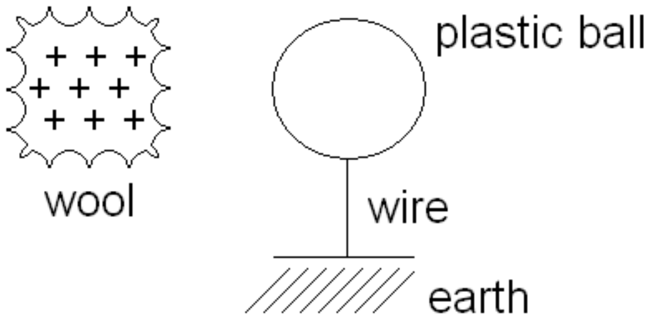
B. Considering that the electrons within an insulator are not free to move beyond the bounds of their atoms, draw the charge configuration on the plastic ball after it has been grounded.



C. Is there any difference between this charge configuration and the situation where the grounding wire was not there?

D. Will removing the grounding wire first and then the piece of wool result in a "net" charge on the plastic ball? Explain.

E. Draw the charge configuration of the plastic ball after grounding the plastic ball if the wool had a positive charge. Draw a few atoms if necessary. Will the plastic ball ever become charged via this process if the grounding wire and wool were removed in any order? Explain your reasoning.



Consider the following statement:

- Hermione: Oh, you're right Harry! Although electrons and ions in the plastic ball still feel the attractive and repulsive force due to the wool, they can only move locally within atoms and molecules in response because they are held by interatomic forces in the insulating plastic ball!

F. Do you agree with Hermione? Justify your response.

PART II: CONTACT

In answering all of the following questions, the following information will be useful:

- For any question in which you are asked to predict the outcome, you will be provided with help in the questions following it to make sense of the situation.
- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing.
- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge that you put on a conductor can rearrange itself until none of the free electrons feel a net force and equilibrium is established.
- For a conductor, excess charges only reside on its outer surface in equilibrium.
- Insulators (e.g., wood, wool, plastic, glass) are materials in which electrons are bound to each atom, they can only move locally within the atom when they feel a force.

Additional notes:

- For questions that refer to whether *significant* net charge is present on an object in a particular situation or whether *significant* force is exerted between two objects in a particular situation, the word *significant* refers to cases in which the consequences would be easily measurable experimentally.

Section XI: Charging an insulator (a net charge on an insulator)

Now that Hermione knows she cannot produce net charge on an insulator through grounding, she is determined to figure out how to charge an insulator. She considers rubbing together two neutral insulators. First she tries rubbing a neutral plastic ball with a neutral piece of wool. She also tries rubbing two identical neutral plastic balls together.

Predict which of these neutral objects when rubbed vigorously with the neutral plastic ball will likely produce a significant amount of charge on the plastic ball.

Let's look at each case separately.

Case 1: Rubbing neutral piece of wool and a neutral plastic ball

Note: Don't worry about which object becomes positively charged or negatively charged by rubbing. Focus on whether or not charge separation might occur.

Although the wool and the plastic ball are both insulators with no free electrons, electrons from the surface atoms can be "peeled" off of one of the insulators by rubbing them with each other. Which insulating material the electrons are peeled off from depends on the insulator's affinity for electrons. Different materials have different affinities for electrons. Certain materials can accept electrons more readily because they have higher affinity for electrons than other materials.

a. Based on this, would you expect any charge transfer between the neutral wool and the plastic ball when the two are rubbed? Justify your response.

b. Suppose we rubbed the neutral piece of wool with the neutral plastic ball and obtained a positive charge on the piece of wool (meaning it transferred electrons from its surface atoms to the plastic ball). What kind of excess charges develop on the plastic ball?

c. When electrons are peeled-off from an insulator (when different insulators are rubbed against each other), that insulator is left with a positive charge. If our piece of wool acquires a +Q charge on the surface where it is rubbed against the plastic ball, what is the magnitude of the negative charge transferred to the plastic ball that was rubbed with the wool?

d. Would you predict that the piece of wool will always become positive when rubbed against all other insulators? For example, will rubbing with fur necessarily produce a positive charge on the plastic because rubbing with wool does? Explain your reasoning (Hint: Fur has a different affinity for electrons than plastic).

e. Instead of the wool and the plastic ball being rubbed, consider the case in which they are merely touched and separated. Would you find that any significant charge would transfer between the two? (Hint: Just by touching, would a significant amount of electrons "peel-off" from the surface atoms of either the wool or the plastic ball.) Explain your answer.

Case 2: Rubbing a neutral plastic ball with another identical neutral plastic ball

When a neutral plastic ball is rubbed against a second identical neutral plastic ball, they both have the same affinity for each other's electrons. Would you predict that any electrons would transfer from one to another?

- Summary: Because their electrons are bound to the atoms, the surface atoms of one type of insulator may lose electrons to another type upon rubbing. Insulators can develop significant charges when rubbed vigorously against another insulator so long as they do not share the same affinity for electrons.

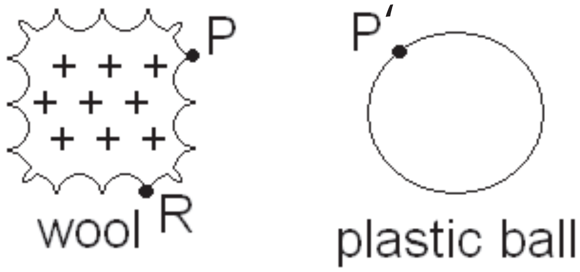
Hermione was pleased to discover that she could develop a charge on an insulator by rubbing it with another insulator composed of a different material; however, there are a few more scenarios she would like to try. She is going to try touching a neutral plastic ball with three different objects: a positively charged piece of wool, a positively charged metal ball, and a neutral metal rod.

Predict which objects, if any, will make the plastic ball charged. If net charge develops on the plastic ball in any of these cases, will it be comparable to the net charge developed on a plastic ball when rubbed vigorously with wool described in the earlier section? Explain your reasoning.

Let's examine each case carefully:

Case 1: Touching a charged piece of wool with a neutral plastic ball

Below is a drawing of the charge configuration of the positively charged wool and the plastic ball. The two objects will be touched together only at points P and P′ shown and then be separated.



