

Formula Weight Calculations

David A. Katz

Department of Chemistry

Pima Community College

THE MEANING OF A CHEMICAL FORMULA

- A chemical formula is a shorthand method of representing the elements in a compound.
- The formula shows:
 - the formulas of the elements in the compound
 - the ratio of the elements to one another.
 - For example, the formula for sodium chloride



tells us that the compound is composed of the elements sodium, Na, and chlorine, Cl, in a one-to-one ratio. That is, one atom of sodium combines with one atom of chlorine.

- When elements combine in different ratios, **subscripts** are added, following the element symbol, to indicate that the number of atoms of that element in the compound if it is greater than one.
- The subscript refers only to the element it immediately follows. For example, the formula for magnesium bromide:



tells us that two bromine atoms combine with one magnesium atom.

- Some elements form stable groups, or **polyatomic ions**, that combine with other elements to form compounds. An example of this is the sulfate polyatomic ion in the compound calcium sulfate:



- In this compound, the SO_4 is called a *sulfate* group or *sulfate polyatomic ion*.
- It consists of one sulfur atom combined with four oxygen atoms.
- The sulfate group cannot exist by itself and must be combined with another element.
- The compound CaSO_4 consists of one calcium atom combined with one sulfate group. Counting atoms, calcium sulfate consists of one calcium atom, one sulfur atom, and four oxygen atoms.

- Another example of an atom combined with a polyatomic ion is barium nitrate:



- This compound consists of a barium atom combined with two nitrate groups.
- Since NO_3 is readily identified as a nitrate group, and barium combines with two nitrates, parentheses are placed around the nitrate and the subscript 2 indicates two nitrate groups.
- Changing the subscripts in the nitrate to N_2O_6 would change the meaning of the formula and is incorrect.
- Counting atoms, barium nitrate consists of one barium atom, two nitrogen atoms, and six oxygen atoms.

- In the compound zinc phosphate:



the polyatomic ion is phosphate, PO_4 .

- In this example, three atoms of zinc combine with two phosphate groups.
- Counting atoms, there are three atoms of zinc, two atoms of phosphorus, and eight atoms of oxygen.

- The compound copper(II) sulfate pentahydrate is a hydrated compound:



- The compound contains water molecules as part of its crystal structure.
- CuSO_4 and H_2O are two separate compounds.
- The polyatomic ion is sulfate, SO_4 .
- In this example, one atom of copper combines with one sulfate group.
- One copper sulfate unit combines with five water molecules.
- Counting atoms, there is one atom of copper, one atom of sulfur, four atoms of oxygen, ten atoms of hydrogen and five more atoms of oxygen (in the water).

**Symbol indicates
the element
sodium**

**Symbol indicates
the element
chlorine**



**No subscripts indicate
only one atom of each
element**

Symbol indicates
the element
magnesium

Symbol indicates
the element
bromine



No subscript
indicates only one
atom of magnesium

Subscript indicates
two atoms of
bromine

Symbol indicates
the element
calcium

Formula indicates
the polyatomic
ion sulfate



Subscript indicates
four atoms of
oxygen in one
sulfate

No subscript
indicates only one
atom of calcium

No subscript
indicates only one
atom of sulfur in
sulfate

Symbol
indicates the
element barium

Formula indicates
the nitrate
polyatomic ion

Subscript indicates
two nitrate
polyatomic ions



No subscript indicates
only one atom of
barium

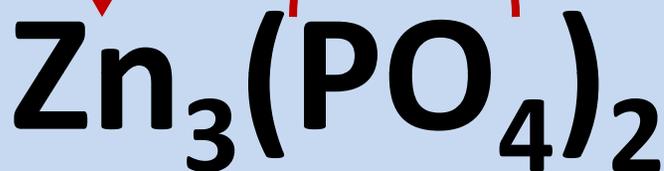
No subscript
indicates only one
atom of nitrogen
in nitrate

Subscript indicates
three atoms of
oxygen in one
nitrate

Symbol
indicates the
element zinc

Formula indicates
the phosphate
polyatomic ion

Subscript indicates
two phosphate
polyatomic ions



Subscript indicates
three atoms of zinc

No subscript
indicates only one
atom of
phosphorous
in phosphate

Subscript indicates
four atoms of
oxygen in one
phosphate

Symbol indicates the element copper

Formula indicates the sulfate polyatomic ion

Dot indicates copper sulfate and water are linked together



No subscript indicates one atom of copper

No subscript indicates only one atom of sulfur in sulfate

Subscript indicates four atoms of oxygen in one sulfate

Coefficient indicates five molecules of water

CALCULATING A FORMULA WEIGHT OR MOLECULAR WEIGHT

- The **formula weight** of a substance (element or compound) is the sum of the atomic weights of all the atoms in the chemical formula of the substance.
- A **molecular weight** of a substance is the sum of all the atomic weights of all the atoms in a molecule of a molecular substance.
- The terms formula weight and molecular weight are often used interchangeably, but **formula weight includes simple or empirical formulas of compounds, as well as, molecular formulas.**

