Chapter 17

Electric Charge, Force, and Energy

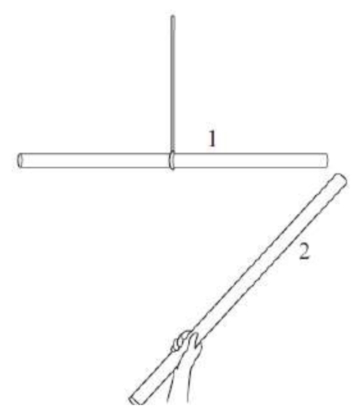
17.1 Electrostatic interactions

OALG 17.1.1 Observe and find a pattern

Equipment: plastic gloves, foam insulation tubes, felt/wool, plastic wrap. If foam tubes are not available, you can use balloons or PVC pipes.

For better results, wear plastic gloves when performing this experiment. If the humidity is too high, blow warm air on your equipment (using a hair dryer) before performing the experiments.

Suspend one tube from a string, as shown in the illustration at right, or place it on a swivel stand that is free to rotate. Before starting the experiments that follow, bring one end of tube 2 near one end of hanging tube 1. Is there any interaction? Now rub one end of each tube vigorously with different materials, as described below.



Caution: Mark the tubes so that you know which one you rubbed with felt and which one you rubbed with plastic wrap. Make sure you do not switch them, remember which end of the tube you rubbed, and do not touch it after rubbing. Make sure only one person holds onto one tube and rubs it with the material described in the following table. Do not pass the tubes and do not exchange the material.

If you have the materials, perform the following experiments:

a. Bring the rubbed end of tube 2 or the material doing the rubbing near the rubbed end of the suspended tube 1 and record the behavior of tube 1. Create a table like the one below and record your observations.

Object 1	**Object 2**	**Record your observations**
Tube 1 rubbed with felt	Tube 2 rubbed with felt	
Tube 1 rubbed with felt	The felt that was used to rub tube 1*	
Tube 1 rubbed with plastic wrap	Tube 2 rubbed with plastic wrap	

Tube 1 rubbed with plastic wrap	The wrap that was used to rub tube 1*	
Tube 1 rubbed with plastic wrap	Tube 2 rubbed with felt	

* The interactions in these experiments are much more pronounced if the experimenter is standing on an insulating board (such as a Styrofoam board).

b. Identify patterns in these observations. Compare these patterns to the patterns you infer from watching the following videos:
http://islephysics.net/pt3/experiment.php?topicid=10&exptid=164

http://islephysics.net/pt3/experiment.php?topicid=10&exptid=165

http://islephysics.net/pt3/experiment.php?topicid=10&exptid=168

c. Compare the patterns in the videos with the patterns identified in Observational Experiment Table 17.1 in the textbook (pages 501-502) Watch the following videos at [https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-experiment-video-29]. Then read and interrogate the text on page 502 to learn what is called electric charge and electric force.

OALG 17.1.2 Observe and find a pattern

Equipment: two foam tubes (or two balloons), suspension set-up, rubbing material, Scotch tape.

a. You have two foam tubes (or balloons); one tube is suspended at its center from a string, and the other is free. Vigorously rub one end of each tube with felt. Slowly bring the rubbed end of the free tube closer and closer to the rubbed end of the hanging tube. Describe your observations. What can you infer about how the electric force depends on the separation between the objects? If you do not have the equipment, Experiment 5 in Observational Experiment Table 17.1 shows you the outcome.

b. Read Conceptual Exercise 17.1 on page 503 in the textbook and repeat the experiments. Summarize your investigations here.

OALG 17.1.3 Observe and explain

Equipment: 2 plastic (PVC) tubes or balloons, hanging set-up, rubbing materials (dry paper towel and felt or fleece), plastic comb, Scotch tape, small pieces of paper and small pieces of aluminum foil used in a kitchen.