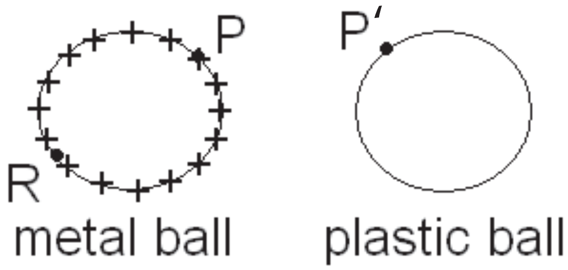
a. Can a significant charge transfer occur from point P to point P′?

b. Will any charge transfer occur from point R on the wool to the plastic ball when points P and P′ are touched? (Hint: Since wool and plastic are insulators, they do not have free electrons.)

- Summary: Rubbing, not merely touching, is necessary to "peel" off electrons from the surface of insulators with lower electron affinity so that the plastic ball develops significant net charge when rubbed with wool in the situation described.

Case 2: Touching a neutral plastic ball with a positively charged metal ball

Below is the initial configuration of the neutral plastic ball and the positively charged metal ball. They will be touched together only at points P and P′ and then separated.



a. Predict if any significant charge transfer will occur to the plastic ball at point P′? (Hint: Even though conduction electrons are free to move in the metal ball, they are not free to move in an insulator.)

b. If a very small amount of charge is transferred to the plastic ball, will it move from the point of contact and distribute to other areas of the plastic ball? (Hint: Electrons do not move freely in an insulator.)

Case 3: Touching a neutral plastic ball with a neutral metal ball

If a neutral metal ball and a neutral plastic ball are just touched, will either of them develop a net charge? Explain.

- Summary: In cases 1, 2, and 3, no significant charge will be transferred between the objects as a result of touching.

Section XII: Charging a conductor through contact

Hermione decides to next investigate how a neutral metal ball would become charged through contact. She knows from her previous experiment that neutral pieces of a metal and an insulator cannot develop significant amount of net charge on either when touched with one another. Hermione is now going to touch a neutral metal ball with three objects and then separate them: (1) another identical neutral metal ball, (2) a positively charged metal ball, and (3) a positively charged piece of wool. (Note: Her hand is not touching the metal balls when touching them because she places the metal balls on insulating stands. This way any charges on the metal ball will not transfer to her body which is also a conductor.)

Lets look at each case separately.

Case 1: Two identical neutral metal balls in contact

Consider the following statement from Hermione:

- Hermione: I suspect that the two identical neutral metal balls will not charge each other.

Do you agree with Hermione's assumption of no net charges developing on the two identical neutral metal balls when they are touched? Explain your reasoning. (Hint: While the two metal balls are in contact, do the free electrons on either of the neutral metal balls feel a net attractive or repulsive force from the other?)

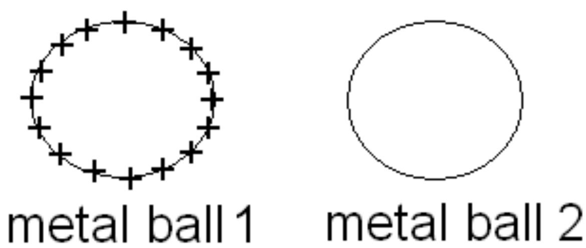
Case 2: Identical metal balls in contact with one charged and one uncharged

Consider the following statement from Hermione:

- Hermione: When the neutral and charged metal balls are put in contact, half of the net charge on the charged ball will transfer to the neutral metal ball.

a. Is Hermione's statement correct that half of the charge on the charged metal ball will transfer to the uncharged identical metal ball? Explain your reasoning.

Drawn below is the charge configuration of the two well-separated metal balls before touching.



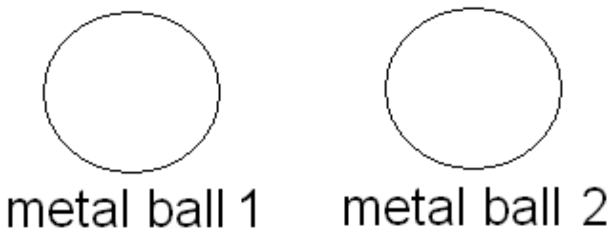
b. If the isolated charged metal ball has a uniform surface charge +Q (before being brought close to the other ball) and it is touched with the identical neutral metal ball and equilibrium is established, what is the net charge (including the sign) on each of the balls once they are separated? (Hint: The combined charge between the two metal balls should sum to +Q. Free electrons can move in a conductor. Like charges repel and try to get away from each other as much as possible. Also, remember that excess charges on a conductor in equilibrium are only on the outer surface.)

Consider the following statement:

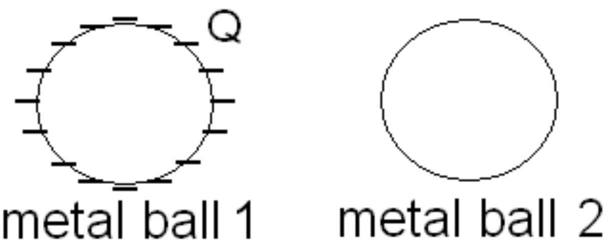
- Harry: Only the free electrons can move. If the free electrons move from the neutral metal ball to the charged one, they can neutralize some of the positive charge on the initially charged ball and leave behind positive charges on the initially uncharged metal ball. I think Hermione is correct that each metal ball will have half of the charge in equilibrium. We can predict that from the symmetry of the two balls, i.e., they are identical balls.

c. Do you agree with Harry? Make sure your answer is consistent with your answer to part b.

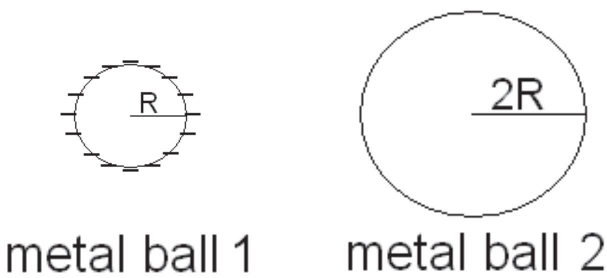
d. Draw the charge configuration of the two well separated metal balls after the initially charged and uncharged balls make contact and then are separated far apart from each other. Explain your reasoning. (Hint: Excess charges only reside on the outer surfaces of a conductor in equilibrium.)