To calculate the formula weight or molecular weight of a compound:

- 1. Determine the number of atoms of each element in the compound**
- 2. Look up the atomic weights of each element**
- 3. Multiply the atomic weight by the number of atoms of that element**
- 4. Add the products of the atomic weights of all the atoms**

1. Calculate the formula weight of sodium chloride, NaCl.

Answer:

Set up a table listing the elements in the compound, the number of atoms of each element, and the atomic weight of each element.

Elements in the compound	Number of atoms of each element	Atomic weight
Na	1	23.0
Cl	1	35.5

Elements in the compound	Number of atoms of each element	Atomic weight
Na	1	23.0
Cl	1	35.5

Multiply the number of atoms times the atomic weight to get the total mass of each element:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Na	1	x	23.0	=	23.0
Cl	1	x	35.5	=	35.5

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Na	1	x	23.0	=	23.0
Cl	1	x	35.5	=	35.5

Add the total masses:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Na	1	x	23.0	=	23.0
Cl	1	x	35.5	=	35.5

Formula weight = 58.5

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Na	1	x	23.0	=	23.0
Cl	1	x	35.5	=	35.5

Formula weight = 58.5

- **Atomic weights and formula weights are expressed:**
 - in **amu** (atomic mass units) for single molecules
 - in **grams** for laboratory quantities.

2. Calculate the formula weight of magnesium bromide, MgBr₂

Answer:

Set up a table similar to the one used in example 1.

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Mg	1	x	24.3	=	24.3
Br	2	x	79.9	=	159.8

Formula weight = 184.1

3. Calculate the formula weight of calcium sulfate,
 CaSO_4

Answer:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Ca	1	x	40.1	=	40.1
S	1	x	32.1	=	32.1
O	4	x	16.0	=	64.0

Formula weight = 136.2

4. Calculate the formula weight of barium nitrate,
 $\text{Ba}(\text{NO}_3)_2$

Answer:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Ba	1	x	137.3	=	137.3
N	2	x	14.0	=	28.0
O	6	x	16.0	=	96.0

Formula weight = 261.3

5. Calculate the formula weight of zinc phosphate,
 $\text{Zn}_3(\text{PO}_4)_2$

Answer:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Zn	3	x	65.4	=	196.2
P	2	x	31.0	=	62.0
O	8	x	16.0	=	128.0

Formula weight = 386.2

5. Calculate the formula weight of copper(II) sulfate pentahydrate, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

Answer:

Elements in the compound	Number of atoms of each element		Atomic weight		Total mass
Cu	1	x	63.6	=	63.6
S	1	x	32.0	=	32.0
O	9	x	16.0	=	144.0
H	10		1.0	=	10.0

Formula weight = 249.6

In the previous section the formulas of NaCl, MgBr₂, CaSO₄, Ba(NO₃)₂, Zn₃(PO₄)₂, and CuSO₄·5H₂O were examined and the formula weights were calculated.

You will notice, however, that there were no units included with the calculated formula weights. So, what units should we use?

If we are talking about these compounds as individual molecules, then the weights or masses would be expressed in **amu's** (atomic mass units).

But, we do not work with individual atoms or molecules, we work with amounts we can handle and measure in a laboratory setting.

So, in a laboratory setting, we use gram quantities. Thus, we can call the weights (or masses) we calculated **gram MOLEcular weights**.

A convenient short name for this is a **MOLE** (abbreviated **mol**). The proper units are **g/mol**

The formula or molecular weights for the compounds are:

Compound	Gram molecular weight
NaCl	58.5 g/mol
MgBr ₂	184.1 g/mol
CaSO ₄	136.2 g/mol
Ba(NO ₃) ₂	261.3 g/mol
Zn ₃ (PO ₄) ₂	386.2 g/mol
CuSO ₄ ·5H ₂ O	249.6 g/mol

Converting from grams to moles and moles to grams

To convert from grams to moles, divide the given mass by the molecular weight:

Sample problem:

How many moles are there in 50.0 g of MgBr_2 ?

Solution:

The first step is to calculate the gram molecular weight of MgBr_2 . Since we did that previously in this exercise, we will use the value of **184.1 g/mol**.

