Calculation of concentration of a solution

The study material explains process of calculation using direct (or indirect) proportionality between various quantities. It is based on definitions of important chemical terms and can give you an understanding of the essential chemical relationships.

Direct Proportionality	***Indirect Proportionality***
if 1 L of a solution contains 0,25 mol of a substance	*5 g of a substance are found in 5 g of 100% pure solid compound*
it follows from this that	*it follows from this that*
2 L of the solution contain 0,5 mol of the substance	*5 g of the substance are found in 10 g of 50% pure solid compound*
(i.e. twice higher volume of the solution contains twice more of moles of the substance)	*(i.e. 10 g of the solid compound contain 50 % = 10 x 0,5 = 5 g of the substance)*
mathematical description:	*mathematical description:*
0,25 mol in 1 L	*5 g of 100%*
*x mol in **2** L*	*x g of **50**%*
*x/0,25 = **2**/1*	*x/5 = 100/**50***
x = (2/1) x 0,25	*x = (100/50) x 5*
x = 0,5	*x = 10*
0,25 mol in 1 L	*5 g of 100%*
** 0,5 mol in 2 L*	** 10 g of **50**%*
↓ ↓	↓ ↑
*** both values** (substance amount and volume) **are changed in the same direction**	*** the values** (mass and %) **are changed in the opposite direction**

Molar weight (MW)
= mass of one mole of a substance in grams (g/mol).

The MW of a molecule is a sum of relative atomic weights A_r (expressed in grams per mole) of all elements building the molecule. The values of A_r are found in the Periodic table, e.g. A_r of H = 1, N = 14, O = 16 → molar weight of HNO_3 = 1x1 + 1x14 + 3x16 = 63 g/mol.

Density of a solution (ρ)
= mass of a specified volume of the solution (g/cm^3 = g/mL = kg/dm^3 = kg/L); it is often labeled on a bottle containing the solution (e.g. ρ = 1,8 g/mL means that 1 mL of the solution weights 1,8 g).

Concentration
= quantity of a substance found in a specified volume (or mass) of a solution

a) **molarity** (molar concentration) = number of moles of a substance per litre of a solution (mol/L) – it can be used if the molar weight (MW) of the substance is known

b) **osmolarity** = number of moles of all particles (including ions to which a molecule dissociates) found in one litre of a solution (osmol/L); the osmotic active particles show an osmotic pressure of the solution

c) **mass concentration** = mass of a substance per specified volume of a solution (g/L, mg/dL,...)

d) **percent concentration** (it is a special type of the mass concentration) = parts (g or mL) of a solute per 100 parts (g or mL) of total solution

Molarity (mol x L^{-1} = mol x dm^{-3} = mol/L = mol/dm = M)
The molarity can be calculated either using the formula c = n/V (c = molarity, n = substance amount in moles, V = final volume of the solution in L) or directly from the definition* of the molar concentration. A direct proportionality between the concentration (c) and a related substance amount (n) is used.

*(*) 1 M solution (read: one molar solution) means that **1 L** of the solution contains 1 mol of a substance*
*(*) 0,5 M solution (read: half molar solution) means that **1 L** of the solution contains 0,5 mol of a substance*

Example - MOLARITY

Preparation of a solution of NaOH having a specified molarity; <u>molar weight</u>: MW(NaOH) = 40 g/mole (**)

1M solution	0,1 M solution
= 1 mol of NaOH in 1 L of the solution	= 0,1 mol of NaOH in 1 L of the solution
= 40 g of NaOH in 1 L of the solution	= 4 g of NaOH in 1 L of the solution
because	*because*
*the mass of 1 mol is 40 g (see MW**)*	*the mass of 1 mol is 40 g (see MW**)*
	it follows from this that
	the mass of 0,1 mol is ten times lower = 4 g
	mathematical description:
	1 mol = 40 g
	<u>0,1 mol = x g</u>
	it is the direct proportionality
	x/40 = 0,1/1
	x = (0,1/1) x 40
	x = 4 g

How many grams of NaOH do you need for preparation of 0,5 L of the NaOH solutions (both 1 M and 0,1 M)?