Design and conduct experiments to examine how neutral (un-rubbed) objects (PVC tubes, balloons), small pieces of paper and small pieces of aluminum foil) interact with rubbed objects such as PVC tubes, balloons, plastic combs, etc.

a. Record your results for all experiments in words and with a picture. Do your results depend on the type of rubbed object? Do your results depend on whether the neutral object is plastic or metal? Remember to describe what you see in as much detail as possible without fancy words, and without trying to explain anything.

b. What is similar in the behaviors of pieces of paper and pieces of aluminum foil when a charged object approaches them? What is different?

c. What can you say about interactions of charged objects with uncharged objects? (Describe the pattern(s) you noticed.) Compare and contrast your findings with the patterns identified in Observational Experiment 17.2 in the textbook on page 504.

d. Devise a mechanistic explanation for how the interaction between the rubbed/charged rod and the un-rubbed rod (plastic or metal) works. Remember, there is *no contact* between the objects. *Hint*: Think about the internal microscopic structure of the rod. Use charge diagrams to illustrate your explanation. Try to come up with at least two competing ideas about the internal structure of materials that could explain why uncharged objects are attracted to charged objects.

e. What are the assumptions that you made in devising your explanation(s)?

OALG 17.1.4 Read and interrogate

Read and interrogate Section 17.1 in the textbook and answer Review Question 17.1.

OALG 17.1.5 Practice

Answer Questions 1 and 2 on page 529 and solve Problems 2 and 3 on page 530 in the textbook.

17.2 Explanations for electrostatic interactions

OALG 17.2.1 Explain

In Activities 17.1.1 and 17.1.2 you found a consistent pattern: Identical objects rubbed with a second material repel each other. The second material in turn attracts the objects it rubbed. What mechanism might explain why rubbing objects makes them attract or repel each other?

OALG 17.2.2 Test the explanation

Your friend Hector says that electric interactions are the same as magnetic interactions because magnets also attract and repel each other. Consequently, he believes that when you rub objects, they become magnetized. What experiment(s) will allow you to test Hector's idea?

a. We decided to test Hector's idea by using a magnet on a pivot with a set of materials that can be charged positively and negatively. Watch the following videos of the experiments that we conducted https://youtu.be/hfXAbx0DKmI and decide which ones can be used to reject Hector's idea and which ones cannot. Explain how you made your decision.

b. Make a judgment about Hector's idea**.**

OALG 17.2.3 Read and interrogate

Read and interrogate Section 17.2 in the textbook and answer Review Question 17.2.

OALG 17.1.5 Practice

Answer Questions 3-5 on page 529 in the textbook.

17.3 Conductors and insulators (dielectrics)

OALG 17.3.1 Observe and explain

a. Watch the experiments at https://youtu.be/m3WPgv2I93I.

b. Describe your observations for each of the 4 experiments.

c. Think of what model of the internal structure of the conducting and dielectric materials could explain your observations?

d. Watch the experiment at http://islephysics.net/pt3/experiment.php?topicid=10&exptid=190. Do you need to adjust the model that you devised to explain the outcome of this experiment?

d. Read and interrogate subsections "Conductors" and "Dielectrics" in Section 17.3. Use the text in these subsections to revise your explanations if necessary.

OALG 17.3.2 Test your ideas

Watch the 4 experiments in the following video https://youtu.be/U4SAcKPKZZI.

a. Sketch the set-up for each experiment and describe the outcome.

b. Can the models of conductors and dielectrics that you devised in Activity 17.3.1 predict the outcomes of the experiments? Justify your answer using charge diagrams such as those in Figures 17.5 and 17.6 on page 508.

OALG 17.3.3 Observe and explain

Watch the following video https://youtu.be/6KhjTI9DTUI and answer the following questions:

a. Why do the light metal strips stick out when a charged rod is brought closer without touching?

b. Why do the light metal strips stick out more at the ends of the metal bar than closer to the middle?

OALG 17.3.4 Observe and explain

An electroscope consists of a metal ball attached to a metal rod that passes from the outside through an insulating support into a glass-fronted metal enclosure. A very lightweight metal needle is connected on a pivot on the metal rod (see the photo on the right).

a. Watch the following two experiments https://youtu.be/WQKXrVETwrs and record the outcomes.
b. Explain the behavior of the electroscope needle (1) when the charged rod touches the electroscope and (2) then when it is brought closer to the charged electroscope without touching.

b. Watch the following experiment https://youtu.be/EY8750PHY-Y and explain the outcome. What can you tell about the electric properties of a human body based on the outcome of the experiment?

c. Read and interrogate subsections "Electroscope" and "Is the human body a conductor or a dielectric" in Section 17.3 of the textbook and answer Review Question 17.3.

d. In the following experiment https://youtu.be/xDznSNxV9eI the experiments that you saw in part **a** are repeated but now the rod that charges the electroscope was rubbed very lightly (it carries a small charge). Describe what you observe and explain the outcome. Why is it different from the outcomes you observed in part **a**?

e. In the following experiment, the experimenter connects a charged electroscope with an uncharged electroscope, the first time with a metal rod and the second time with a plastic rod https://youtu.be/Zqch7ySSufo. Explain the results of the experiments and why the experimenter uses wooden tongs with the inside rubber to pick up the rods connecting the electroscopes.

