01

# CHEMICAL FOUNDATIONS

## C. ATOMIC MASS, MOLAR MASS, & THE MOLE

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# ATOMIC MASS

**Objective:** *How to think about atomic mass*

Atoms are incredibly small and incredibly light. As such, the mass of any single atom, or even a single molecule, is an incredibly small number.

For example, consider that the mass of a single hydrogen atom is $1.674 \times 10^{-24}$ grams (g). Rather inconveniently, the periodic table of elements reports the measured *average* mass of atoms in atomic mass units (amu), so a single hydrogen atom weighs, on average, 1.008 amu.

Neither the mass in amu nor the mass in grams of a *single* atom is very practical because you will likely never work with samples on this scale.

But the gram is a fairly convenient unit of mass in a lab setting. So, in practice, it would be beneficial if the masses reported on the periodic table *could* represent gram amounts.

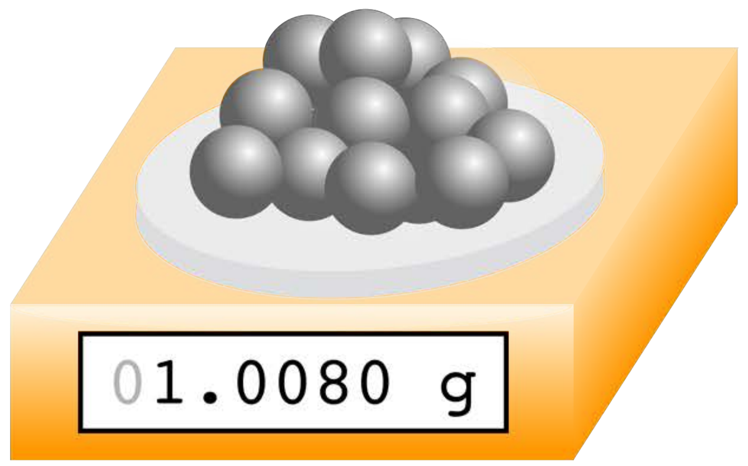
For instance, we would like

| | | |
|---|---|---|
| Hydrogen | to have a mass of | 1.008 g |
| Carbon | to have a mass of | 12.01 g |

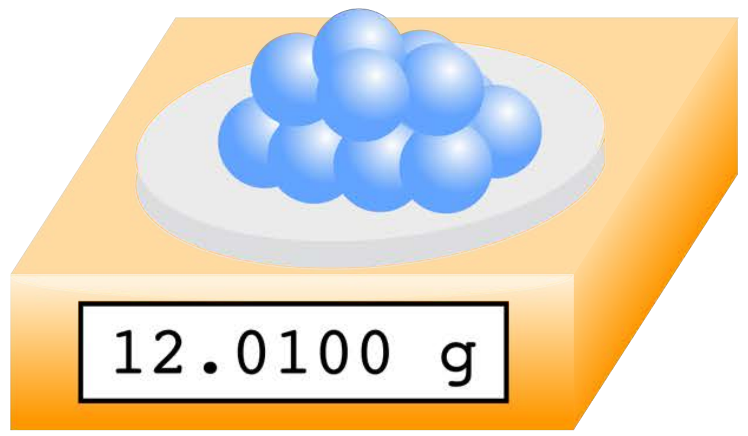
But how can we accomplish this?

Imagine two scales. Let's say we place hydrogen and carbon atoms, one by one, until the scale reads exactly 1.008 g and 12.01 g, respectively. How many atoms of each did this take?