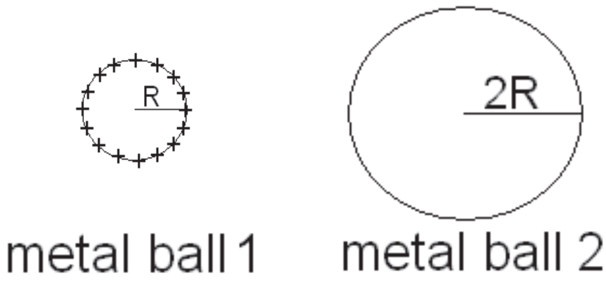
e. If the metal ball initially had a -Q charge, what would happen when it is touched with the neutral metal ball and then they are separated a considerable distance (see the figure below)?



f. If the uncharged metal ball were twice the radius of the negatively charged metal ball (see below) and they were touched and separated, which ball will carry larger magnitude charge? (Hint: Like charges repel and will always try to get as far away from each other as possible. Also, excess charges only reside on the outer surface of a conductor in equilibrium.)



g. If the charged metal ball had a +Q charge on it, what would happen when it is touched and separated from the neutral metal ball of twice its radius? (Hint: The free electrons in the neutral metal ball feel an attractive force towards the positively charged ball and positive charges repel each other. Also, in equilibrium, excess charges are on the outer surface of a conductor.)



Case 3: Positively charged wool and neutral metal ball in contact

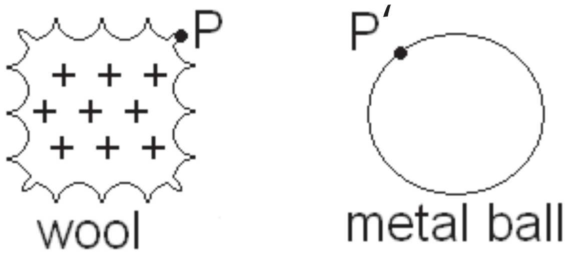
Consider the following statement from Hermione:

- Hermione: The positively charged piece of wool when brought in contact with a neutral metal ball will result in an attractive force between it and the metal ball. However, electrons can't move freely in an insulator. Thus, a very small number of electrons, if any, would transfer from the metal ball to the positively charged piece of wool to neutralize the excess positive charge at the point of contact. Those electrons are not free to distribute themselves throughout the piece of wool. The charge transfer is not significant.

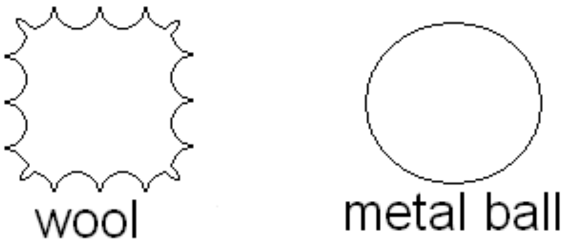
a. Explain why you would or wouldn't agree with Hermione's prediction that at most a very small amount (negligible amount) of charge transfer would occur between the charged piece of wool and the metal ball.

b. Draw the charge configuration of the metal ball and the piece of wool after they touch at points P and P ′ (there is some positive charge on the wool at point P) and are then separated a considerable distance. Justify your drawing. (Hint: Since the objects just touched and insulators do not have free electrons, charges may transfer only from the areas of the charged wool that the metal ball touch.

Before touching:



After touching:



c. As a result of contact between the wool and metal ball, is there any significant charge transfer from the wool to the metal ball? Explain your answer.

d. Does your drawing agree with Hermione's statement? Explain why or why not.

PART III SITUATIONS WITH CONDUCTING OR INSULATING CAVITIES

In answering the following questions, the following information will be useful:

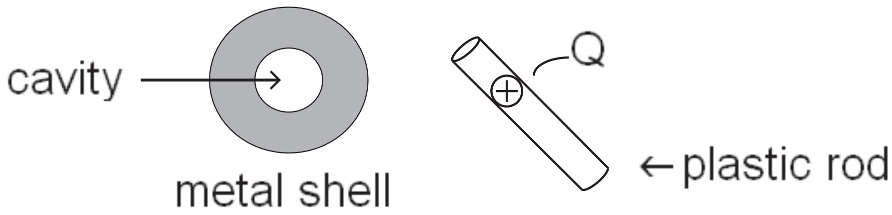
- For any question in which you are asked to predict the outcome, you will be provided with help in the questions following it to make sense of the situation.
- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing.
- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge that you put on a conductor can rearrange itself.
- For a conductor, excess charges only reside on its outer surface in equilibrium.
- Insulators (e.g., wood, wool, plastic, glass) are materials in which electrons are bound to each atom or molecule, they can only move locally within the atom or molecule when they feel a force.

Additional notes:

- For questions that refer to whether *significant* net charge is present on an object in a particular situation or whether *significant* force is exerted between two objects in a particular situation, the word *significant* refers to cases in which the consequences would be easily measurable experimentally.

Section XIII: Conductors with or without a cavity and point charges

The students from Hogwarts are now given a neutral spherical metal shell with an empty spherical cavity in the center. There is also a point charge, +Q on a plastic rod, near the metal shell. The students are asked to determine if the charged plastic rod feels a force from the metal shell.



- Harry: Since the metal shell isn't charged, I don't think that the point charge on the plastic rod outside should feel a force due to the shell.
- Ron: But wait Harry! Don't charges outside the metal shell induce charges on the surface of the metal shell? Shouldn't that cause an attractive force between the point charge and the metal shell?

a. With whom, if either, do you agree? Explain.

Lets examine the situation carefully:

b. Recall the earlier case of a metal ball with no cavity and a charged comb nearby. In the charge distributions you drew for that case, the inside of the metal ball was neutral. Can carving a metal cavity in the neutral region change anything about this charge distribution? Explain.

c. Are the free electrons in the metal shell attracted to or repelled by the charge +Q?

d. On the figure above, draw the charge configuration on the metal shell with a charge +Q outside. (Hint: Recall that, in equilibrium, induced charges on the surface of a conductor are always on its outer surface and not on the inner surface, i.e. the wall of the cavity.)

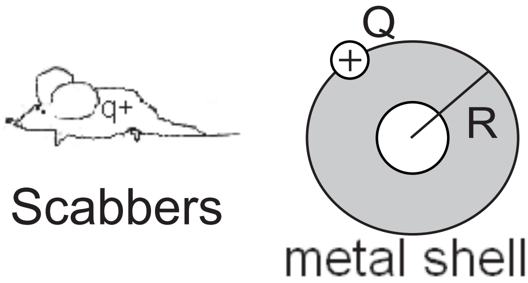
e. Will the rearrangement of electrons on the metal shell due to the external point charge +Q result in an attraction between the metal ball and the charge +Q?

f. Make sure your previous responses are consistent with whether you agree with Ron or Harry earlier.

