SECTION 5.1

The Mole and the Avogadro Constant

Key Terms

mole
Avogadro constant

People have learned to group things in different ways for convenience and efficiency, both at home and in the workplace. Eggs are sold by the dozen. Recordable DVDs are often sold in packs of 50 or 100.

Chemists work with large quantities of atoms and molecules on a daily basis. In this section, you will learn how to count and measure these large quantities in order to conduct research.

Grouping Items for Convenience

Table 5.1 shows how various consumer items are organized into convenient units that represent groups of items. Each unit can be used for different kinds of items, but the unit is always constant. For example, a dozen can be used to describe items such as doughnuts, flowers, and eggs, but a dozen always means 12. Paper, like the kind shown in **Figure 5.1**, is often sold in reams. Unlike some of the other quantities, such as a pair or a dozen, a ream is generally used only to describe paper products.

Table 5.1 Common Units

Item	Unit	Number
socks	pair	2
eggs	dozen	12
pencils	gross (12 dozen)	144
paper	ream (one package of sheets of paper)	500

Figure 5.1 Paper is counted by the ream. Each ream contains 500 sheets of paper.
Describe *What are other counting units for groups of items?*

The Mole

Items such as those listed in **Table 5.1** are easy to count because they are macroscopic (large enough to see). Chemists also use a convenient unit when counting individual particles (atoms, molecules, ions, and formula units) of a substance. These entities, however, are obviously too small and numerous to count directly. For convenience, chemists use a special counting unit, called the mole, to count and measure individual particles of substances.

mole the SI base unit that is used to measure the amount of a substance; it contains as many particles (atoms, molecules, ions, or formula units) as exactly 12 g of the isotope carbon-12

Avogadro constant the number of particles in one mole of a substance; a value that is equal to 6.02×10^{23} particles

Using the Mole to Count Particles

The **mole** is the SI base unit that is used to measure the amount of a substance. One mole (mol) of a substance is the amount of the substance that contains as many particles (atoms, molecules, ions, or formula units) as the number of atoms in exactly 12 g of the isotope carbon-12, or $6.022\,141\,79 \times 10^{23}$ particles of the substance. This value is called the **Avogadro constant**, named in honour of Italian scientist Amedeo Avogadro (1776–1856). Its symbol is N_A.

The value of the Avogadro constant is usually rounded to 6.02×10^{23} for convenience. Scientists continue to develop more accurate methods for determining the experimental value of the Avogadro constant. The value has changed somewhat since it was first proposed more than 100 years ago. Even though the value is experimental, chemists use the Avogadro constant to determine the number of representative particles, such as atoms, molecules, ions and formula units, in a substance. For example, if you have one mole of iron atoms, you have 6.02×10^{23} atoms of Fe(s). One mole of water represents 6.02×10^{23} molecules of $H_2O(\ell)$. Also, one mole of sodium chloride contains 6.02×10^{23} formula units of NaCl(s).

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The Avogadro constant can describe any substance, just as a dozen can describe any item. Chemists work with moles in a way that is similar to how a grocer might work with dozens of oranges. For example, three dozen oranges is the same as 36 oranges.

$$3\ \cancel{\text{dozen}} \times \frac{12}{1\ \cancel{\text{dozen}}} = 36$$

In comparison, chemists might work with the fructose (fruit sugar), $C_6H_{12}O_6(s)$, molecules in the oranges. They could calculate the number of fructose molecules in three moles (3.0 mol) of fructose in a similar way.

$$3.0\ \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}\ \text{molecules}}{1\ \cancel{\text{mol}}} = 1.8 \times 10^{24}\ \text{molecules}$$

What Is a "Particle"?

Chemists need to "count" different types of particles. It is important to know what kind of particle is being discussed. For example, when a problem refers to oxygen, $O_2(g)$, you usually want to find out the number of molecules. However, there might be a reason you would want to count the number of oxygen atoms, O. The representative particles for different elements and compounds are listed below.

Representative Particles for Elements and Compounds

- The representative particles for pure, monatomic elements, such as iron, Fe(s), are *atoms*.
- The representative particles for diatomic molecules, such as oxygen, $O_2(g)$, and compounds, such as water, $H_2O(\ell)$, are molecules.
- The representative particles for pure ionic compounds, such as sodium chloride, NaCl(s), are *formula units*.