OALG 17.3.5 Observe, explain and test your explanation

a. Watch the following experiment https://youtu.be/wou-B6LVU5M and explain how it is possible to charge the electroscope without touching it with a charged object.

b. What sign of charge is on the electroscope? How do you know? Hint: do not forget that the human body is a conductor.

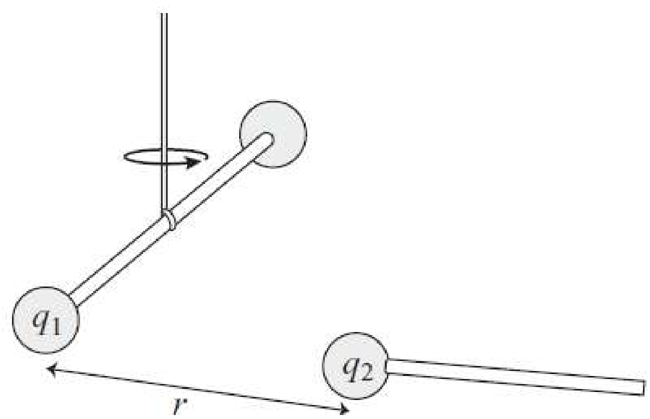
c. One way to test your hypothesis is to bring the same negatively charged rod to the electroscope and observe the needle. If the charge on the electroscope is the same as the charge on the rod, it will deflect even more. If it is the opposite charge, then the needle will deflect less. Predict what will happen to the deflection of the electroscope needle if it has the charge that you identified in part **b**. After you make your prediction, watch the video at https://youtu.be/HdERlwbvM80. Did the outcome match your prediction? Do you need to revise your answer in part **b**?

OALG 17.3.4 Practice

Answer Questions 13-18 on page 529 and solve Problem 5 on page 530 in the textbook.

17.4 Coulomb's force law

OALG 17.4.1 Find a pattern



Charles Coulomb used a torsion balance (see the figure at right) to measure the force that one charged ball exerts on another charged ball to find out how the force between two electrically charged objects depends on the magnitudes of the charges and on their separation. Coulomb could not measure the absolute magnitude of the electric charge on the metal balls. However, he could divide charges in half by touching a charged metal ball with an identical uncharged ball.

a. The table that follows provides data that resemble what Coulomb might have collected. Represent the data graphically. What are the independent variables and what is the dependent variable in Coulomb's experiment? Then analyze the changes in the dependent variable as you change only *one* independent variable at a time. Use this analysis technique (controlling variables) to find patterns in the data and devise a mathematical relationship based on these observations.

Charges (q_1, q_2)	**Distance**	**Force**

1, 1 (unit)	1 (unit)	1 (unit)
1/2, 1	1	1/2
1/4, 1	1	1/4
1, 1/2	1	1/2
1, 1/4	1	1/4
1/2, 1/2	1	1/4
1/4, 1/4	1	1/16
1, 1	2	1/4
1, 1	3	1/9
1, 1	4	1/16

b. After you constructed your mathematical relationship, compare it to Equation 17.1 on page 513. How are they similar and how are they different?

OALG 17.4.2 Represent and reason

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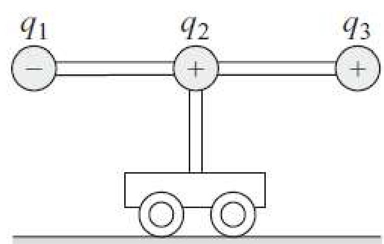


The metal balls on the cart in the figure at right have charges of equal magnitude and are very light. The rods supporting and connecting them are made of an insulating material and are also light. The cart initially rests on a smooth table.

a. Draw labeled arrows representing the electric forces that are exerted on the left metal ball. Represent the ball with a dot.

