Section 2 The Nature of Charge: Tiny and Indivisible

What Do You See?

Learning Outcomes

In this section, you will

- **Detect** the number of hidden pennies in a container without opening the container.
- **Explain** why the masses of containers with pennies can only have certain values.
- **Describe** the Millikan oil-drop experiment.
- **Explain** the meaning of quantization of electric charge.

What Do You Think?

It's easy to share a box of popcorn with a friend at the movies. It is a bit tougher to share a slice of pizza equally, but it can be done with a knife. You can keep cutting it but each piece will still be pizza. However, at some point, you will separate the cheese from the crust and the pieces will no longer be pizza.

- **Can you think of something that cannot be split into smaller pieces and retain its identity?**

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

In this *Investigate*, you will try to find the mass of a single penny in a closed container. The container may have one or more pennies but you will not have that information. You will find the mass of an empty container, using a balance, and the mass of the container with the pennies. You will then compare your results to those of the other groups.

1. Your teacher will provide you with a set of film canisters or other containers that contain pennies. Your goal is to determine the mass of a single penny.

   Do not open the containers. To develop a strategy, assume that each container has a mass of 5 g and each penny has a mass of 2 g.

   a) Make a list of possible masses of containers that have 1 penny, 2 pennies, 5 pennies, etc. Make this list for at least ten containers.

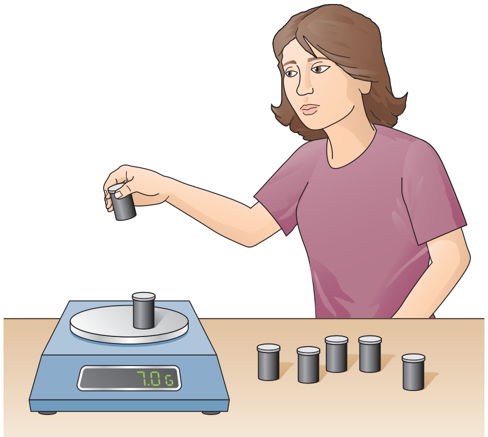
   b) Suppose you were given only the masses of the ten containers you calculated in *Step 1.a*) and not the mass of a penny. Describe how you could find the mass of a single penny.

2. Now, measure the mass of an empty container using a balance. Then measure the mass of each container, including the penny or pennies inside.

   a) Explain how you can find the mass of one penny using the measurements you are permitted to make. It is very possible that no container has only one penny. Write down your strategy.

   b) What do you determine the mass of a penny to be?

   c) Compare your value of the mass of a penny with that of another group. How does your confidence in your value change as you compare it with more and more groups? Scientists use similar methods to share and compare results with other scientists to make scientific progress.



3. Suppose you obtain a new set of containers with nickels in them. Suppose that each container is 5 g and each nickel is 5 g.

   a) What are some possible masses you would expect for four of the containers?

   b) A lab group stated that they measured the mass of a container of nickels and it was 23 g. Your lab group thinks that they must have made an error. Explain to the first group in writing why you think that there is a problem.

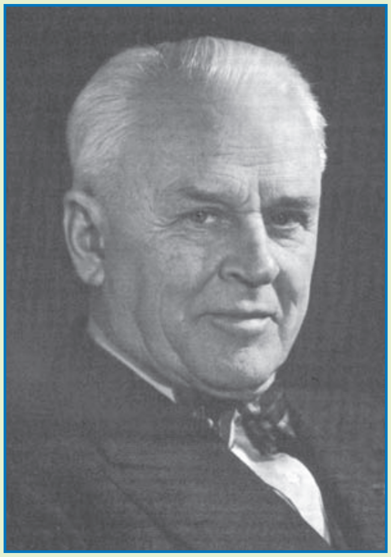
   c) When your lab group measured the mass of the container, you also found it to be 23 g. You now have a problem—a mystery—a puzzle. It is this kind of puzzle where calculations do not support the actual measurements that challenges and intrigues physicists. How could this be? It would be great to open up the container, but this may not be possible. Can you solve the puzzle? Suggest at least three different solutions to this puzzle.

Physics Talk

QUANTIZATION OF CHARGE

Millikan's Oil-Drop Experiment

In 1910, Robert A. Millikan completed an experiment very similar in concept to the section you just completed. He did not measure containers of pennies. He measured the forces on charged oil drops. These measurements allowed him to calculate the charge on each drop. Millikan made hundreds of measurements. He always found that the oil drop had 1 charge, 2 charges, 5 charges, 17 charges, and other whole numbers of charges. He never found 3.5 charges or 4.7 charges or 11.2 charges. He showed that it was not possible to have a fraction of a charge, and concluded from his oil-drop experiment that there is a basic unit of charge.