Learning Check

1. Why has the value of the Avogadro constant changed over the years, since it was first proposed?
2. Explain what a mole is, in your own words.
3. If you had two moles of hydrogen atoms, how many individual hydrogen atoms would you have?
4. Suppose that you were in a space station and looked down at Earth. Do you think you would be able to see one person standing in a field? What about one mole of people standing in a field? Explain.
5. Suppose that you need 2000 sheets of paper. How many reams of paper do you need?
6. **Table 5.1** shows the different units that are often used to count different kinds of items in a group. Why might a dozen not be an appropriate unit to use to count paper?
7. Use print and Internet sources to research why the isotope carbon-12 was used to define the mole. Write a brief summary of your findings.

Visualizing the Mole

The Avogadro constant is a huge quantity. Because atoms, molecules, ions, and formula units are so small, scientists need to use quantities nearly as large as the Avogadro constant for practical applications. When it is written out, the Avogadro constant looks like this:

602 214 179 000 000 000 000 000

What does a mole look like? **Figure 5.2** shows samples of several different substances. Each sample has 6.02×10^{23} atoms, molecules, or formula units. In other words, each sample has one mole of particles.

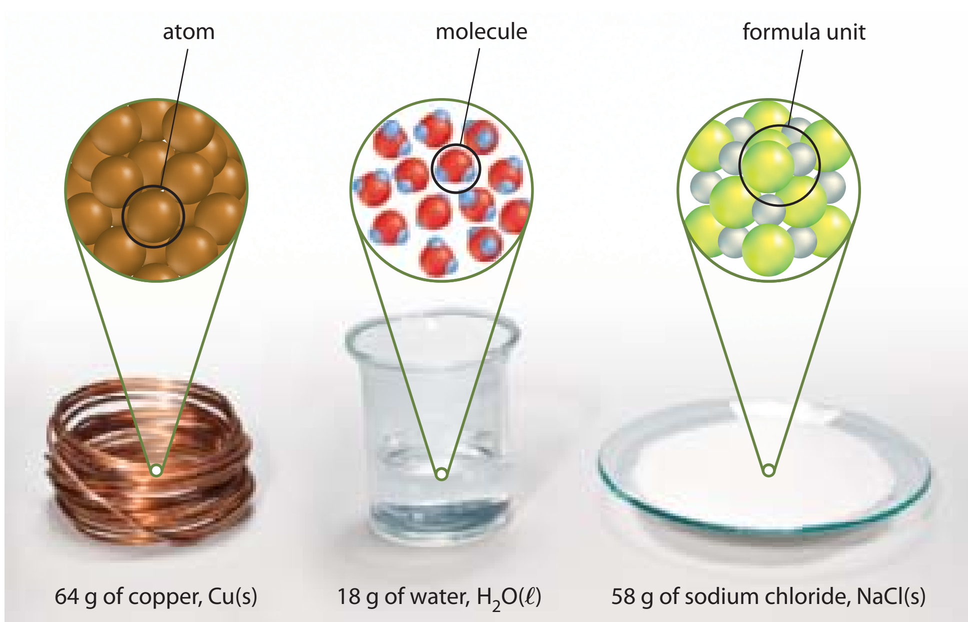


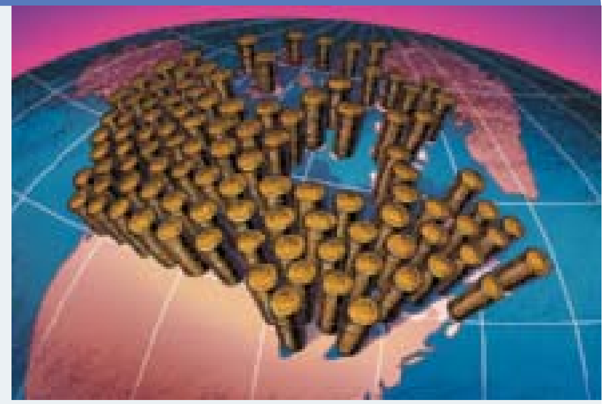
Figure 5.2 Each of these samples contains one mole (1.0 mol) of a different substance.

Figure 5.3 Imagine how many individual grains of sand this beach contains. If a beach contained one mole of sand grains , it would be 1000 m wide, 10 m deep, and 5.5 million km long!

Even though you have seen what a mole of several different substances looks like, it is still sometimes difficult to visualize the size of a mole. For example, try to imagine the size of a beach, like the one in **Figure 5.3**, that contains one mole of grains of sand. Activity 5.1 provides a hands-on example that demonstrates the size of a mole.