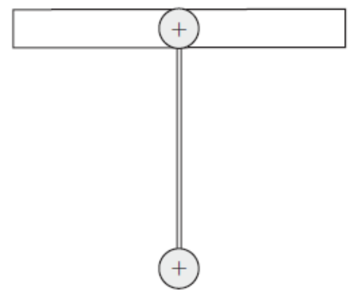
b. Draw labeled arrows representing the electric forces that are exerted on the center metal ball.

c. Draw labeled arrows representing the electric forces exerted that are exerted on the right metal ball.

d. Draw labeled arrows representing the electric forces that are exerted on the whole cart (a system with three charged balls).

e. Will the cart tend to accelerate either to the left or to the right? Explain your answer.

OALG 17.4.3 Represent and reason



A positively charged ball of mass m hangs at the end of a string. Another positively charged ball is secured at the top end of the string to a wooden support, as shown on the right.

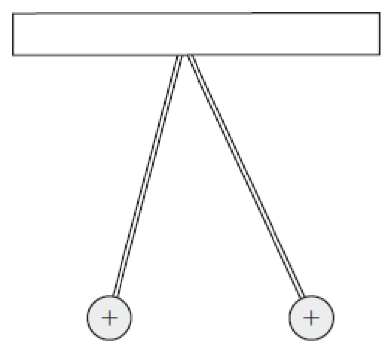
a. Draw a force diagram for the hanging ball if both balls are positively charged.

b. Represent the diagram mathematically using Newton's second law.

c. Draw a force diagram for the hanging ball if the top ball is negatively charged.

d. Represent the diagram mathematically using Newton's second law.

OALG 17.4.4 Represent and reason



Two equal-mass stationary balls hang at the end of strings, as shown on the right. The ball on the left has electric charge $+5Q$, and the ball on the right has electric charge $+Q$. The strings make angles less than 45° with respect to the vertical plane.

a. Draw a force diagram for the left ball.

b. Apply Newton's second law in component form for the right ball in both the horizontal x-direction and the vertical y-direction.

c. Draw a force diagram for the right ball.

d. Based on your analysis, rank the forces $F_{\text{S on }Q}$, $F_{5Q\text{ on }Q}$, and $F_{\text{E on }Q}$, listing the largest force first.

e. Explain your ranking.

f. Decide which string makes a bigger angle with the vertical plane or if both strings make the same angle.

OALG 17.4.5 Read ad interrogate

Read and interrogate Section 17.4 and answer Review Question 17.4.

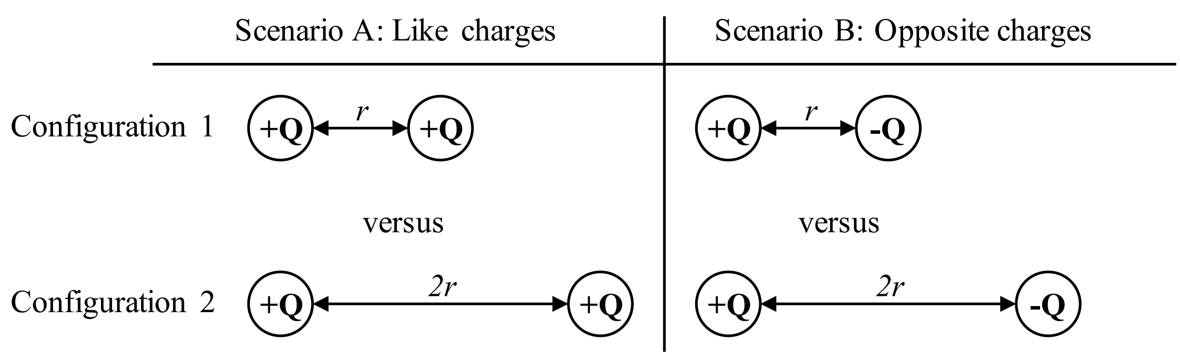
OALG 17.4.6 Practice

Answer Questions 6-8 on page 529 and solve Problems 9, 10, 15, and 19 on page 530 in the textbook.