**Hydrogen**



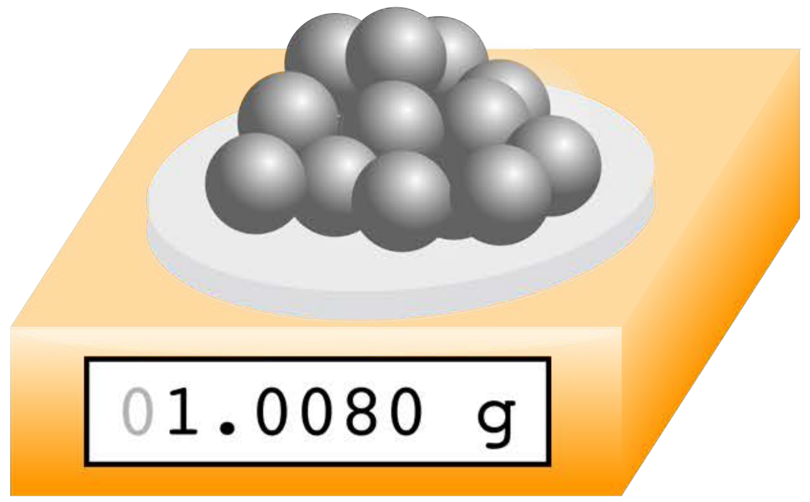

**Carbon**



# THE MOLE & AVOGADRO'S NUMBER

**Objective:** *Understand the concept of a mole*
*Understand the relationship between the mole and Avogadro's number/constant*

Let's figure out how many atoms of hydrogen were needed in order for this scale to read $1.008$ g.




We can determine this by using the mass of a single H atom:

$$1.008 \text{ g H} \times \frac{1 \text{ atom H}}{1.674 \times 10^{-24} \text{ g}} = 6.022 \times 10^{23} \text{ atoms H}$$

If we had solved for the number of carbon atoms, we would also find that we need $6.022 \times 10^{23}$ atoms of carbon.

Actually, if we have $6.022 \times 10^{23}$ atoms of any element, we would get a mass equal to its atomic mass but in grams. This constant quantity is referred to as Avogadro's number.

$$N_A = 6.022 \times 10^{23} \frac{\text{particles}}{\text{mol}}$$

Avogadro's number also defines the mole (mol), which is the unit of amount of substance equal to $6.022 \times 10^{23}$ particles (such as atoms, ions, molecules, nuclei, etc.).

In a lab setting, we are often working with very large numbers of atoms or molecules, so the mole becomes a much more practical unit to work with.

# MOLAR MASS

**Objective:** *Be able to determine molar mass*

So, very rarely will we ever work with atomic mass, the mass in amu of a single atom. Almost always, we are interested in the molar mass (or atomic weight), the mass in grams of 1 mole of atoms.

$$\begin{array}{lclcl} 1.008\text{ g H} & = & 6.022\times 10^{23}\text{ atoms H} & = & 1\text{ mol H} \\ 12.01\text{ g C} & = & 6.022\times 10^{23}\text{ atoms C} & = & 1\text{ mol C} \\ 16.00\text{ g O} & = & 6.022\times 10^{23}\text{ atoms O} & = & 1\text{ mol O} \\ 14.01\text{ g N} & = & 6.022\times 10^{23}\text{ atoms N} & = & 1\text{ mol N} \end{array}$$

### Concept Question

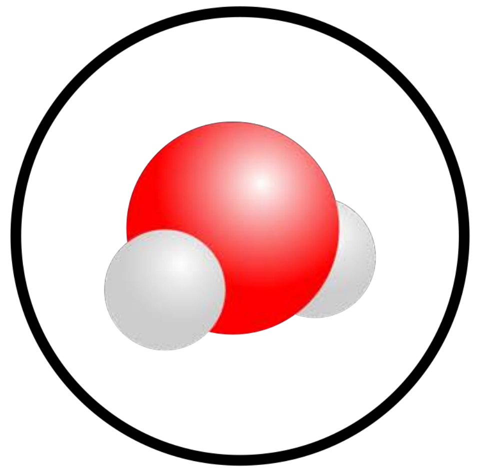
**Which sample contains a greater number of atoms?**