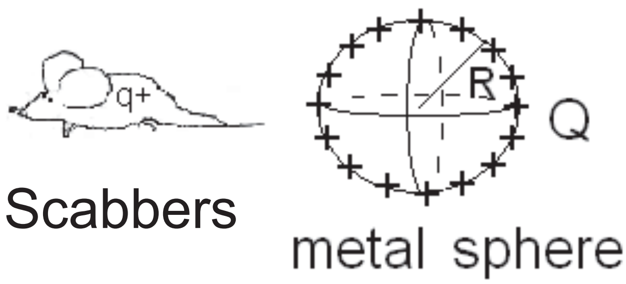
- Summary: Carving a cavity in a solid spherical metal ball will not change the induced charge distribution due to the presence a charged object outside such as the charged plastic rod. In particular, the induced charges would be identical to the case without the cavity (on the outer surface of the metal object).

Ron is furious when Professor Snape decides that he is going to use his pet rat, Scabbers, during a lab. He uses the rat in three scenarios to test the students' knowledge about the forces due to induced charges on the conductors. Scabbers has a +q charge from rubbing against the carpet. Assume that the charge +q on Scabbers is significantly smaller than charge +Q on spherical metal objects in all situations below so that the charge on Scabbers does not distort the charge distribution on the spherical metal objects.

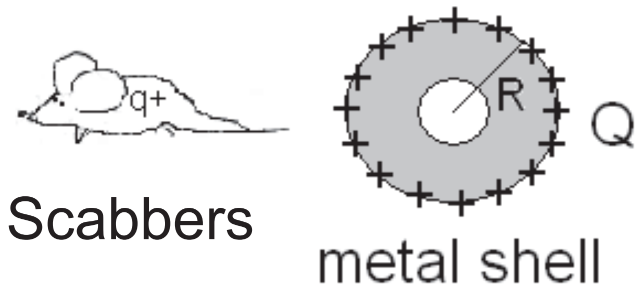
Setup 1: First, Scabbers is set outside a spherical metal shell. Professor Snape places a localized point charge, +Q, on the metal shell. The following figure depicts the outer surface of the metal shell before equilibrium is established.



Setup 2: Second, he places Scabbers outside a neutral solid metal sphere (no cavity) that has the same point charge, +Q, uniformly distributed on its surface.



Setup 3: Lastly, Snape places Scabbers next to a spherical metal shell that has a charge +Q uniformly distributed on its surface. The outer radii are the same in all three cases and Scabbers can be treated as having charge +q that does not distort the charge distribution of +Q on the spherical metal objects. Also, the charge on Scabbers is at the same distance from the center of the three spherical metal objects.



Snape asks the students if they know which setups will produce an electric force on Scabbers and if any of these forces will be the same once equilibrium is established.

- Ron: All surfaces have charges, so my poor Scabbers is going to feel a force in every case. However, I don't think the force will be the same in each setup. It will depend on whether the charged object has a cavity or not and the distribution of the charge on the surface of the spherical cavity even if the charge is +Q in all cases.

- Harry: Ron, I agree that all of these will cause a force on Scabbers, but I think that the forces will be the same since all of the charges have the same magnitude, +Q, and the metal surfaces are spherical so in equilibrium, the charge +Q will be uniformly distributed on the outer metal surface.

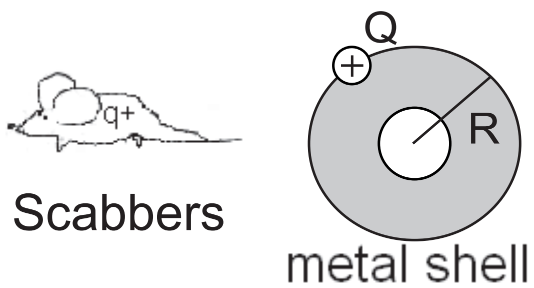
a. Predict who is right, Ron or Harry?

Note: Any excess charge uniformly distributed over a spherical conductor can be treated as a point charge of the same magnitude and sign at the center of the sphere for the purpose of finding the force on an outside object. This phenomenon is not valid if the charge distribution is non-spherical. Assume that Scabbers has very small charge +q that does not distort the charge on the spherical metal object.

b. Based upon the note above, in which of the cases above will the force on Scabbers be the same?

Let's examine the first case systematically:

Case 1: Localized point charge placed on a metal shell (before equilibrium is established)



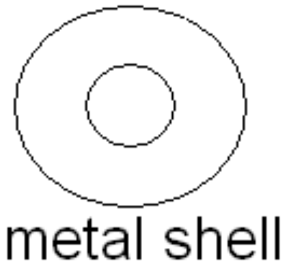
Consider the following statements from Hermione and Harry:

- Hermione: The localized charge +Q that Professor Snape has placed on the spherical metal object consists of a large number of excess positive charges in a small region. If the magnitude of charge on one proton or electron is $e = 1.6 \times 10^{-19}$ Coulombs then the number of positive charges making up the point charge $+Q$ is $N = Q/e$, which may be very large!
- Harry: Yes and since these positive charges making up the point charge repel each other and the free electrons can move in a metal, the free electrons from the initially neutral part of the metal will come and partly neutralize the +Q charge. This movement of free electrons will produce excess positive charges elsewhere on the surface so that when equilibrium is established, the charge +Q will be uniformly distributed on the outer surface of the conductor.

a. Explain why you agree or disagree with Hermione and Harry.

b. If the charge initially placed on the metal shell is +Q, what will be the net charge that will reside uniformly on the outer surface after equilibrium is established?

c. Draw the charge configuration of the metal shell on which Professor Snape placed charge +Q after equilibrium is established.