17.5 Electric potential energy

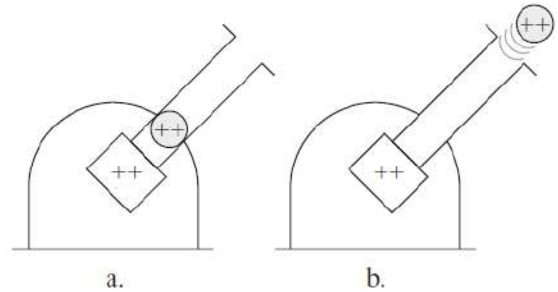
OALG 17.5.1 Represent and reason

In the diagram below, two different configurations of charged objects for two different scenarios are shown. In configuration 2, the two objects are further apart than in configuration 1. Scenario A involves 2 objects carrying the same charge, and scenario B involves 2 objects with opposite charge. If we consider the two charged objects together as a system, which configuration (1 or 2) has more electrical potential energy? Study scenarios A and B separately from each other, i.e., compare configuration 1 to configuration 2 in scenario A, then *separately* compare configuration 1 to configuration. 2 in scenario B. Draw diagrams and energy bar charts as needed and justify your reasoning by using physics you already understand.



OALG 17.5.2 Represent and reason

Two positively charged objects are held near each other in the muzzle of a cannon (see part (a) of the figure at right). When the “trigger” holding the cannonball is released, the positively charged cannonball flies out the end of the muzzle, as shown in part (b). Certain types of energy have increased. Describe a type of energy decrease that you think

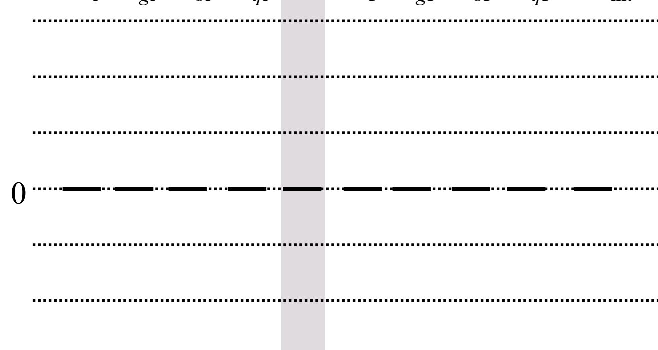


might compensate for the increase in these other energies. *Note:* The situation shown in part (a) of the illustration is similar to that of a compressed spring; instead of the coils of the spring being squeezed together, two like charges are squeezed or pushed together. In part (b) of the illustration, this compressed electric "spring" is more relaxed.

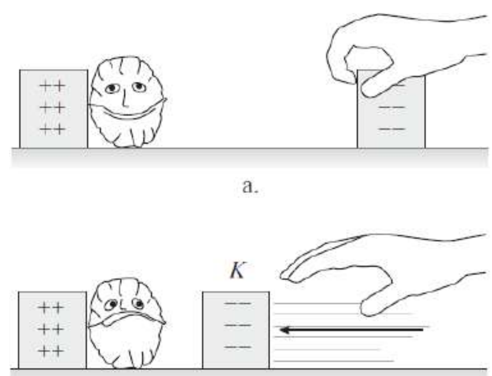
a. Using the language of energy, explain in words the described process, going from the initial state to the final state. Indicate your system choice.

b. Draw an energy bar chart representing the initial and final states.

$$K_i+U_{gi}+U_{si}+U_{qi}+W = K_f+U_{gf}+U_{sf}+U_{qf}+\Delta U_{int}$$



OALG 17.5.3 Represent and reason

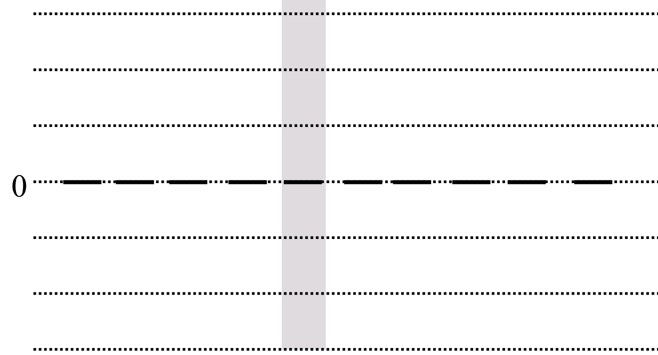


Imagine the energy changes of two opposite-sign charged objects used as a nutcracker, as illustrated in the figure to the right. What happens when the negatively charged block shown in part (a) is released and moves near the nut, as shown in part (b)? What type of energy decreases to make up for the increase in kinetic energy? *Note:* The situation shown in part (a) is similar to that of a stretched spring. Instead of the coils of a spring being stretched, the two opposite charges are pulled apart—like stretching a spring. In part (b), this stretched electric "spring" is in the process of relaxing.

a. Using the language of energy, explain in words the process described above going from the initial state to the final state. Indicate your system choice.

b. Draw an energy bar chart representing the initial and final states.

$$K_i + U_{gi} + U_{si} + U_{qi} + W = K_f + U_{gf} + U_{sf} + U_{qf} + \Delta U_{int}$$



OALG 17.5.4 Reason

a. Does the analogy of a compressed spring for a system consisting of two similarly charged objects pushed close to each other makes sense? Explain your opinion.

b. Does the analogy of a stretched spring for a system consisting of two oppositely charged objects pulled apart makes sense? Explain your opinion.

c. What are the limitations of both analogies?