**10 g Cu or 10 g Mg**

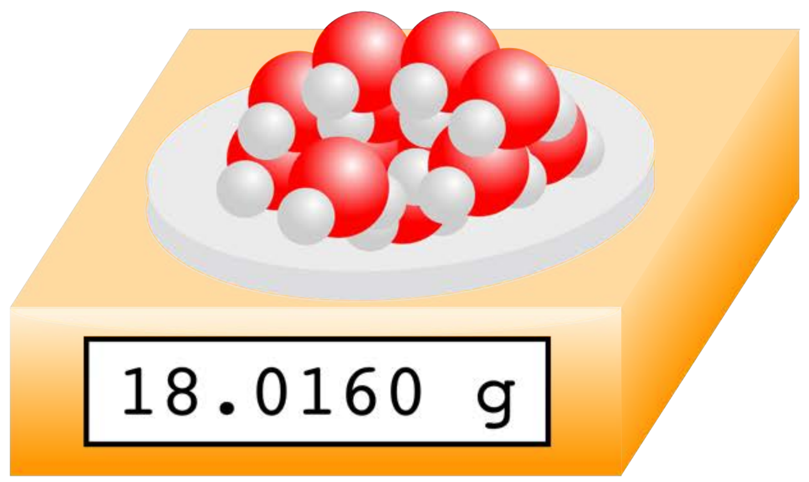
The Mg sample since each Mg atom (63.55 amu or g/mol) weighs more than each Cu atom (24.30 amu or g/mol).

The concepts of the mole and molar mass are also extendable to molecules since we will rarely work with single molecules.

**1 molecule $H_2O$**



**1 mole $H_2O$**




The mass of 1 molecule of water is:

$$\begin{array}{lclcl} 1\text{ molecule }H_2O & = & 2\text{ atoms H} & + & 1\text{ atom O} \\ & = & 2\times(1.008\text{ amu}) & + & 1\times(16.00\text{ amu}) \\ 1\text{ molecule }H_2O & = & 18.016\text{ amu} & & \end{array}$$

The mass of 1 mole of water (its *molar mass*) is:

$$\begin{array}{lclcl} 1\text{ mole }H_2O & = & 2\text{ mol H} & + & 1\text{ mol O} \\ & = & 2\times(1.008\text{ g}) & + & 1\times(16.00\text{ g}) \\ 1\text{ mole }H_2O & = & 18.016\text{ g} & & \end{array}$$

# PROBLEMS

## Fundamental Concepts

1. Determine the number of atoms in a $10.0$ g sample of Cu and a $10.0$ g sample of Mg.

2. What is the total mass (in units of grams) of $8.65 \times 10^{22}$ atoms of Ni?

3. Determine the molar masses of cobalt (III) sulfate and glucose ($C_{12}H_{22}O_{11}$).

4. What is the total mass (in units of grams) of $4.86$ mol calcium carbonate? How many moles are in a $25.0$ g sample of ammonium carbonate?

5. Calculate the number of molecules in $175$ g $P_4O_{10}$.

## Problem-Solving Skills

6. What mass, in grams, of Ag would contain the same number of atoms as a $5.00$ g sample of Ca?

7. How many atoms are present in $50.0$ g water?

8. One molecule of a *molecular element* has a mass of $4.65 \times 10^{-23}$ g. What is the chemical formula?

9. How many grams of carbon are contained in a $13.25$ g sample of carbon suboxide ($C_3O_2$)?

10. Which of the following sample contains the greatest number of moles of substance?

    i. $5.0$ g Fe
    ii. $5.0$ g He
    iii. $5.0 \times 10^{23}$ atoms Ne
    iv. $5.0 \times 10^{-2}$ mol B
    v. $5.0$ mg Ca

# PROBLEM 1

Determine the number of atoms in a 10.0 g sample of Cu and a 10.0 g sample of Mg.

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

First, using the periodic table, determine that the molar masses of Cu and Mg are 63.55 g/mol and 24.31 g/mol, respectively.