Consider the following statement from Ron:

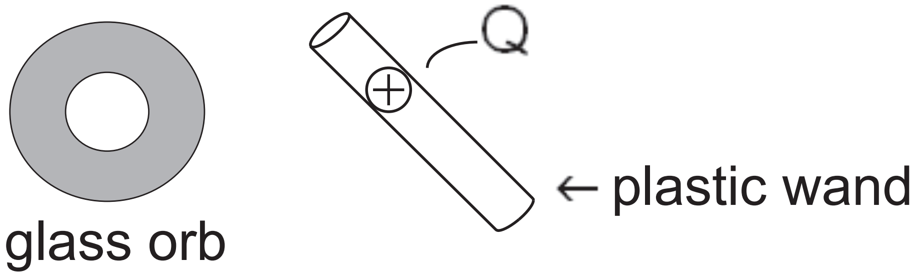
- Ron: Oh! So after equilibrium is established, there is no difference between the charge configuration in this setup and that in setup 3 in which the charge was already uniformly distributed on the metal shell.

d. Explain why you agree or disagree with Ron.

e. Will Scabbers feel a force in all three cases? Will this force be the same in cases 1,2, and 3? Is this force attractive? Explain your reasoning. (Hint: For the purpose of considering the force on Scabbers, the total excess charge uniformly distributed on the surface of the sphere behaves as a point charge at its center.)

Section XIV: Insulators with or without a cavity and point charges

Draco Malfoy wants to perform a spell using a glass orb that Professor Trelawney gave Hermione. He brings his plastic wand, with an excess point charge +Q on it, near the glass orb a cavity, as shown below.



- Ron: Malfoy, why are you wasting your time? Your plastic wand will not have any effect on the glass orb because glass is an insulator and the charges in it won't move in response to the external charge on the plsatic wand.

A. Do you agree with Ron's assessment? Explain your reasoning.

B. On the figure above, draw the charge configuration of the glass orb while the point charge (plastic wand) is near by. Draw atoms if necessary.

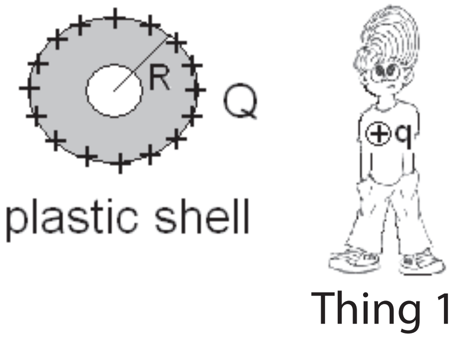
C. Will the point charge cause any movement of charges beyond their local atom/molecule within the glass orb?

D. Will the two objects attract or repel each other in this situation? Explain.

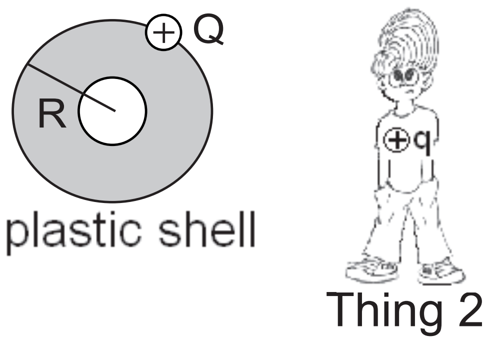
E. Considering only the local movement of the charges within the glass orb compared to that on the metal cavity earlier in Section XIII, will the force between the point charge and the orb be greater or smaller in magnitude than if it was a metal orb?

Let's consider a few other situations. The Cat in the Hat pulls out of his hat Thing 1, Thing 2, and Thing 3, each of which has a point charge +q on their chest. The three setups are shown below. Assume the distance of charge +q in each setup from the center of the plastic object is the same. Assume that Thing 1, Thing 2, and Thing 3 are placed far away from the charged plastic objects, i.e. the following figures depict the objects before they are brought closer together. Assume that charge +q is small compared to +Q on spherical objects in the situations below so that the charge +q does not distort the charge distribution on the spherical objects. Also, ignore any polarization of Thing 1, Thing 2 and Thing 3 by charge +q.

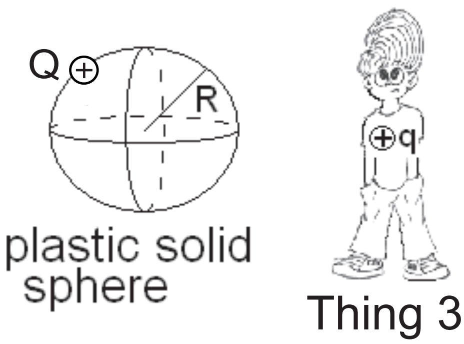
Setup 1: The Cat places Thing 1 close to a plastic spherical shell with a uniform surface charge, +Q.



Setup 2: He then puts Thing 2 close to a plastic spherical shell that has a localized point charge +Q placed on it. Note that the figure shows the outer surface of the plastic shell.



Setup 3: Finally, Thing 3 is set close to a plastic solid sphere with a localized point charge +Q. The outer radii are the same in all three cases.



a. Are the forces due to the charges on the plastic object necessarily the same on Thing 1, Thing 2, and Thing 3?

b. In setup 2, we have a localized point charge +Q. Once the charge is placed on the plastic shell, will it distribute itself uniformly on the surface of the plastic shell? (Hint: There are no free electrons in an insulator.)

c. In setup 2, the point charge +Q is not spherically distributed. Would you expect the force felt by Thing 2 to be the same as the force felt by Thing 1 in setup 1?

d. In setup 3, would you expect the localized point charge +Q to move and distribute itself throughout the plastic solid sphere?

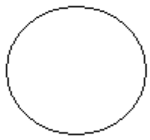
e. Will you expect the force on Thing 3 in setup 3 to be the same as the force on Thing 1 in setup 1 due to the charges on the plastic objects in the two cases?

f. Let's take a look at setup 1. How would the force felt by Thing 1 in setup 1 compare to the case in which the shell was made of metal instead of plastic? (Hint: If the charge distributions are identical in the two cases, should the electrostatic forces be identical too?)

Posttest: Basics of Charging Conductors and Insulators

In answering the following questions, the following information will be useful:

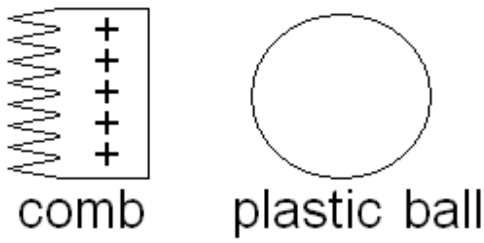
- Like charges exert repulsive forces on each other. Unlike charges exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing. For example, a neutral sphere with no charges nearby can be shows as follows:



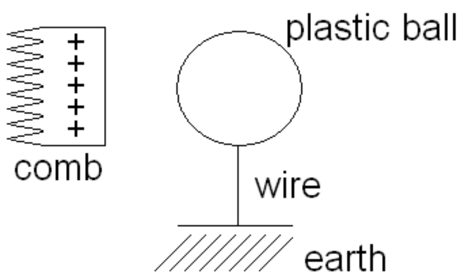
- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge you put on a conductor can rearrange itself. Core electrons in conductors do not move.
- For a conductor, excess charges only reside on its outer surface in equilibrium. Electrostatic equilibrium is established when there is no net force (including all forces) on the free electrons (conduction electrons). For example, excess positive or negative charges on an isolated metal sphere will distribute uniformly on the outer surface in equilibrium:

- Insulators (e.g., wood, wool, plastic, glass) are materials in which there are no conduction electrons and electrons can only move locally within the atoms or molecules when they feel a force, e.g., due to the presence of external charges.