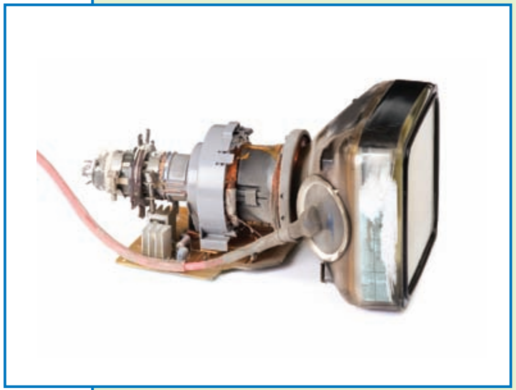
Millikan's experiment has been conducted many times. Nobody has found fractional charges. In other words, electric charge is quantized. Each **quantum** is the smallest, indivisible unit of charge that cannot be further subdivided. By way of analogy, consider United States money. There is a smallest unit of money, the penny. A dime is equal to ten pennies, a quarter, 25 pennies. In U.S. currency you cannot pull half a cent or 0.375 cents out of your pocket.

Physics Words

quantum: smallest, indivisible unit of charge that cannot be further subdivided.

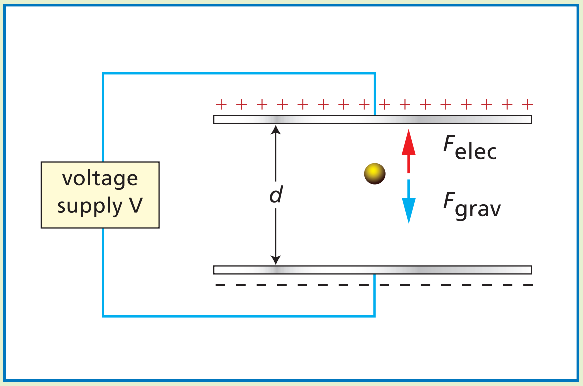
electron: a negatively charged particle with a charge of 1.6×10^{-19} C (coulombs) and a mass of 9.1×10^{-31} kg.

When the atom was discovered, scientists thought it was uncuttable. That is why they were called atoms from the Greek word *atomos*. The *a* means not and *tomos* means cut. Therefore, *atomos* means indivisible or not cuttable. But upon further investigation, it was realized that the atoms have internal parts.



In 1895, J.J. Thomson discovered one of these parts, the **electron**, a tiny negatively charged particle that is part of the atom. He did this by analyzing electron beams in a tube very similar to the tube where electrons travel in a picture-tube TV, not the flat-screen TV. (The flat-screen also uses electrons, but in a different way.) A television picture tube is a modern version of Thomson's apparatus. These electrons hit the screen and make the TV images.

Your penny lab was easy compared to Millikan's oil-drop experiment. The oil drops are so small that in Millikan's experiment he had to view them through a microscope. To find their mass required some ingenuity as well. Millikan sprayed the oil droplets between a positively charged plate and a negatively charged plate. If the oil drop had a negative charge, it would be repelled from the negative plate and attracted to the positive plate. If the positive plate were on top, the electric force would be pulling the drop up, while gravity would be pulling the drop down. If the two forces were equal, the drop would come to rest and remain suspended (or travel at a slow constant speed). By calculating the electrical force and the gravitational force, the charge on the oil drop (i.e., the charge of the electrons) could be found. Millikan won the Nobel Prize for this experiment.



The diagram above shows the oil drop, the electrical plates, and the battery voltage that provides the charge on the plates. The voltage is adjusted so that the oil drop is suspended or moves with a constant speed (no acceleration).

The weight of the oil drop (*mg*) can be found by observing the oil drop as it falls because of air resistance. You can calculate the electrical force from the voltage, charge, and distance between the plates. You can calculate the gravitational force from the mass and the acceleration due to gravity. The voltage of the power supply and the distance between the plates can be measured. Using the equations below, you can find the charge on the oil drops.

$$F_{elec} = F_{grav}$$

$$\frac{qV}{d} = mg$$

$$q = \frac{mgd}{V}$$

Checking Up

1. What led to the discovery that charges are only present in whole numbers?
2. Explain the experiment Millikan used to determine the charge on an electron.
3. How would you calculate the weight of an oil drop?

From Millikan's and many additional experiments, the charge on an electron was determined to be 1.6×10^{-19} C (coulombs). You could expect to see twice this charge, three times this charge, nine times this charge, and any other whole number multiple of this charge. If you never see a fractional part of this charge, you assume that the charge is indivisible.