Because the molar mass gives us the mass of 1 mol of each sample, we can convert from the mass (in g) to the number of moles:

$$10.0\ \mathrm{g\ \cancel{Cu}} \times \frac{1\mathrm{mol\ Cu}}{63.55\ \cancel{\mathrm{g}}} = 0.157_4\ \mathrm{mol\ Cu} \quad \& \quad 10.0\ \mathrm{g\ \cancel{Mg}} \times \frac{1\ \mathrm{mol\ Mg}}{24.31\ \cancel{\mathrm{g}}} = 0.411_4\ \mathrm{mol\ Mg}$$

Now we can use Avogadro's number to determine the number of atoms for each sample.

$$0.157_4\ \cancel{\mathrm{mol}}\ \mathrm{Cu} \times \frac{6.022 \times 10^{23}\ \mathrm{atoms\ Cu}}{1\ \cancel{\mathrm{mol}}} = 9.48 \times 10^{22}\ \mathrm{atoms\ Cu} \quad \& \quad 0.411_4\ \cancel{\mathrm{mol}}\ \mathrm{Mg} \times \frac{6.022 \times 10^{23}\ \mathrm{atoms\ Mg}}{1\ \cancel{\mathrm{mol}}} = 2.48 \times 10^{23}\ \mathrm{atoms\ Mg}$$

More often we will perform these types of conversions in one step rather than two explicit steps as shown above.

$$10.0\ \mathrm{g\ \cancel{Cu}} \times \frac{1\cancel{\mathrm{mol}}\ \mathrm{Cu}}{63.55\ \cancel{\mathrm{g}}} \times \frac{6.022 \times 10^{23}\ \mathrm{atoms\ Cu}}{1\ \cancel{\mathrm{mol}}} = 9.48 \times 10^{22}\ \mathrm{atoms\ Cu}$$

$$10.0\ \mathrm{g\ \cancel{Mg}} \times \frac{1\ \cancel{\mathrm{mol}}\ \mathrm{Mg}}{24.31\ \cancel{\mathrm{g}}} \times \frac{6.022 \times 10^{23}\ \mathrm{atoms\ Mg}}{1\ \cancel{\mathrm{mol}}} = 2.48 \times 10^{23}\ \mathrm{atoms\ Mg}$$

# PROBLEM 2

What is the total mass (in units of grams) of $8.65 \times 10^{22}$ atoms of Ni?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

First, using the periodic table, determine that the molar masses of Ni is $58.69$ g/mol.

We can use Avogadro's number to determine the number of moles of the sample.

$$8.65 \times 10^{22} \text{ \cancel{atoms} Ni} \times \frac{1 \text{ mol Ni}}{6.022 \times 10^{23} \text{ \cancel{atoms}}} = 0.143_6 \text{ mol Ni}$$

Because the molar mass gives us the mass of 1 mol of each sample, we can convert from the number of moles to the total mass:

$$0.143_6 \text{ \cancel{mol} Ni} \times \frac{58.69 \text{ g}}{1 \text{ \cancel{mol} Ni}} = 8.43 \text{ g Ni}$$

More often we will perform these types of conversions in one step rather than two explicit steps as shown above.

$$8.65 \times 10^{22} \text{ \cancel{atoms} Ni} \times \frac{1 \text{ \cancel{mol} Ni}}{6.022 \times 10^{23} \text{ \cancel{atoms}}} \times \frac{58.69 \text{ g}}{1 \text{ \cancel{mol} Ni}} = 8.43 \text{ g Ni}$$

# PROBLEM 3

Determine the molar masses of cobalt (III) sulfate and glucose ($C_{12}H_{22}O_{11}$).