Practice working with moles and the Avogadro constant helps to reinforce your understanding of quantities in chemical reactions. Examine the Sample Problem on the next page, and then complete the Practice Problems that follow.

Activity 5.1 One Big Pile of Pennies



Natural Resources Canada states that the area of Canada (land and water) is 9 984 670 km^2. If this entire area were covered with one mole of pennies, how deep do you think the pile would be?

Materials

- 20 pennies
- centimetre ruler

Procedure

1. Stack 20 pennies.
2. Measure the height of the stack. Then measure the diameter of one penny.

Questions

1. Calculate the radius of a penny.
2. Use the formula for the volume of a cylinder, $V = 2\pi r^2 h$, to find the volume of your stack of pennies in cubic centimetres.
3. Use a proportion to find the volume of one mole of pennies in cubic centimetres, using the volume for your stack of pennies.
4. Since the area of Canada is in square kilometres, convert the volume you calculated in step 3 to cubic kilometres.
5. To determine the depth of one mole of pennies spread over Canada, divide the volume you calculated in step 4 by the area of Canada.
6. The land area of Ontario is 1 076 395 km^2. If only Ontario were covered with one mole of pennies, how deep would the pile be?
7. Why do you think chemists work with moles of chemicals when they perform chemical reactions?

Sample Problem

Using the Avogadro Constant

Problem

Earth has an equatorial circumference of 40 076 km. If you lined up 22 grains of salt, end to end, the line would be 1.0 cm long. If you could line up one mole of grains of salt, end to end, around Earth, how many times would the line encircle the planet?

What Is Required?

You need to determine how long a line of 6.02×10^{23} grains of salt is. Then you can figure out how many times the line would encircle Earth.

What Is Given?

You know the length of a line of 22 grains of salt: 1.0 cm
You know the circumference of Earth: 40 076 km

Plan Your Strategy	Act on Your Strategy
Calculate the length of a line of 6.02×10^{23} grains of salt in centimetres.	$6.02 \times 10^{23}\ \cancel{\text{grains}} \times \frac{1.0\ \text{cm}}{22\ \cancel{\text{grains}}}$ $= 2.736\ 36 \times 10^{22}$ cm
Convert the length of the line to kilometres. There are 100 cm in 1 m, and 1000 m in 1 km.	$2.736\ 36\ \text{cm} \times 10^{22}\ \cancel{\text{cm}} \times \frac{1\ \cancel{\text{m}}}{100\ \cancel{\text{cm}}} \times \frac{1\ \text{km}}{1000\ \cancel{\text{m}}}$ $= 2.736\ 36 \times 10^{17}$ km
Calculate the number of times the line would go around Earth.	$2.736\ 36 \times 10^{17}\ \cancel{\text{km}} \times \frac{1\ \text{Earth circumference}}{40\ 076\ \cancel{\text{km}}}$ $= 6.8 \times 10^{12}$ Earth circumferences

Check Your Solution

The units cancelled properly. The size of the final answer seems appropriate.

Practice Problems

1. An average refrigerator has a volume of 0.6 m^3. If a grain of salt has a volume of 9.39×10^{-11} m^3, how many refrigerators would one mole of salt grains fill?
2. If you drove for 6.02×10^{23} days at a speed of 110 km/h, how far would you travel?
3. How long would it take to count 6.02×10^{23} raisins, if you counted at a rate of one raisin per second?
4. A ream of paper (500 sheets) is 4.8 cm high. If you stacked 6.02×10^{23} sheets of paper on top of each other, how high would the stack be, in kilometres?
5. The total volume of the Rogers Centre is 1.6×10^6 m^3. If the volume of 100 peas is about 55 cm^3, how many Rogers Centres would 6.02×10^{23} peas fill?
6. Canada's coastline is 243 042 km long. If you laid 6.02×10^{23} metre sticks end to end along the coast of Canada, how many rows of sticks would there be?
7. Earth's oceans contain about 1.31×10^9 km^3 of water. One tablespoon is equal to 15 cm^3. If you could remove 6.02×10^{23} tablespoons of water from Earth's oceans, would you completely drain them?
8. Suppose that you were given 6.02×10^{23} pennies when you were born and you lived for 100 years. How much money, in dollars, would you have to spend each second if you wanted to spend all this money in your lifetime?
9. How would the mass of pennies you were given in question 8 compare with the mass of Earth? The mass of 10 pennies is about 24 g. The mass of Earth is 5.98×10^{24} kg.
10. If a row of approximately 5.0×10^7 atoms measured 1.0 cm, how long would a row of 6.02×10^{23} atoms be?