1M solution	0,1 M solution
= 1 mole of NaOH in 1 L of the solution	= 0,1 mole of NaOH in 1 L of the solution
= 40 g of NaOH in 1 L of the solution	= 4 g of NaOH in 1 L of the solution
40 g in 1 L	4 g in 1 L
<u>x g in 0,5 L</u>	<u>x g in 0,5 L</u>
it is the direct proportionality	*it is the direct proportionality*
x/40 = 0,5/1	x/4 = 0,5/1
x = (0,5/1) x 40	x = (0,5/1) x 4
x = 20 g	**x = 2 g**

We need 20 g (2 g respectively) of NaOH to prepare 0,5 L of 1 M (0,1M) solution.

Problems

1.1 300 mL of a solution contain 17,4 g of NaCl (MW = 58 g/mol). What is the concentration of the solution?

solution:

MW = 58 g/mol	⇒	1 mol = 58 g
		<u>x mol = 17,4 g</u>
		it is the direct proportionality
		x/1 = 17,4/58
		x = 0,3 mol
17,4 g of NaCl = 0,3 mol of NaCl	⇒	17,4 g in 300 mL
		= 0,3 mol in 300 mL
		<u>x mol in 1000 mL</u> (because 1 L = 1000 mL)
		it is the direct proportionality
		x/0,3 = 1000 /300
		x = (1000/300) x 0,3
		x = 1 mol
definition of the molarity	⇒	1 mol is found in in1000 mL = 1 mol/L = **1M solution**

Molar concentration of the solution is 1 mol/L.

1.2 2,5 L of a solution contain 4,5 g of glucose (MW = 180 g/mol). What is the molarity of the solution? (0,01 M)

1.3 What is the mass of glycine (MW = 75 g/mol) found in 100 mL of its 3 mM solution? (22,5 mg)

solution:

3 mM solution	⇒	3 mmol in 1 L of the solution *(= definition of molarity)*
		= 0,003 mol in 1000 mL of the solution
		x mol in 100 mL
		it is the direct proportionality
		x/0,003 = 100/1000
		x = (100/1000) x 0,003
		x = 0,0003 mol
MW = 75 g/mol	⇒	75 g of glycine = 1 mol of glycine
		x g of glycine = 0,0003 mol of glycine
		it is the direct proportionality
		x/75 = 0,0003/1
		x = (0,0003/1) x 75
		x = 0,0225 g = **22,5 mg**

The solution contains 22,5 mg of glycine.

1.4 How many grams of NaCl (MW = 58,5 g/mol) are found in 2 L of its 0,1 M solution? (11,7 g)

1.5 Calculate the volume of 0,1 M solution of $CaCl_2$ containing 4 mmol of Cl^-. (20 mL)

solution:

$CaCl_2 \rightarrow 1\ Ca^{2+} + 2\ Cl^-$	⇒	1 mol of $CaCl_2$ contains 2 mol of Cl^-
0,1 M solution of $CaCl_2$	⇒	0,1 M solution of $CaCl_2$ is 0,2 M solution of Cl^-
		(because 1 molecule of $CaCl_2$ contains 2 Cl^-)
4 mmol of Cl^-	⇒	= 0,004 mol of Cl^-
0,2 M solution of Cl^-	⇒	= 1000 mL of the solution contains 0,2 mol of Cl^-
		x mL of the solution contains 0,004 mol of Cl^-
		it is the direct proportionality
		x/1000 = 0,004/0,2
		x = (0,004/0,2) x 1000
		x = 20 mL

4 mmol of Cl^- are found in 20 mL of the solution.

1.6 Calculate the volume of 0,2 M solution of Na_2HPO_4 containing 2 mmol of Na^+. (5 mL)

Osmolarity (osmol/L)

The osmolarity is related to all solutes dissolved in a solution. It is expressed as number of all osmotic active particles found in one litre of the solution. The osmotic active particles are either ions to which a molecule found in the solution dissociates or other molecules-nonelectrolytes (e.g. glucose which doesn´t dissociate) present in the solution. The value of the osmolarity of dissolved substance is either higher or the same as molarity of the substance found in the solution.

isotonic solutions = solutions having the same value of the osmotic pressure or osmolarity (e.g. blood plasma x saline)

hypotonic solution = solution of lower osmolarity in relation to the other solution

hypertonic solution = solution of higher osmolarity in relation to the other solution

Example - OSMOLARITY

A solution contains 150 mmol/L of NaCl and 100 mmol/L of glucose
⇒ **molarity** (= molar concentration) of NaCl is 150 mmol/L and molarity of glucose is 100 mmol/L