***— answer —***

**Objective:** *Be able to determine the molar masses of molecular and ionic compounds*

First, realize that the chemical formula for cobalt (III) sulfate is $Co_2(SO_4)_3$. This means that 1 mol $Co_2(SO_4)_3$ and 1 mol $C_{12}H_{22}O_{11}$ are composed of:

$$1 \text{ mole } Co_2(SO_4)_3 = 2 \text{ mol Co} + 3 \text{ mol S} + 12 \text{ mol O}$$

$$1 \text{ mole } C_{12}H_{22}O_{11} = 12 \text{ mol C} + 22 \text{ mol H} + 11 \text{ mol O}$$

Therefore, we can find that the molar mass of cobalt (III) sulfate is 406.04 g/mol and the molar mass of glucose is 343.30 g/mol.

$$\begin{array}{lcccr}
2 \text{ mol Co} & \rightarrow & 2\ \mathrm{mol\ Co} \times \dfrac{58.93\ \mathrm{g}}{1\ \mathrm{mol\ Co}} & = & 117.86\ \mathrm{g} \\
3 \text{ mol S} & \rightarrow & 3\ \mathrm{mol\ S} \times \dfrac{32.06\ \mathrm{g}}{1\ \mathrm{mol\ S}} & = & 96.18\ \mathrm{g} \\
12 \text{ mol O} & \rightarrow & 12\ \mathrm{mol\ O} \times \dfrac{16.00\ \mathrm{g}}{1\ \mathrm{mol\ O}} & = & 192.00\ \mathrm{g} \\
\hline
 & & & & 406.04\ \mathrm{g}
\end{array}$$

$$\begin{array}{lcccr}
12 \text{ mol C} & \rightarrow & 12\ \mathrm{mol\ C} \times \dfrac{12.01\ \mathrm{g}}{1\ \mathrm{mol\ C}} & = & 144.12\ \mathrm{g} \\
22 \text{ mol H} & \rightarrow & 22\ \mathrm{mol\ S} \times \dfrac{1.008\ \mathrm{g}}{1\ \mathrm{mol\ H}} & = & 22.176\ \mathrm{g} \\
11 \text{ mol O} & \rightarrow & 11\ \mathrm{mol\ O} \times \dfrac{16.00\ \mathrm{g}}{1\ \mathrm{mol\ O}} & = & 176.00\ \mathrm{g} \\
\hline
 & & & & 342.30\ \mathrm{g}
\end{array}$$

# PROBLEM 4

What is the total mass (in units of grams) of 4.86 mol calcium carbonate? How many moles are in a 25.0 g sample of ammonium carbonate?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

First, realize that the chemical formulas for calcium carbonate and ammonium carbonate are $CaCO_3$ and $Al_2(CO_3)_3$, respectively.

Second, using the periodic table, determine that the molar masses of $CaCO_3$ and $Al_2(CO_3)_3$ are 100.09 g/mol and 233.99 g/mol, respectively.

Because the molar mass gives us the mass of 1 mol of each sample, we can convert between mass (in g) and the number of moles:

$$4.86\ \cancel{\text{mol CaCO}_3} \times \frac{100.09\ \text{g}}{1\ \cancel{\text{mol CaCO}_3}} = 486\ \text{g CaCO}_3$$

$$25.0\ \cancel{\text{g Al}_2(\text{CO}_3)_3} \times \frac{1\ \text{mol Al}_2(\text{CO}_3)_3}{233.99\ \cancel{\text{g}}} = 0.107\ \text{mol Al}_2(\text{CO}_3)_3$$

# PROBLEM 5

Calculate the number of molecules in 175 g $P_4O_{10}$.

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

First, using the periodic table, determine that the molar mass of $P_4O_{10}$ is 283.88 g/mol.