Next, set up the problem using dimensional analysis.

The conversion factor is: **1 mole MgBr_2 = 184.1 g MgBr_2**

$$? \text{ moles MgBr}_2 = 50.0 \text{ g MgBr}_2 \times \frac{1 \text{ mole MgBr}_2}{184.1 \text{ g MgBr}_2}$$

$$= 0.271 \text{ mole MgBr}_2$$

To convert from moles to grams, multiply the given mass by the molecular weight:

Sample problem:

How many grams are there in 1.60 moles of CaSO_4 ?

Solution:

The first step is to calculate the gram molecular weight of CaSO_4 . Since we did that previously in this exercise, we will use the value of **136.2 g/mol.**

Next, set up the problem using dimensional analysis.

The conversion factor is: $1 \text{ mole } \text{CaSO}_4 = 136.2 \text{ g } \text{CaSO}_4$

$$\begin{aligned} ? \text{ g CaSO}_4 &= 1.60 \text{ mole CaSO}_4 \times \frac{136.2 \text{ g CaSO}_4}{1 \text{ mole CaSO}_4} \\ &= 218 \text{ g CaSO}_4 \end{aligned}$$

A note on the definition of a Mole

The Mole is a standard SI unit for the amount of a substance.

It is officially defined as **6.0221421×10^{23} formula units of a substance**. (A formula unit is an atom of an elemental substance, a molecule of a molecular substance, or a formula unit of a more complex substance.)

The Mole has its origins with a hypothesis formulated by the Italian scientist Amedeo Avogadro (1776-1856). In 1811, Avogadro pointed out that:

“Gay-Lussac has shown in an interesting Memoir (Mémoires de la Société d'Arcueil, Tome II.) that gases always unite in a very simple proportion by volume, and that when the result of the union is a gas, its volume also is very simply related to those of its components. observed that gases combined in volume quantities in the same numerical ratio as the elements in a compound.”

For example, two volumes of hydrogen gas would combine with one volume of oxygen gas to form water, H_2O .



Avogadro went on to state:

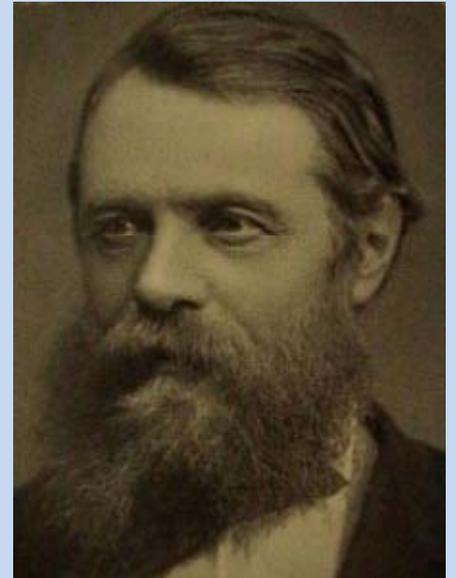
“But the quantitative proportions of substances in compounds seem only to depend on the relative number of molecules which combine, and on the number of composite molecules which result. It must then be admitted that very simple relations also exist between the volumes of gaseous substances and the numbers of simple or compound molecules which form them. The first hypothesis to present itself in this connection, and apparently even the only admissible one, is the supposition that the number of integral molecules in any gases is always the same for equal volumes, or always proportional to the volumes.”

This second statement is the basis for Avogadro's Hypothesis (sometimes referred to Avogadro's Law) which can be stated, in modern terms as:

Equal volumes of different gases (at the same temperature and pressure) have the same numbers of particles.

In 1865, an Austrian scientist, Johann Josef Loschmidt (1821-1895), in a paper On the Size of the Air Molecules, calculated the diameter of an air molecule to be 0.000000969 mm.

To do this, he had to calculate the number of molecules there were in a given volume of gas. That number was $2.687 \times 10^{19}/\text{cm}^3$ (equivalent, in modern terms, to 1.2×10^{24} molecules/mol).