Osmolarity of the solution can be calculated as a **sum of molarity of all particles present in the solution**:

- NaCl → Na^+ + Cl^- (= 1 mol of NaCl dissociates to 1 mol of Na^+ and 1 mol of Cl^- = 2 mol of osmotic active particles) ⇒ if molarity of NaCl is 150 mmol/l the molarity of Na^+ is 150 mmol/L and the molarity of Cl^- is 150 mmol/L as well
- glucose → glucose (it is not dissociated = 1 mol of osmotic active particle) ⇒ its molarity is 100 mmol/L

⇒ **osmolarity** of the solution is (2 x 150) + 100 = **400 mosmol/L**

Problems

1.7 Calculate the osmolarity of each of the four solutions. Which of the solutions are isotonic?
a) 0,15 M NaCl (0,30 osmol/L)
b) 0,15 M $MgCl_2$ (0,45 osmol/L)
c) 0,15 M Na_2HPO_4 (0,45 osmol/L)
d) 0,15 M glucose (0,15 osmol/L)

solution:

NaCl → Na^+ + Cl^-	⇒	1 mol of NaCl contains 2 mol of osmotic active particles
2 ions		0,15 mol of NaCl contains x mol of osmotic active particles
		it is the direct proportionality
		x/2 = 0,15/1
		x = (0,15/1) x 2
		x = 0,3 mol of osmotic active particles = 0,3 osmol
0,15 M NaCl = 0,15 mol/L NaCl	⇒	0,15 x 2 = **0,30 osmol/l** solution of NaCl
$MgCl_2$ → Mg^{2+} + 2 Cl^-		
3 ions	⇒	0,15 x 3 = **0,45 osmol/L** solution of $MgCl_2$
Na_2HPO_4 → 2 Na^+ + HPO_4^{2-}		
3 ions	⇒	0,15 x 3 = **0,45 osmol/L** solution of Na_2HPO_4
glucose → glucose		
1 molecule	⇒	0,15 x 1 = **0,15 osmol/L** solution of glucose

0,15 M solution of $MgCl_2$ is isotonic with 0,15 M solution of Na_2HPO_4. The solutions of 0,15 M NaCl and 0,15 M glucose are hypotonic compared with the solutions of 0,15 M $MgCl_2$ and Na_2HPO_4.

1.8 Saline (= physiological solution) is 150 mM solution of NaCl. Which of the following solutions are isotonic with saline?

a) 300 mM glucose
b) 50 mM $CaCl_2$
c) 300 mM KCl
d) 0,15 M NaH_2PO_4

Help: *calculate the osmolarity of the saline and compare it with calculated osmolarities of the solutions*

solution:

NaCl → Na^+ + Cl^-	⇒	150 x 2 = **300 mosmol/L**
glucose → glucose	⇒	300 x 1 = **300 mosmol/L**
$CaCl_2$ → Ca^{2+} + 2 Cl^-	⇒	50 x 3 = 150 mosmol/L
KCl → K^+ + Cl^-	⇒	300 x 2 = 600 mosmol/L
NaH_2PO_4 → Na^+ + $H_2PO_4^-$	⇒	0,15 M = 150 mM ⇒ 150 x 2 = **300 mosmol/L**

Saline is isotonic with 300 mM solution of glucose and 0,15 M solution of NaH_2PO_4.

1.9 Calculate osmolarity of 100 mM solutions of
a) NaH_2PO_4 (200 mosmol/L)
b) Na_2HPO_4 (300 mosmol/L)
c) Na_3PO_4 (400 mosmol/L)

1.10 Calculate molarity of 120 mosmol/L solutions of:
a) NaH_2PO_4 (60 mM)
b) Na_2HPO_4 (40 mM)
c) Na_3PO_4 (30 mM)

solution:
Molarity is either lower or the same as osmolarity. The osmolarity depends on number of ions to which a molecule dissociates. If the osmolarity of the solution is 120 mosmol/L it must be divided by number of ions to find a value of the related molarity.