Since the molar mass gives us the mass of 1 mol of $P_4O_{10}$, we can convert from the total mass to the number of moles:

$$175\ \text{g}\ \cancel{\text{P}_4\text{O}_{10}} \times \frac{1\ \text{mol}\ \text{P}_4\text{O}_{10}}{283.88\ \cancel{\text{g}}} = 0.616_5\ \text{mol}\ \text{P}_4\text{O}_{10}$$

We can use Avogadro's number to determine the number of molecules in the sample.

$$0.616_5\ \text{mol}\ \cancel{\text{P}_4\text{O}_{10}} \times \frac{6.022 \times 10^{23}\ \text{molecules}\ \text{P}_4\text{O}_{10}}{1\ \cancel{\text{mol}}} = 3.71 \times 10^{23}\ \text{molecules}\ \text{P}_4\text{O}_{10}$$

More often we will perform these types of conversions in one step rather than two explicit steps as shown above.

$$175\ \text{g}\ \cancel{\text{P}_4\text{O}_{10}} \times \frac{1\ \text{mol}\ \cancel{\text{P}_4\text{O}_{10}}}{283.88\ \cancel{\text{g}}} \times \frac{6.022 \times 10^{23}\ \text{molecules}\ \text{P}_4\text{O}_{10}}{1\ \cancel{\text{mol}}} = 3.71 \times 10^{23}\ \text{molecules}\ \text{P}_4\text{O}_{10}$$

# PROBLEM 6

What mass, in grams, of Ag would contain the same number of atoms as a 5.00 g sample of Ca?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

We have to determine how many atoms are in a 5.00 g sample of Ca using its molar mass (40.08 g/mol).

$$5.00\ \cancel{\text{g Ca}} \times \frac{1\ \cancel{\text{mol}}\ \text{Ca}}{40.08\ \cancel{\text{g}}} \times \frac{6.022 \times 10^{23}\ \text{atoms Ca}}{1\ \cancel{\text{mol}}} = 7.51_2 \times 10^{23}\ \text{atoms Ca}$$

Now, we can find determine how much an equivalent number of atoms of Ag would weigh, in grams, using its molar mass (107.9 g/mol).

$$7.51_2 \times 10^{23}\ \cancel{\text{atoms}}\ \text{Ag} \times \frac{1\ \cancel{\text{mol}}\ \text{Ag}}{6.022 \times 10^{23}\ \cancel{\text{atoms}}} \times \frac{107.9\ \text{g}}{1\ \cancel{\text{mol}}\ \text{Ag}} = 13.5\ \text{g Ag}$$

*Note: It should be expected that the mass of the Ag sample would weigh more than the mass of the Ca sample because each atom (or each mole) of Ag weighs more than each atom (or each mole) of Ca.*

# PROBLEM 7

How many atoms are present in 50.0 g water?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

We have to determine how many molecules of $H_2O$ are in a 50.0 g sample of $H_2O$ using its molar mass (18.016 g/mol).

$$50.0\ \text{g}\ \cancel{\text{H}_2\text{O}} \times \frac{1\ \cancel{\text{mol}}\ \text{H}_2\text{O}}{18.016\ \cancel{\text{g}}} \times \frac{6.022 \times 10^{23}\ \text{molecules H}_2\text{O}}{1\ \cancel{\text{mol}}} = 1.67_1 \times 10^{24}\ \text{molecules H}_2\text{O}$$

Because there are 3 atoms (2 atoms of H and 1 atom of O) in 1 molecule of $H_2O$:

$$1.67_1 \times 10^{24}\ \cancel{\text{molecules}}\ \text{H}_2\text{O} \times \frac{3\ \text{atoms}}{1\ \cancel{\text{molecule}}\ \text{H}_2\text{O}} = 5.01 \times 10^{24}\ \text{atoms}$$

# PROBLEM 8

One molecule of a *molecular element* has a mass of $4.65 \times 10^{-23}$ g. What is the chemical formula?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

*Understand what a molecular element is*

*Be able to use the molar mass to identify an element*

A molecular element is an element that exists as a molecule, such as the nonmetal diatomics ($H_2$, $O_2$, $N_2$, $Cl_2$, $Br_2$, $I_2$, and $F_2$) and the nonmetal polyatomics ($P_4$ and $S_8$). This is in contrast to atomic elements, such as the metals and semi-metals on the periodic table, which exist as single atoms.