From Dozens to Moles

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You have learned how to convert between individual items and dozens of items. Now you are going to use the same steps to work with individual particles and moles of particles. A comparison of dozens and moles is shown in **Figure 5.4**.

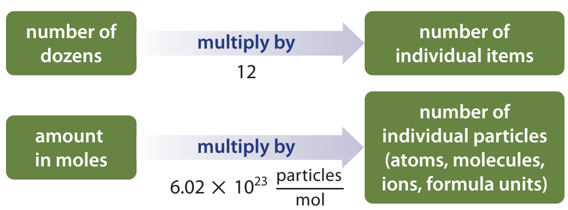

Figure 5.4 This graphic organizer shows how to convert from amount in moles to number of particles.

Converting Moles to Number of Particles

Again, because atoms, molecules, ions, and formula units are so small, chemists work with moles of these particles instead of dozens of them. For example, chemists know that 1 mol of carbon contains 6.02×10^{23} atoms of carbon, and 2 mol of carbon dioxide contains $2 \times 6.02 \times 10^{23} = 1.20 \times 10^{24}$ molecules of carbon dioxide. The relationship between moles, individual particles, and the Avogadro constant can be expressed as

$$n = \frac{N}{N_A}, \text{ where } n \text{ is the amount in moles}$$

N is the number of individual particles
N_A is the Avogadro constant

If you know the amount of particles (in mol) and you want to find the number of individual particles, you can rearrange the above relationship as follows:

$$N = n \times N_A$$

The following Sample Problem demonstrates how to work with this relationship.

Sample Problem

Converting Amount in Moles to Number of Particles

Problem

Hydrazine, $N_2H_4(\ell)$, is a versatile compound that is used in pharmaceuticals, rocket fuels, and airbags. Suppose that a chemical sample in an airbag contains 3.65 mol of hydrazine.

a. How many molecules are in the sample?

b. How many atoms are in the sample?

What Is Required?

You need to find the number of molecules in the hydrazine sample.

You need to find the number of atoms in the hydrazine sample.

What Is Given?

You know the amount of hydrazine: 3.65 mol

You know the Avogadro constant, N_A: 6.02×10^{23}

You know the relationship between moles, individual particles, and the Avogadro constant: $N = n \times N_A$

You know the number of atoms in each hydrazine molecule: two nitrogen atoms + four hydrogen atoms = six atoms total

Plan Your Strategy	Act on Your Strategy
a. Use the relationship between moles, individual particles, and the Avogadro constant to find the number of molecules of hydrazine.	$N = n \times N_A$ $N = 3.65\ \cancel{\text{mol}} \times \dfrac{6.02 \times 10^{23}\text{ molecules}}{1\ \cancel{\text{mol}}}$ $= 2.197\,300 \times 10^{24}$ molecules $= 2.20 \times 10^{24}$ molecules
b. Multiply the number of hydrazine molecules by the number of atoms in each molecule.	$2.197\,300 \times 10^{24}\ \cancel{\text{molecules}} \times \dfrac{6\text{ atoms}}{1\ \cancel{\text{molecule}}}$ $= 1.318\,38 \times 10^{25}$ atoms $= 1.32 \times 10^{25}$ atoms

Check Your Solution

In part a, since 22 is between 3 and 4 times 6.02 (based on comparing 22.0×10^{23} to 6.02×10^{23}), the answer is reasonable.

In part b, since there are 6 times as many atoms as molecules (based on comparing 2.2 to 13.2), the answer is reasonable.

Practice Problems

11. A Canadian penny contains 0.106 mol of copper. How many atoms of copper are in a Canadian penny?

12. The head of a small pin contains about 8×10^{-3} mol of iron. How many iron atoms are in the head of the pin?

13. How many molecules of oxygen gas are in a room that contains 8.5×10^{3} mol of oxygen gas?

14. If a marble countertop contains 849 mol of calcium carbonate, $CaCO_3(s)$, how many formula units of calcium carbonate are in the countertop?

15. A recipe calls for half a teaspoon of salt, which contains 5.23×10^{-2} mol of sodium chloride. How many formula units of sodium chloride are needed?

16. A window-cleaning solution contains 3.86 mol of acetic acid, $CH_3COOH(\ell)$. How many molecules of acetic acid are in the solution?

17. A fuel tank used in a barbecue contains 2.0×10^{2} mol of propane, $C_3H_8(g)$. What is the total number of atoms in the tank?