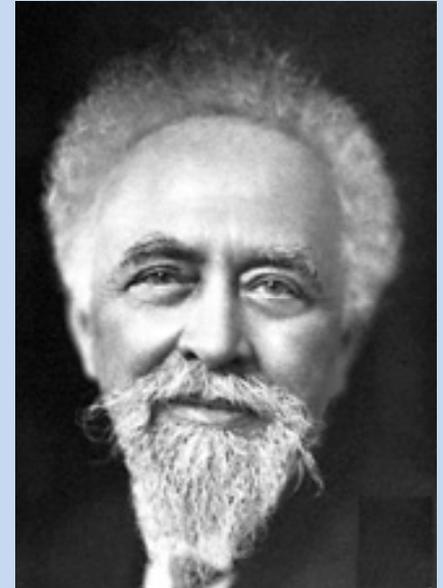
The term “Avogadro Number” or “Avogadro’s Constant” was used by Jean Baptiste Perrin, (1870-1942), a French physicist, in a 1909 paper, Brownian Movement and Molecular Reality:

“It has become customary to name as the gram-molecule of a substance, the mass of the substance which in the gaseous state occupies the same volume as 2 grams of hydrogen measured at the same temperature and pressure. Avogadro's proposition is then equivalent to the following:

“Any two gram-molecules contain the same number of molecules.”

This invariable number N is a universal constant, which may appropriately be designated *Avogadro's Constant.*”

Perrin came up with a value of Avogadro’s constant as 70.5×10^{22} .



Another calculation of Avogadro's number was made by American physicist Robert Millikan when he determined the charge on an electron. The charge on a mole of electrons had been known for some time and is the constant called the Faraday.

Millikan used the value of the Faraday as 9,650 electrostatic units and divided it by the electron charge of 4.774×10^{-10} electrostatic units to get a value of 6.062×10^{23}



Today, the best estimate of the value of a Faraday, according to the National Institute of Standards and Technology (NIST), is 96,485.3383 coulombs per mole of electrons.

The best estimate of the charge on an electron based on modern experiments is $1.60217653 \times 10^{-19}$ coulombs per electron.

If you divide the charge on a mole of electrons by the charge on a single electron you obtain a value of Avogadro's number of $6.02214154 \times 10^{23}$ particles per mole.

Avogadro's number is used in calculations when the number or mass of individual atoms or molecules is needed.

When to use Avogadro's Number

When a problem asks ask how many **atoms**, **molecules**, or **particles** are present in a sample or what is the mass of a single **atom** or **molecule** these are the key words to look for.

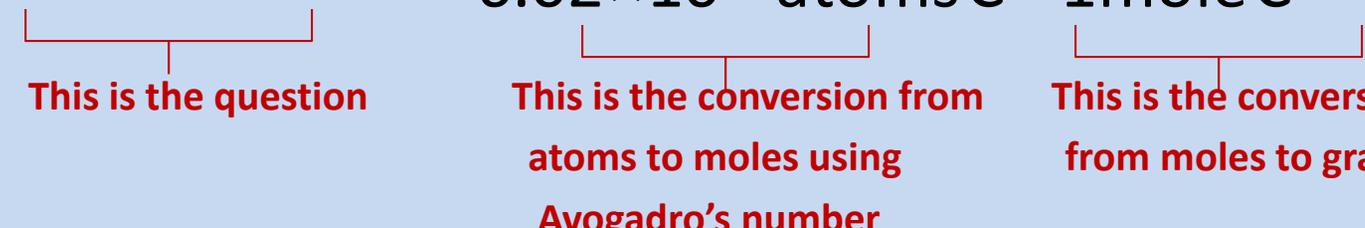
Sample problem:

What is the mass of an **atom** of carbon?

Solution:

We know that one mole of carbon atoms has a mass of 12.0 g

$$\text{?g C} = 1 \text{ atom C} \times \frac{1 \text{ mole C}}{6.02 \times 10^{23} \text{ atoms C}} \times \frac{12.0 \text{ g C}}{1 \text{ mole C}}$$



This is the question

This is the conversion from atoms to moles using Avogadro's number

This is the conversion from moles to grams

$$\begin{aligned} ?\text{g C} &= 1\text{atomC} \times \frac{1\text{moleC}}{6.02 \times 10^{23} \text{ atomsC}} \times \frac{12.0\text{gC}}{1\text{moleC}} \\ &= 1.99 \times 10^{-23} \text{ g C} \end{aligned}$$

Sample problem:

How many **molecules** of sulfur dioxide, SO_2 , are there in 5.0 mg of SO_2 ?

Solution:

Calculate the formula mass of SO_2 :

The formula mass is **64.0 g/mol**

$$?\text{molecules SO}_2 = 5.0\text{mgSO}_2 \times \frac{1\text{g SO}_2}{1000\text{ mg SO}_2} \times \frac{1\text{mole SO}_2}{64.0\text{g SO}_2} \times \frac{6.02 \times 10^{23}\text{ molecules SO}_2}{1\text{mole SO}_2}$$

This is the question

This is the
conversion
from mg to g

This is the
conversion
from g to moles

This is the conversion from
moles to number of
molecules

$$= 4.70 \times 10^{19} \text{ molecules SO}_2$$