We are given the mass of $1$ molecule (units of g/molecule). We can use Avogadro's number/constant to convert this from the mass per molecule to the mass per mole, which is the molar mass of the unknown molecular element.

$$\frac{4.65 \times 10^{-23}\ \text{g}}{1\ \cancel{\text{molecule}}} \times \frac{6.022 \times 10^{23}\ \cancel{\text{molecules}}}{1\ \text{mol}} = 28.0\ \frac{\text{g}}{\text{mol}}$$

With a molar mass of $28.0$ g/mol, the identity of the molecular element is most likely $N_2$.

# PROBLEM 9

How many grams of carbon are contained in a 13.25 g sample of carbon suboxide ($C_3O_2$)?

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

We have to determine how many molecules of $C_3O_2$ are in a 13.25 g sample using its molar mass (68.03 g/mol).

$$13.25\ \text{g}\ \cancel{\text{C}_3\text{O}_2} \times \frac{1\ \cancel{\text{mol}}\ \text{C}_3\text{O}_2}{68.03\ \cancel{\text{g}}} \times \frac{6.022\times10^{23}\ \text{molecules}\ \text{C}_3\text{O}_2}{1\ \cancel{\text{mol}}} = 1.17_3\times10^{23}\ \text{molecules}\ \text{C}_3\text{O}_2$$

Because there are 3 atoms of C in 1 molecule of $C_3O_2$:

$$1.17_3\times10^{23}\ \cancel{\text{molecules}}\ \text{C}_3\text{O}_2 \times \frac{3\ \text{atoms C}}{1\ \cancel{\text{molecule}}\ \text{C}_3\text{O}_2} = 3.51_9\times10^{23}\ \text{atoms C}$$

Finally, we can use the molar mass of C (12.01 g/mol) and Avogadro's number to find the total mass of carbon in the sample.

$$3.51_9\times10^{23}\ \cancel{\text{atoms}}\ \text{C} \times \frac{1\ \cancel{\text{mol}}\ \text{C}}{6.022\times10^{23}\ \cancel{\text{atoms}}} \times \frac{12.01\ \text{g}}{1\ \cancel{\text{mol}}\ \text{C}} = 7.02\ \text{g C}$$

*Note: We could have solved this problem using mass percentages, which will be shown in the corresponding section.*

# PROBLEM 10

Which of the following sample contains the greatest number of moles of substance?

i. $5.0$ g Fe
ii. $5.0$ g He
iii. $5.0 \times 10^{23}$ atoms Ne
iv. $5.0 \times 10^{-2}$ mol B
v. $5.0$ mg Ca

***– answer –***

**Objective:** *Be able to use the molar mass to convert between the number of moles and the mass of a sample*

*Be able to use Avogadro's number/constant to convert between the number of moles and the number of atoms/molecules/particles*

Choice (iii) is actually fairly close to the value of Avogadro's number ($6.022 \times 10^{23}$), so it is ~$1$ mol but is also slightly *less than* $1$ mol.

We can then immediately eliminate choices (iv) and (v) because these are both very small numbers relative to choice (iii).

Now, we can set up the conversion from mass to moles for choices (i) and (ii) to find the best answer:

$$5.0\ \text{g Fe} \times \frac{1\ \text{mol Fe}}{55.85\ \text{g}} = 0.090\ \text{mol Fe} \quad \& \quad 5.0\ \text{g He} \times \frac{1\ \text{mol He}}{4.00\ \text{g}} = 1.3\ \text{mol He}$$

Choice (ii) contains the greatest number of moles. You should realize that you did not need to actually compute any of the numbers because only choices (ii) and (iii) were ~1 mol, but choice (ii) >1 mol and choice (iii) <1 mol.