Percent concentration (g/**100** g or ml/**100** mL or g/**100** mL = **%**)
It is generally expressed as parts of a solute per 100 parts of total solution (per cent = „per one hundred“)
There are three basic forms of the expression:

a) weight per unit weight (w/w) it is expressed in grams of solute per 100 g of the solution (g/100g = %)

10% (w/w) solution of NaOH means that 100 g of the solution contain 10 g of NaOH
(it is prepared from 10g of NaOH and 90g of H_2O)

10% (w/w) solution of KCl means that 100 g of the solution contain 10 g of KCl
(it is prepared from 10g of KCl and 90g of H_2O)

b) volume per unit volume (v/v) it is expressed in millilitres of solute per 100 mL of the solution (ml/100 mL = %)

5% (v/v) solution of alcohol means that 100 mL of the solution contain 5 mL of alcohol
(it is prepared from 5 mL of alcohol and the rest of water to reach 100 mL of the solution)

c) weight per unit volume (w/v) it is expressed in grams of solute per 100 mL of the solution (g/100 mL = %)

This expression of the percent concentration is often used in a medicine. It can be used if the solution is diluted (= its concentration is low) as much as its density is close to density of distilled water (i.e 1 mL ~ 1 g)

2% (w/v) solution of KOH means that 100 mL of the solution contain 2 g of KOH

If a solution of specified percent concentration may be prepared we use the same mass of a substance regardless the chemical formula of the substance (molar weight of the substance is not used in the calculation):

***5%** solution of a protein is prepared from **5 g** of the protein and 95 g (mL) of water.*
***5%** solution of glucose is prepared from **5 g** of glucose and 95 g (mL) of water.*
***5%** solution of NaCl is prepared from **5 g** of NaCl and 95 g (mL) of water.*

Example - PERCENT CONCENTRATION

1.11 Calculate mass of NaCl and mass of water which are needed for preparation of 600 g of 5% solution. (30 g of NaCl and 570 g of water)

solution:

5% (w/w) solution	⇒	5 g of NaCl in 100 g of its solution
		x g of NaCl in 600 g of its solution
		it is the direct proportionality
		x/5 = 600/100
		x = (600/100) x 5
		x = 30 g of NaCl
600 - 30 = **570 g of water**		

or 5% = 5/100 = 0,05 ⇒ 600 g $\times$ 0,05 = 30 g

The solution is prepared from 30 g of NaCl and 570 g (= mL) of water (because the density of water ρ = 1g/mL).

1.12 What mass of Na_2CO_3 (purity 96%) do you need to prepare 250 g of 8% solution? (20,83 g)
solution:

8% (w/w) solution	⇒	8 g of Na_2CO_3 in 100 g of the solution
		x g of Na_2CO_3 in 250 g of the solution
		it is the direct proportionality
		x/8 = 250/100
		x = (250/100) $\times$ 8
		x = 20 g
purity of Na_2CO_3 is 96%	⇒	100 g of the solid substance contain 96 g of Na_2CO_3
		x g of the solid substance contain 20 g of Na_2CO_3
		it is the direct proportionality
		x/100 = 20/96
		x = (20/96) $\times$ 100
		x = 20,83 g
*the **indirect** proportionality can be used as well*	⇒	*we need 20 g of 100% pure Na_2CO_3*
		or x g of 96 % pure Na_2CO_3
		x/20 = 100/96
		*x = (100/96) $\times$ 20 = **20,83 g***

We need 20,83 g of 96% Na_2CO_3 to prepare 250 g of 8% solution.

Problems

1.13 Calculate volumes of ethanol and water found in 250 mL of 39% (v/v) solution of ethanol. (97,5 mL of ethanol, 152,5 mL of water).

1.14 How many grams of NaOH (purity 98%) is needed for preparation of 0,5 L of its 10% (w/v) solution? (51 g)

1.15 45 g of $NaNO_3$ were used for preparation of 3% (w/v) solution. Calculate the volume of the solution. (1,5 L)

Conversion between molarity and percent concentration

It is useful to start the conversion from definitions of the concentrations:

- molarity = substance amount of a solute found in 1 L of its solution (mol/L)
- percent concentration: mass of a substance in 100 g of its solution (g/100 g = %)

1) molarity → percent concentration **mol/L → g/100 g = %**

⇒ the volume (V = 1 L) must be converted to the mass (m) of the solution using its density ρ (ρ = m/V)
⇒ the substance amount can be then expressed as the number of moles found **in 100 g** of the solution
⇒ the substance amount is finally converted to the mass of a substance using molar weight (m = n $\times$ MW)