Current theories of physics state that a $\frac{1}{3}$ charge and a $\frac{2}{3}$ charge can exist. There is evidence for these fractional charges and the quarks (the tiniest known components from which matter is made) associated with them. The Millikan oil-drop results lead to the conclusion that these quarks always join up to make a total charge of +1 or −1.

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
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Calculations Involving Electric Charges

Sample Problem 1

Can an object have a charge of 9.6×10^{-19} C?

Because each charge is 1.6×10^{-19} C, a charge of 9.6×10^{-19} C can be the sum of 6 charges.

$(6 \times 1.6 \times 10^{-19}\ \text{C} = 9.6 \times 10^{-19}\ \text{C})$

Sample Problem 2

Can an object have a charge of 2.4×10^{-19} C?

Because each charge is 1.6×10^{-19} C, a charge of 2.4×10^{-19} C can be the sum of 1.5 charges

$(1.5 \times 1.6 \times 10^{-19}\ \text{C} = 2.4 \times 10^{-19}\ \text{C})$.

This value is impossible. Millikan's oil-drop experiment demonstrates that charge is quantized and you cannot have one and a half charges.

Determine whether objects can have the following charges:

1. 8.0×10^{-19} C
2. 4.2×10^{-19} C
3. 16×10^{-19} C
4. 24×10^{-19} C
5. 2.4×10^{-18} C

Simulating Millikan's Oil-Drop Experiment

The Millikan oil-drop experiment can be completed in a high-school lab. The experiment requires the use of a microscope, and incredible patience, to view the drops. Some computer simulations may be available on the Internet. You may decide to investigate using one of these or to design a computer simulation or game that works like the Millikan oil-drop experiment. Your created simulation should have the following features:

- The screen should look like the apparatus, with a variable power supply and oil drops between the plates.
- The drop should be able to get a new charge.
- The drop should be able to move.
- The voltage should be allowed to vary so that the net force on the drop is zero and the drop travels at constant velocity or is at rest.
- The velocity of the drop should be measurable to determine if it is traveling at a constant velocity.
- New drops should be able to be inserted between the plates.

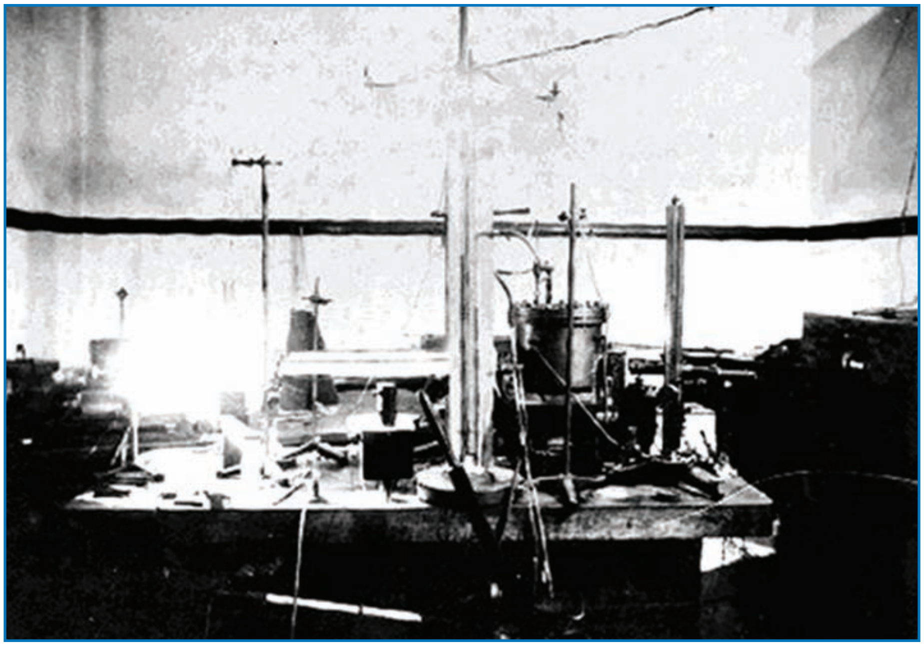
Map out a design for this computer simulation and if you can, create the simulation and test it with other students.

What Do You Think Now?

At the beginning of the section you were asked the following:

- **Can you think of something that cannot be split into smaller pieces and retain its identity?**

Review what you have learned about Millikan's oil-drop experiment. How do you know that the charge on an electron is quantized?



An early example of Robert Millikan's setup for the oil drop experiment.

Physics
Essential Questions

What does it mean?

The electron's charge is said to be quantized. That charge has been measured to be 1.6×10^{-19}C. Is it possible to have 5.0×10^{-19}C of charge?