18. Freon™, $CCl_2F_2(g)$, is a refrigerant that is no longer used in car air conditioners because it damages the ozone layer. A sample contains 4.82 mol of Freon™.

a. How many molecules of Freon™ are in the sample?

b. How many atoms, in total, are in the sample?

19. Glauber's salt is a common name for sodium sulfate decahydrate, $Na_2SO_4 \cdot 10H_2O(s)$. It is used in the manufacture of detergents. Suppose that a sample of 36.2 mol of sodium sulfate decahydrate is required.

a. What number of sodium atoms would be in the sample?

b. What number of water molecules would be in the sample?

20. A sample of sucrose, $C_{12}H_{22}O_{11}(s)$, contains 0.16 mol of oxygen, atoms (O).

a. What amount in moles of sucrose is in the sample?

b. How many atoms of carbon are in the sample?

Figure 5.5 Even though there seem to be a lot of bubbles in a soft drink, there is only about 0.1 mol of carbon dioxide in 1 L.

***Determine** the number of carbon dioxide molecules in 1 L of a soft drink.*

Converting Number of Particles to Amount in Moles

As mentioned earlier, working with individual particles of different chemicals is not practical for chemists in a lab. Instead, chemists work with amounts in moles of chemicals. So, rather than describing a particular sample of carbon dioxide, as 2.4×10^{24} molecules of carbon dioxide, chemists describe it as 4.0 mol of carbon dioxide. Similarly, in the equation for a chemical reaction, the coefficients can represent the amount in moles of chemicals that react. Moles can also be used to describe the amount of carbon dioxide in a soft drink, such as the one in **Figure 5.5**.

To convert from individual particles to moles of particles, you can use the relationship involving the Avogadro constant, which you learned earlier:

$$n = \frac{N}{N_A}$$

This conversion is illustrated in **Figure 5.6**. The following Sample Problem demonstrates how to use it.

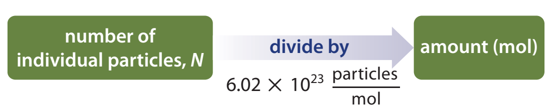

Figure 5.6 The Avogadro constant is used to convert individual particles to moles of particles, and vice versa.

Sample Problem

Converting Number of Particles to Amount in Moles

Problem

A commercial product that people sometimes take to settle an upset stomach contains magnesium hydroxide, $Mg(OH)_2(aq)$, a base. If a teaspoon of stomach medicine contains 4.1×10^{21} formula units of magnesium hydroxide, what amount in moles of magnesium hydroxide is in the teaspoon?

What Is Required?

You are asked to find the amount in moles in a sample of magnesium hydroxide.

What Is Given?

You know the number of formula units: 4.1×10^{21}.

You know the Avogadro constant: 6.02×10^{23}.

You know that you need to use the following relationship: $n = \frac{N}{N_A}$.

Plan Your Strategy	Act on Your Strategy
Write the relationship between moles, individual particles, and the Avogadro constant. Substitute the known values into the formula.	$n = \frac{N}{N_A}$ $= \frac{4.1 \times 10^{21} \text{ formula units}}{6.02 \times 10^{23} \text{ formula units/mol}}$ $= 6.8 \times 10^{-3}$ mol

Check Your Solution

If you substitute your answer back into the relationship $N = n \times N_A$, the answer is the same as the given number of formula units.

Practice Problems

21. A gold coin contains 9.51×10^{22} atoms of gold. What amount in moles of gold is in the coin?

22. A patient in a dentist's office is given 1.67×10^{23} molecules of dinitrogen monoxide (laughing gas), $N_2O(g)$, during a procedure. What amount in moles of dinitrogen monoxide is the patient given?

23. A sheet of drywall contains 1.2×10^{26} formula units of gypsum (calcium sulfate dihydrate), $CaSO_4{\bullet}2H_2O(s)$. What amount in moles of gypsum is in the sheet of drywall?

24. Limewater, a weak solution of calcium hydroxide, $Ca(OH)_2(s)$, is used to detect the presence of carbon dioxide gas. Suppose that you are given a solution that contains 8.7×10^{19} formula units of calcium hydroxide. What amount in moles of calcium hydroxide is in the solution?

25. If there are a total of 7.3×10^{29} atoms in a sample of glucose, $C_6H_{12}O_6$ (s), what amount in moles of glucose is in the sample?

26. A sample of aluminum oxide, $Al_2O_3(s)$, contains 8.29×10^{25} total atoms. Calculate the amount in moles of aluminum oxide in the sample. **Hint:** This is a two-step problem. Calculate the number of formula units first.