1.a) Draw the charge configuration of a neutral plastic ball while a positively charged comb is held nearby. Draw atoms if nece

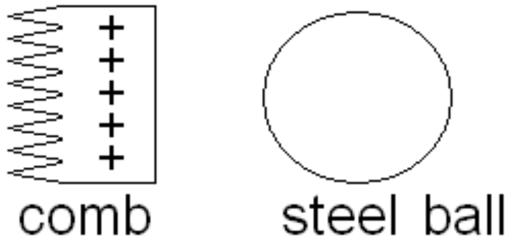


1.b) While holding the positively charged comb near the plastic ball, you connect the plastic ball to Earth by a thin metal wire. Draw the charge configuration in the plastic ball after it has been grounded this way. Draw atoms if necessary.

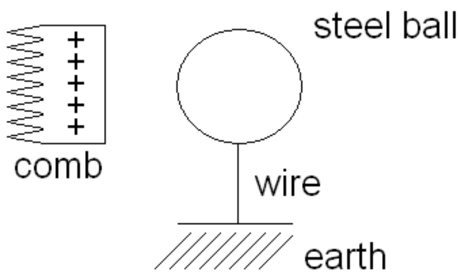


1.c) Will the order in which the comb and the grounding wire are removed affect whether excess charge is retained on the plastic ball? If so, specify which should be removed first in order to ensure that there is excess charge on the plastic ball and explain your reasoning. If not, explain why the order is not important.

2.a) Draw the charge configuration of a neutral steel ball while a positively charged comb is held nearby.

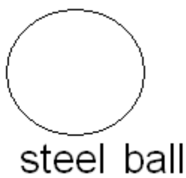


2.b) Draw the charge configuration of the steel ball after it has been grounded by a piece of metal wire.



2.c) Will the order in which the comb and the grounding wire are removed affect whether excess charge is retained on the plastic ball? If so, specify which should be removed first in order to ensure that therer is excess charge on the metal ball and explain your reasoning. If not, explain why the order is not important.

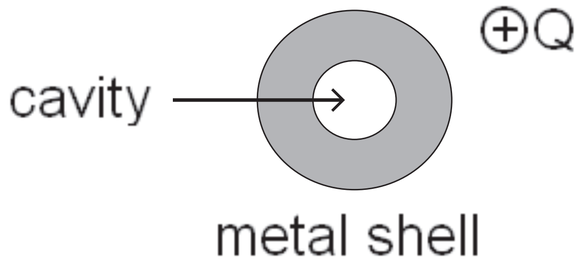
Draw the charge configuration on the steel ball if both the grounding wire and the comb are removed one by one for the order of removal in which the steel ball develops an excess charge.



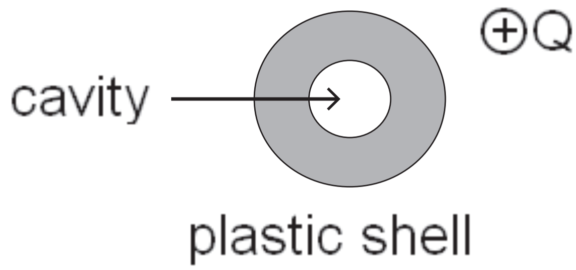
3) Does any significant charge develop on each ball when you touch two identical neutral metal balls and separate them a considerable distance? If so, why? If not, why not?

4) If a neutral piece of plastic is rubbed against a neutral piece of wool, will each of them become charged? If so, why? If not, why not?

5. a) A point charge, +Q, is located outside a neutral spherical metal shell with an empty spherical cavity at the center. Draw the charge configuration of the metal shell and explain whether or not the point charge feels a force from the metal shell?



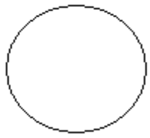
5. b) Draw the charge configuration of the spherical shell if it were made of plastic (Draw atoms if necessary). Will the point charge feel a force from the plastic shell? Explain.



Supplementary Problems: Basics of Charging Conductors and Insulators

In answering the following questions, the following information will be useful:

- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing. For example, a neutral sphere with no charges nearby can be shown as follows:



- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge you put on a conductor can rearrange itself. Core electrons in conductors do not move.
- For a conductor, excess charges only reside on its outer surface in equilibrium. Electrostatic equilibrium is established when there is no net force (including all forces) on the free electrons. For example, excess positive or negative charge on a metal sphere will distribute uniformly on the outer surface in equilibrium:

- Insulators (e.g., wood, wool, plastic, glass) are materials in which there are no conduction electrons and electrons can only move locally within the atom or molecules when they feel a force, e.g., due to the presence of external charges.

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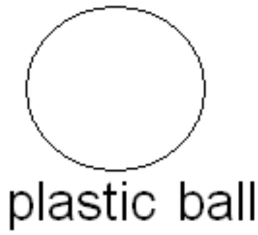
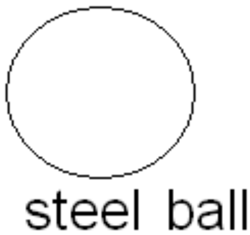
1. Most objects are typically electrically neutral. Explain why that is the case.

2. How does an object become charged? How would you charge a piece of plastic? A piece of metal?

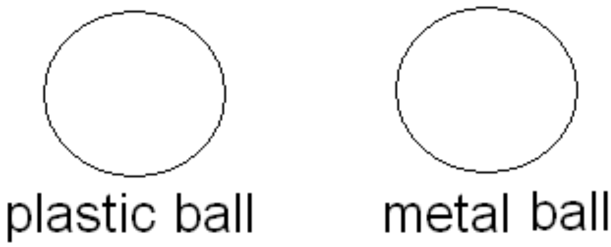
3. a) Draw the charge configuration of a neutral plastic ball (how excess charges inside are arranged) when there are no other charges nearby. If you think that the positive and negative charges are overlapping in each atom to make the net charge zero locally, you need not draw anything.