How do you know?

Describe Millikan's oil-drop experiment. What feature of Millikan's data shows that the electron charge is quantized, that is, it comes in discrete, indivisible units? Why would the use of a computer simulation of Millikan's oil-drop experiment not be considered evidence for the charge on an electron?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	Symmetry — laws of physics are the same everywhere	* Experimental evidence is consistent with models and theories

* When you measure the size of an object, you expect that any length is possible. You think that length is continuous. Similarly, you think that time can be broken into smaller and smaller intervals with no limit imposed by nature. (You may have limits due to the technologies available for measuring distance or time.) Charge is different.

You can have 1 charge, 2 charges, 35 charges, but you can't have parts of charges. The surprising experimental result that charge is quantized has led some physicists to wonder if length and time may also be quantized. Why would you believe that charge comes in small, indivisible units? Can you believe that time comes in small bits? Would this notion change the way you observe the world?

Why should you care?

If the negatively charged electrons come as quantized, whole-number units of electric charge, and if matter is normally electrically neutral, then should you expect the positive charge to also be quantized? What might be the consequence for the atom to be made of little blocks of positive and negative charges? How can you demonstrate the peculiar idea of charge in your museum display? How can you help people understand that you cannot find a half-charge?

Reflecting on the Section and the Challenge

When the atom was discovered, people originally thought the basic units of the elements such as hydrogen, carbon, and iron could not be further divided. But, upon further investigation, it was realized that the atoms have internal parts! One of them is the electron. As you can tell so far, the electrons are indivisible, having no internal parts.

Electrons are part of an atom. In your museum exhibit, you will have to include the charge on an electron. You may also find a way to tell how the Millikan oil-drop experiment helped scientists find out about the charge and its indivisibility. You may choose to make a part of the exhibit dealing with electrons and electric charge interesting by making it interactive.

Physics to Go

1. Two students are playing tug-of-war with a rope. How is this game similar to the two forces in the Millikan oil-drop experiment?
2. A doughnut can be split into two pieces. Does the result of Millikan's experiment suggest that the electric charge cannot be split into two pieces?
3. Assume that a container has a mass of 10 g and each penny has a mass of 3 g.
   a) Make a list of possible masses of five containers that have 1 penny, 2 pennies, 5 pennies, 10 pennies, and 12 pennies.
   b) List two masses you would not find for a container with pennies.
4. What is the net electric charge on a metal sphere having an excess of 3 elementary charges (electrons)?
5. How many coulombs are equivalent to the charge of 100 electrons?
6. How many electrons does it take to have a charge of –1 C?
7. Active Physics *Plus* Which electric charge is possible?
   a) 6.32×10^{-18} C b) 3.2×10^{-19} C
   c) 8.0×10^{-20} C d) 2.4×10^{-19} C
8. Active Physics *Plus* An oil drop has a charge of -4.8×10^{-19} C. How many excess electrons does the oil drop have?
9. "Quarks" are particles that have charges $+\frac{1}{3}, -\frac{1}{3}, +\frac{2}{3}, -\frac{2}{3}$. They are important in subatomic physics.
   a) Show how three quarks can combine to create a particle with a total charge of +1.
   b) Show how three quarks can combine to create a particle with a total charge of 0.
   c) Show how three quarks can combine to create a particle with a total charge of –1.

10. Describe how you could make Millikan's oil-drop experiment into an exciting interactive display.

11. *Preparing for the Chapter Challenge*

J.J. Thomson, the discoverer of the electron, tried to describe the significance of the discovery of this tiny particle: "Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen, which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science?" Create a quote of your own that captures the significance of the discovery of the electron. Perhaps the quote could be displayed near the entrance to your proposed museum exhibit.

Inquiring Further

Estimating the size of an atom

At one time, the atom was thought to be uncuttable. It is now recognized that the atom has internal parts, one of which is the electron. The electron seems to be uncuttable, but forms a tiny fraction of the atom's mass. The size and mass of an electron raises an interesting question that will be examined in upcoming sections: How big is an atom?

Here is a way to obtain a rough estimate of the size of an atom. One cubic centimeter of olive oil is poured onto the surface of a large pond. The oil spreads out into an oil slick. When it stops spreading, the area of the oil slick is measured to be 100 square meters.

a) Assuming the oil layer is one atom thick, what is the size of the atom?

b) Perhaps the "smallest bit" of olive oil is not a single atom, but combinations of atoms, called molecules. If you are not sure whether the oil layer is one atom thick, then the answer you obtained estimates the size of a molecule. Would that be a maximum or a minimum size for an atom?