OALG 17.5.5 Read and interrogate

Read and interrogate Section 17.5 in the textbook.

a. Compare and contrast graphs for the electric potential energy of interaction U_q of two charged objects (q_1 and q_2) as a function of the distance between them and for the electric force between them. Consider both like-charged objects and oppositely-charged objects.

b. Evaluate the mathematical representation for U_q derived on page 519 of the textbook: Consider case 1: $r = \infty$ and then let r decrease for the case where q_1 and q_2 are both + or both –. Does the mathematical representation for U_q behave the way you think it should – consistent with Activity 17.5.1? Discuss. Next, consider case 2: $r = \infty$ and then let r decrease for the case where q_1 is + and q_2 is –. Does the mathematical representation for U_q behave the way you think it should – consistent with Activity 17.5.1? Explain.

c. Answer Review Question 17.5.

OALG 17.5.6 Practice

Answer Questions 9-12 and 29 on page 529 and solve Problems 21, 22, 26, and 29 on page 530 in the textbook.

17.6 Skills for analyzing processes involving electric charge

OALG 17.6.1 Regular problem

Solve the following problem, using the problem-solving steps outlined below and then compare your solution to the solution in Example 17.7 in the textbook.

Two electrically charged objects with charges $q_1 = +1.0 \times 10^{-9}$ C and $q_2 = +2.0 \times 10^{-9}$ C are separated by 1.0 m. Where should you place a third electrically charged object so that the net electric force exerted on it by the first two objects is zero?

Sketch and translate • Sketch the process described in the problem statement. Label the physical quantities. • Identify the unknowns. • Choose an appropriate system.	
Simplify and diagram • Decide whether you can consider the charged objects to be point-like. Decide what other interactions you will consider and what interactions you can ignore. • Construct a force diagram for the system. Choose appropriate coordinate axes. • If you are using the work-energy principle, construct an energy bar chart. Decide where the zeros for potential energies are.	
Represent mathematically • Use the force diagram to apply the component form of Newton's second law to the process (or use the energy bar chart to apply the generalized work-energy equation). • If necessary, use kinematics equations to describe the motion of the object.	
Solve and evaluate • Rearrange the equation and solve for the unknown quantity.	

• Verify that your answer is reasonable with respect to sign, unit, and magnitude. • Also make sure the equation applies for limiting cases, such as objects having very small or very large charge.	

OALG 17.6.2 Apply

Two small metal spheres with a mass of 15 g each are hung by very light (e.g. silk) threads whose lengths are both 1.2 m from a common point. When the spheres are given equal quantities of positive charge (so each has a charge $+q$), each thread makes an angle of 25° from the vertical (i.e., the angle between the two threads is 50°).

a. Draw a diagram to illustrate the situation. Draw a force diagram for one sphere. (Remember to include a coordinate system.)

b. Apply Newton's second law in the x- and y-directions to find the charge q on the sphere. (Don't forget that Earth also exerts a force on the sphere.)

c. Evaluate your answer any way you like (this is a good opportunity to use a limiting/special case.)

OALG 17.6.3 Equation Jeopardy

The application of Newton's second law for a positively charged object at one instant of time is shown in the mathematical representation that follows. Other charged objects are along a horizontal line.

$$(4.0\,\text{g})a_x = \left(9.0\times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2\right)\left[-\frac{\left(200.0\times 10^{-9}\ \text{C}\right)\left(30.0\times 10^{-9}\ \text{C}\right)}{\left(0.2\ \text{m}\right)^2} - \frac{\left(900.0\times 10^{-9}\ \text{C}\right)\left(30.0\times 10^{-9}\ \text{C}\right)}{\left(0.3\ \text{m}\right)^2}\right]$$

a. Draw a force diagram for the object at the instant the mathematical representation applies.