3. b) Draw the charge configuration of a neutral steel ball when there are no other charges around. If you think that the positive and negative charges are overlapping in each atom to make the net charge zero (locally), you need not draw anything.

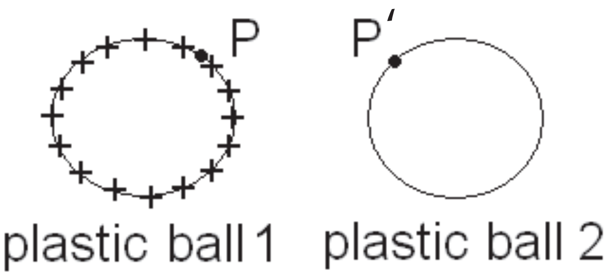


4. a) A neutral metal ball and a neutral plastic ball are touched together and then separated a considerable distance. Draw the charge configurations of the two materials after they are separated a considerable distance:

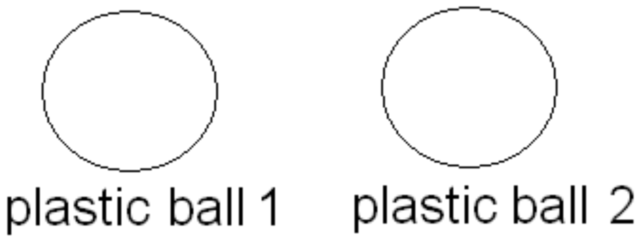


4. b) A plastic ball with a positive charge uniformly distributed over its surface is touched with an uncharged plastic ball at points P and P ′ and then the two are separated a considerable distance. Draw the charge configuration of both balls after they have been separated a considerable distance. Explain.

Before touching:

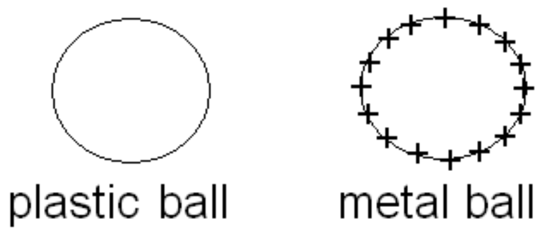


After touching and separating them far away:

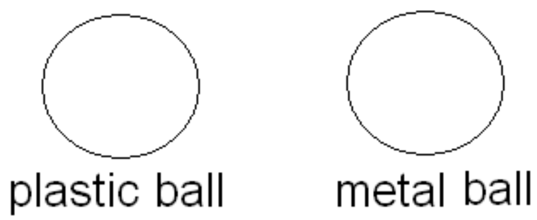


4. c) If a neutral plastic ball is touched with a metal ball that has a charge +Q uniformly distributed on its surface and then the two are separated by a considerable distance, will the plastic ball acquire any significant charge? Draw the charge configuration below after the balls have been touched and separated a considerable distance. Explain your reasoning.

Before touching:

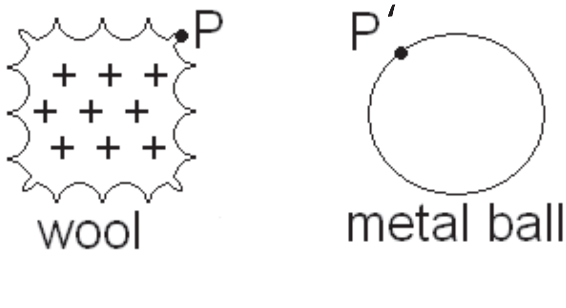


After touching and separating them far away:

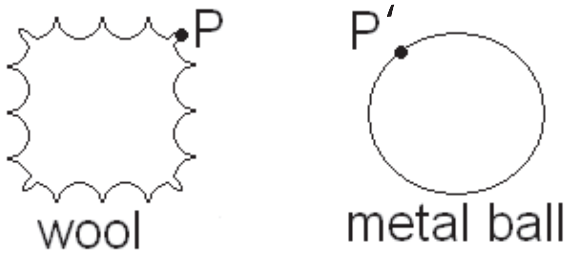


4. d) A neutral metal ball is touched with a positively charged piece of wool and then the two are separated a considerable distance. Will the metal ball acquire a significant charge as a result of their contact (i.e., when points P and P ′ touch)?. Draw the charge configuration of the wool and the metal ball after they have been touched and separated a considerable distance. Explain.

Before touching:

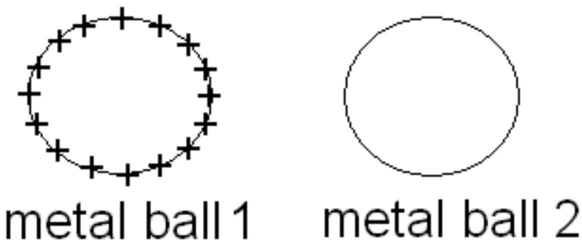


After touching and separating them far away:

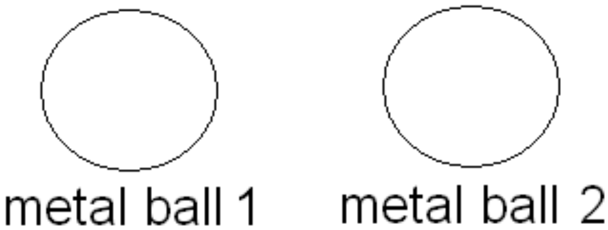


5. a) A metal ball has a uniformly distributed charge +Q on its surface and it is touched with another identical but neutral metal ball and then separated by a considerable distance. What would be the magnitude and sign of charge on both balls after they are separated? Draw the charge configuration of the metal balls after they have been touched and separated a considerable distance. Justify your reasoning.

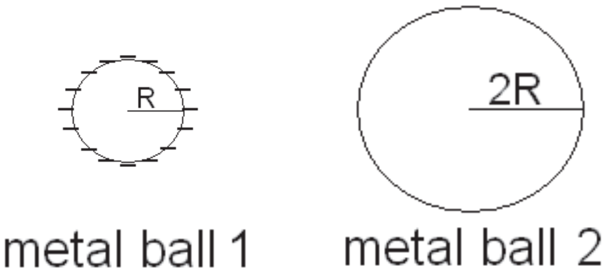
Before touching:



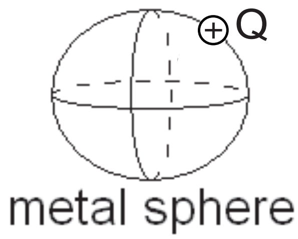
After touching and separating them far away:



5. b) If the neutral metal ball had twice the radius of the charged metal ball, which ball would carry a greater net charge after they are touched and separated a considerable distance? Explain your reasoning.