27. Trinitrotoluene, or TNT for short, has the chemical formula $C_7H_5N_3O_6(s)$. If a stick of dynamite is pure TNT and it contains 2.5×10^{25} atoms in total, what amount in moles of TNT does it contain?

28. A sample of rubbing alcohol solution contains ethanol, $C_2H_5OH(\ell)$. If the sample contains 1.25×10^{23} atoms of hydrogen in the ethanol, what amount in moles of ethanol is in the sample?

29. A cleaning solution contains 7.9×10^{26} molecules of ammonia, $NH_3(aq)$. What amount in moles of ammonia is in the solution?

30. A muffin recipe calls for cream of tartar, or potassium hydrogen tartrate, $KHC_4H_4O_6(s)$. The amount of cream of tartar that is required contains 2.56×10^{23} atoms of carbon. What amount in moles of potassium hydrogen tartrate is required?

Section 5.1 REVIEW

Section Summary

- People group common items into units of quantity for convenience. Chemists also group atoms, molecules, ions, and formula units into units of quantity for convenience.
- A mole is the amount of substance that contains as many particles (atoms, molecules, ions, or formula units) as the number of atoms in exactly 12 g of the isotope carbon-12.
- The mole is the SI base unit that is used to measure the amount of a substance.
- Chemists use the mole to count very small particles, such as atoms, molecules, ions, and formula units.
- The Avogadro constant allows chemists to convert back and forth between individual particles and moles of particles.

Review Questions

1. K/U Define "mole" in your own words. Use an example to illustrate your definition.
2. K/U Compare a mole and a dozen. Provide one similarity and one difference.
3. K/U Is the value that is presently accepted for the mole, $6.022\ 141\ 79 \times 10^{23}$ particles, an exact number? Explain.
4. T/I If the volume of one mole of water at room temperature is 18.02 mL, what is the volume of one molecule of water, in litres?
5. C Use a flowchart to show the process of converting moles of phosphorus, $P_4(s)$, to atoms of phosphorus.
6. T/I Calculate the number of formula units of sodium chloride in 0.0578 mol.
7. T/I Calculate the number of particles in each sample. Indicate the correct type of particle (atom, molecule, ion, or formula unit).
   a. 0.156 mol Au(s)
   b. 7.8 mol $MgCl_2(s)$
   c. 15.2 mol $H_2O_2(\ell)$
8. T/I Calculate the amount in moles of molecules for each substance listed.
   a. a sample of ammonia, $NH_3(g)$, containing 8.1×10^{20} atoms of hydrogen
   b. a sample of diphosphorus pentoxide, $P_2O_5(s)$, containing a total of 4.91×10^{22} atoms of phosphorus and oxygen
9. T/I A sample of ethanol, $C_2H_5OH(\ell)$, contains 2.49×10^{23} molecules of ethanol. A sample of carbon contains 1.65 mol of carbon atoms. Which sample, the ethanol or the carbon, contains the greater amount in moles of carbon?
10. T/I If there are 4.28×10^{21} atoms of hydrogen and oxygen in a sample of water, what amount in moles of water is in the sample?
11. A Aluminum oxide, $Al_2O_3(s)$, forms a thin coating on an aluminum surface, such as the body of an airplane, when aluminum is exposed to oxygen in air. This coating helps to reduce further corrosion of the aluminum. Suppose that a sample contains 2.6 mol of aluminum oxide.
    a. How many formula units are in the sample?
    b. How many atoms, in total, are in the sample?
    c. How many aluminum atoms are in the sample?

12. A Zinc chloride hexahydrate, $ZnCl_2{\bullet}6H_2O(s)$, is used in the textile industry, often to prepare fireproofing agents. In a particular fireproofing solution, 0.46 mol of zinc chloride hexahydrate is used.
    a. How many formula units of zinc chloride hexahydrate are in the solution?
    b. How many atoms of chlorine are in the solution?
13. C Draw a graphic organizer that shows the conversions between number of particles and amount in moles.
14. A Arrange the following three samples from largest to smallest in terms of their numbers of representative particles:
    - 3.92 mol of octane, $C_8H_{18}(\ell)$
    - 6.52×10^{23} atoms of copper, Cu(s)
    - 1.25×10^{24} formula units of sodium hydrogen carbonate, $NaHCO_3(s)$.
15. T/I Calculate the number of atoms in 6.0 mol of fluorine, $F_2(g)$, molecules.