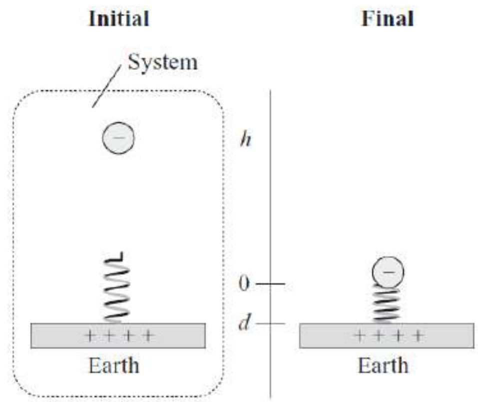
b. Sketch a situation that the mathematical representation might describe at that particular instant.

c. In words, write a problem for which the mathematical representation is a solution (it applies at only one instant in time).

d. Determine one change that could be made in the situation so that the net force exerted on the object of interest is zero.

OALG 17.6.4 Represent and reason

A negatively charged ball, initially at rest, falls until it hits a massless spring, which it compresses while stopping. The bottom of the spring rests on a positively charged block.

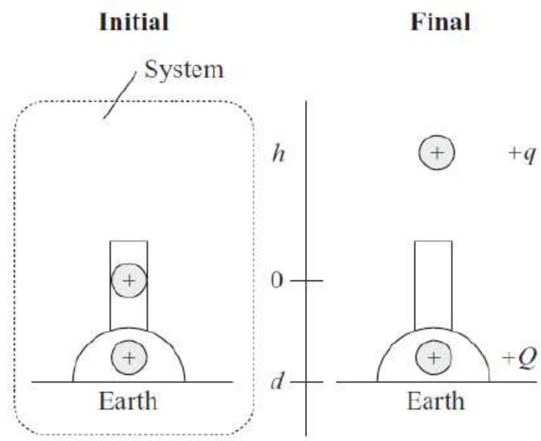


a. Draw a bar chart consistent with the process.

b. Apply the generalized work–energy equation to the process.

OALG 17.6.5 Represent and reason

a. Chris releases the trigger on an electric cannon. The cannonball with charge $+q$ and mass m fires vertically upward due to its repulsion from the stationary ball with a charge $+Q$. The cannonball reaches the apex of its flight at distance h above its starting position. Represent the process physically with a bar chart and mathematically.



b. Now, suppose that the charge $+Q$ is reduced to $+Q/2$. Represent this process with a bar chart and mathematically. In words, describe how reducing the charge affects the process.

OALG 17.6.6 Bar–chart Jeopardy

The bar charts below could represent many processes. For each bar chart:

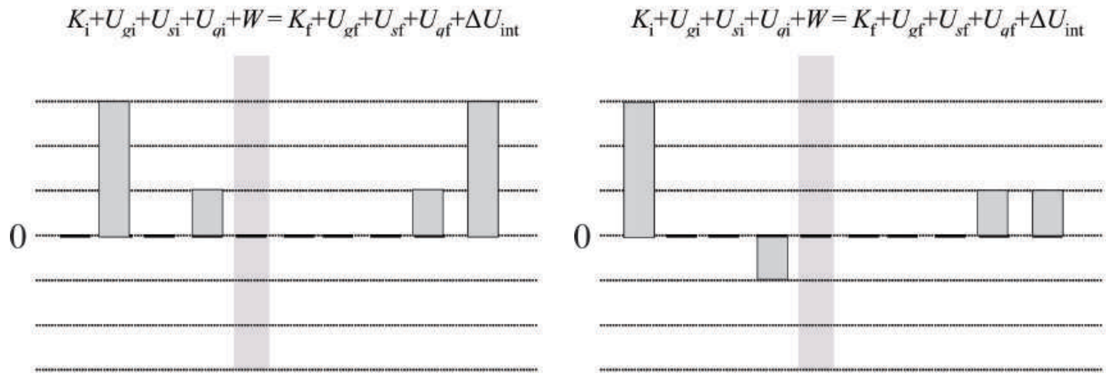
a. Draw an initial–final sketch of one possible process described by the bar chart on your whiteboard.

b. Describe the process in words.

c. Convert the bar chart into the work–energy relationship as applied to this process and put it on your whiteboard.

1.

2.



OALG 17.6.7 Equation Jeopardy

The mathematical representation below describes one or more physical processes.