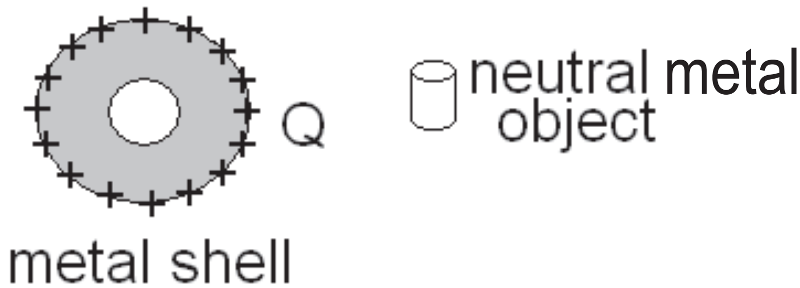


6. a) If you put a point charge, +Q, in a localized region on the surface of a metal sphere as shown below, draw what will happen to these charges after equilibrium is established? Explain.



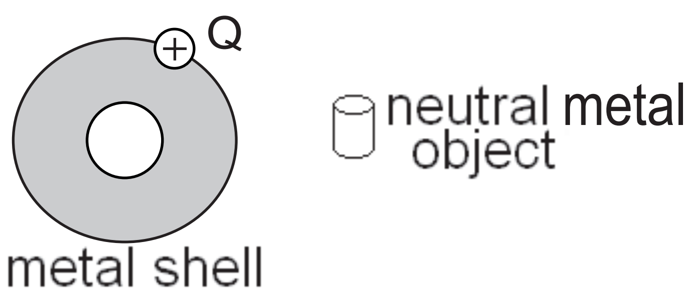
6. b) What will happen to the charges after some time if the sphere were made of plastic? Explain.

7. a) If a metal shell has a charge +Q uniformly distributed on its surface as shown below, would a neutral metal object outside the shell feel a force due to the charge +Q on the metal shell. Explain your reasoning.



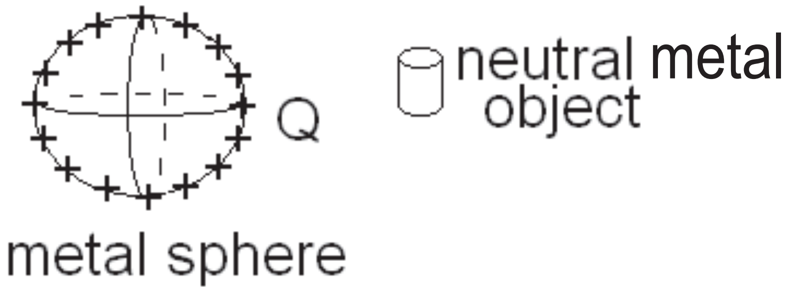
7. b) How would your answer change, if at all, if the spherical shell were made of plastic and the charge was uniformly distributed on its surface exactly as in the case of the metal shell?

8. a) If you put a localized point charge, +Q, on a metal shell, as shown below, will a neutral metal object outside the shell feel a force due to the charge? Justify your answer. (Hint: If there is a rearrangement of charges on the metal shell, feel free to include it.)



8. b) Would your answer change if the shell were made of plastic? Explain.

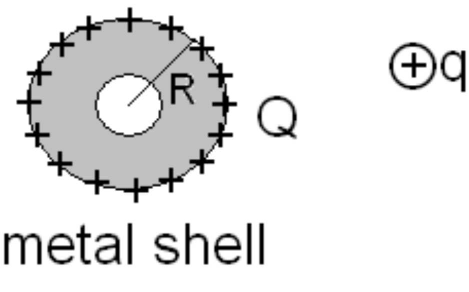
9. a) A neutral solid metal sphere (no cavity) has the same charge, +Q, (same charge as in the last two questions) uniformly distributed on its surface. Will a neutral metal object outside the sphere feel a force due to the charge +Q? Is the force the same as that of questions 7 and/or 8? Explain.



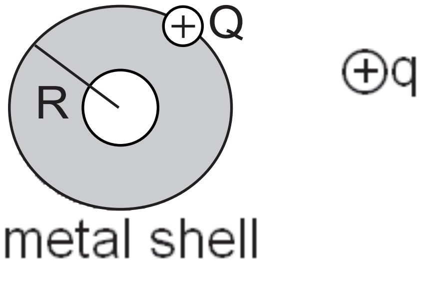
9. b) If the metal sphere were replaced with a plastic sphere, would the neutral metal object feel a force due to the uniform surface charge +Q on the plastic sphere? Justify your answer.

10. Consider the following scenarios. In each case, the distance of charge +q from the center of the metal ball is the same.

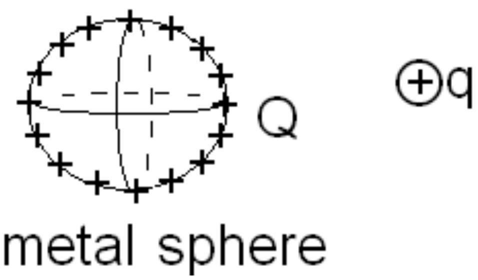
Case 1: A point charge +q is placed outside a metal shell which has a +Q charge uniformly distributed on its surface, before being brought close to the point charge +q.



Case 2: The same point charge +q is outside a metal shell on which a point charge +Q is placed in a localized spot on its surface, before being brought close to the point charge +q.



Case 3: A point charge +q is placed outside an isolated solid metal sphere which has a charge +Q uniformly distributed on its surface, before being brought close to the point charge +q.



10. a) In equilibrium, in which of the three cases above will the point charge +q (outside the metal ball) feel a force as a result of the charge +Q on the metal ball? Explain your reasoning.

10. b) Which of the cases above will have the same force exerted on the point charge +q (outside the metal ball) by the charges on the metal ball? Explain your answer.

10. c) Suppose the metal shells and the solid metal sphere (in the three cases above) were replaced with plastic objects of the same shape. How would your answer to part (a) differ, if at all? Explain your reasoning.

10. d) Would your answer to part (b) be different for the plastic case? Justify.