2) percent concentration → molarity **% = g/100 g → mol/L**

⇒ the mass of the solution (m = 100 g) must be converted to volume (V) using its density ρ (ρ = m/V)
⇒ the mass of a substance can be then expressed as the mass found **in 1 L** of the solution
⇒ the mass of the substance is finally converted to the substance amount (n) using MW (m = n $\times$ MW)

Example - CONVERSION BETWEEN MOLARITY AND PERCENT CONCENTRATION

1.16 Calculate the percent concentration of 5,62 M solution of HNO_3 (ρ = 1,18 g/cm^3, MW = 63 g/mol). (30%)

solution:

5,62 M = 5,62 molar solution	⇒	**5,62 mol** of HNO_3 are found in **1 L** of the solution
		(it is derived from the definition of molarity)
1) the **volume** 1 L is converted to the **mass** of the		
solution using the density: ρ = m/V → **m = ρ x V**	⇒	5,62 mol of HNO_3 are found in **1180 g** of the solution
(m = 1,18 g/mL x 1000 mL = 1800 g)		
2) the substance amount is expressed as number	⇒	5,62 mol of HNO_3 are found in **1180** g of the solution
of moles found in **100 g** of the solution		x mol of HNO_3 are found in **100** g of the solution
		it is the direct proportionality
		x/5,62 = 100/1180
		x = (100/1180) x 5,62
		x = 0,476
		0,476 mol of HNO_3 are found in **100** g of the solution
3) the substance amount is converted to the mass	⇒	63 g = 1 mol
using the value of molecular weight (MW)		x g = 0,476 mol
		it is the direct proportionality
		x/63 = 0,476/1
		x = (0,476/1) x 63
		x = 29,988 ≈ 30,0
		30 g of HNO_3 are found in **100** g of the solution
		= 30 g /100 g = **30%**

The percent concentration of *5.62 M* HNO_3 is 30%.

1.17 Calculate the molar concentration of 10% HCl (ρ = 1,047 g/cm^3, MW = 36,5 g/mol). (2,87 M)

solution:

10% solution	⇒	**10 g** of HCl are found in **100 g** of the solution
		(it is derived from the definition of percent conc.)
1) the **mass** 100 g is converted to **volume** of the		
solution using the density: ρ = m/V → **V = m/ρ**	⇒	10 g of HCl are found in **95,5 mL** of the solution
(V = 100/1,047 = 95,5 mL)		
2) the mass of HCl is expressed as number of	⇒	10 g of HCl are found in **95,5** mL of the solution
grams found in **1000 mL** (= 1L) of the solution		x g of HCl are found in **1000** mL of the solution
		it is the direct proportionality
		x/10 = 1000/95,5
		x = (1000/95,5) x 10
		x = 104,7
		104,7 g of HCl are found in **1000** mL of the solution
3) the mass of HCl is converted to the substance	⇒	1 mol = 36,5 g
amount using the value of MW		x mol = 104,7 g
		it is the direct proportionality
		x/1 = 104,7/36,5
		x = (104,7/36,5) x 1
		x = 2,87
		2,87 mol of HCl are found in **1000 mL** of the solution
		= 2,87 mol/L = **2,87 M**

The molar concentration of 10% HCl is 2,87 M.

Problems

1.18 Calculate the molar concentration of 30% HNO_3 (ρ = 1,18 g/cm^3, MW = 63 g/mol). (5,62 M)

1.19 Calculate the percent concentration of 2,87M HCl (ρ = 1,047 g/cm^3, MW = 36,5 g/mol). (10%)

1.20 What is the percent concentration of normal saline solution (= physiologic solution) if its molarity is 150 mM. Use the simplification: 1mL of the solution = 1g. (0,9%)

1.21 Calculate molarity of the solution containing 14 g of KOH (MW = 56,1 g/mol) in 100 mL of the solution. Use the simplification: 1mL of the solution = 1g. (2,5 M)

1.22 Calculate the molarity of 70% $HClO_4$ (ρ = 1,67g/cm^3, MW = 100,5 g/mol). (11,63 M)

1.23 Calculate the percent concentration of 11,63 M $HClO_4$ (ρ = 1,67g/cm^3, MW = 100,5 g/mol). (70%)

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