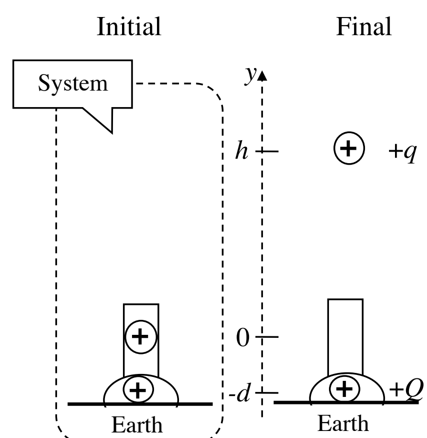
$$\frac{1}{2}\left(1.67\times10^{-27}\,\text{kg}\right)v_i^2+\frac{1}{2}\left(1.67\times10^{-27}\,\text{kg}\right)v_i^2=\frac{\left(9.0\times10^{9}\,\text{N}\cdot\text{m}^2/\text{C}^2\right)\left(1.6\times10^{-19}\,\text{C}\right)^2}{1.0\times10^{-15}\,\text{m}}$$

a. Draw a bar chart that is consistent with the mathematical representation.

b. Sketch the initial–final states that the mathematical representation might describe.

c. In words, write a problem for which the mathematical representation could be a solution.

OALG 17.6.8 Regular problem



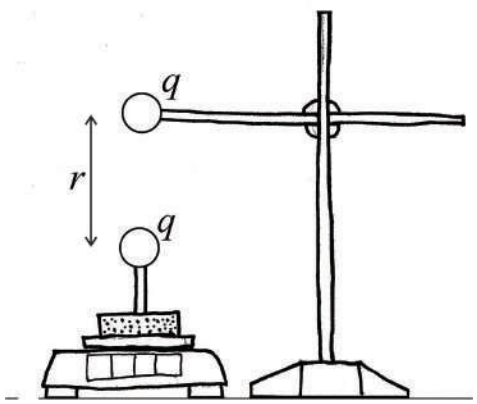
Solve this problem using the 4-step problem-solving strategy: Chris releases the trigger on an electric cannon. The cannon ball with charge $+q = 1.0\times10^{-8}$ C and mass m = 0.5 kg fires vertically upward due to its repulsion from the stationary ball with a charge $+Q = 1.0\times10^{-7}$ C. They are initially d = 0.2 m apart. The cannon ball reaches the top of its flight a distance h above its starting position. Assume g =10 N/kg. Represent the process physically with a bar chart and mathematically, then find the max height h. Remember to evaluate your answer.

OALG 17.6.9 Regular problem

Work on this problem using the 4-step problem-solving strategy. A 0.50-kg cart with a metal ball with electric charge $q = +2.0\times10^{-8}$ C starts at rest with its metal ball 0.1 m to the right of a fixed sphere with a positive charge $Q = +3.0\times10^{-7}$ C. When released, the cart travels toward a fixed sphere to the right with charge $-Q$. The fixed charges are separated by 1.0 m. How fast is the cart moving when its charged metal ball gets 0.1 m from the fixed sphere with negative charge?

OALG 17.6.10 Linearization problem

You have a set-up that consists of two metal spheres, stands and an electronic scale. You charge both spheres with equal charges q. You zeroed the scale when no object was on it. You change the distance r and record the corresponding scale readings. Your data are in the table below.



r (cm)	m (g)
5.0	132
6.0	118
7.0	105
8.0	100
9.0	95
10.0	90

Make a list of physical quantities that you can determine from your data, and determine their values.

OALG 17.6.11 Apply

Equipment: balloon, woolen glove, baking soda

You "write" a letter G with your finger on a rubber balloon using a glove made of wool. Then you bring the balloon close to a plate covered with uncharged baking soda. Some powder grains jump from the plate and stick to the balloon at the places rubbed with wool (see the photo on the right).

a. Explain why the neutral baking soda grains onto the balloon's rubbed part and not onto other parts and why they remain at the locations where the balloon was rubbed?

b. Compare and contrast the outcome of this experiment with how a photocopier works. Read and interrogate sub-section "Photocopier" in Section 17.7 in the textbook.

OALG 17.6.12 Practice

Answer Questions 25-27 on page 529 and solve Problems 31 33-35, 38, 39, and 54 on pages 531-533 in the textbook.