ACID-BASE AND REDOX REACTIONS ON SUBMICRO LEVEL: MISCONCEPTIONS AND CHALLENGE

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ABSTRACT

From experiences all over the world we know that formulae and chemical equations are memorized very often or are equalized by counting the number of "atoms on the left and right side of the equation". Looking to our Chemical triangle lecturers, students are jumping from the Macro level just to the Symbolic level. If we would go first from the Macro level to the Submicro level and explain chemical reactions with involved atoms, ions and molecules, then learners would understand chemistry more successfully. With a special questionnaire we are investigating the ability of university students and chemistry teachers in Indonesia, Tanzania and Germany to interpret given chemical equations with involved particles. We could find that a lot of misconceptions are present and should be challenged. *[African Journal of Chemical Education—AJCE 9(1), January 2019]*

INTRODUCTION

There is a true story of the year 2003 at one of the Secondary schools at Kilimanjaro area in Tanzania. The teacher of a Form-VI class (highest level in schools) did a titration of hydrochloric acid, asked the students to interpret the change of indicator color – and soon the well-known equation was developed at the blackboard: $HCl + NaOH \rightarrow NaCl + H_2O$. Author Barke interrupted the lesson with the question: "Please let us know which particles are reacting". The teacher looked irritated and pointed out that „HCl and NaOH" are involved. So Barke went to the blackboard, drafted a beaker model and wrote inside "H^+(aq) and Cl^-(aq)" separated from each other. Suddenly a young girl came up with a beaker-model of NaOH solution: "Na^+(aq) and OH^-(aq)". After some discussion about the function of sodium and chloride ions the students recognized that H^+(aq) ions and OH^-(aq) ions react to form H_2O molecules – other ions remain without reacting. The 50-years-old teacher came to Barke and noticed: "Thanks for opening my eyes to neutralization. Why did you not come 30 years earlier – I would have explained neutralization every time like you have done it today".

This story shows that the Submicro level of the Chemical triangle (see Figure in [1]) seems so important to understand neutralization in the scientific way. Also many other acid-base and redox reactions are confusing if one ignores the ions, that especially the reacting ions explain chemistry in a modern way. BROENSTED proposed since 1928 his idea to look to the particles which react ([1], [7]): for example, H_3O^+(aq) ions are proton donors which transfer protons to other base particles. We will investigate this context with students of our universities.

Ions as Important Particles

In chemistry teaching atoms and molecules as smallest particles of matter are well-known – but ions have been ignored in many curricula around the world: Misconceptions can be stated if particles in salt solutions, in ocean water or in mineral water are asked [2]. One example: If a precipitation of barium sulfate from barium chloride and magnesium sulfate solution should be described, one is mostly writing: "$BaCl_2 + MgSO_4 \rightarrow BaSO_4 + MgCl_2$".

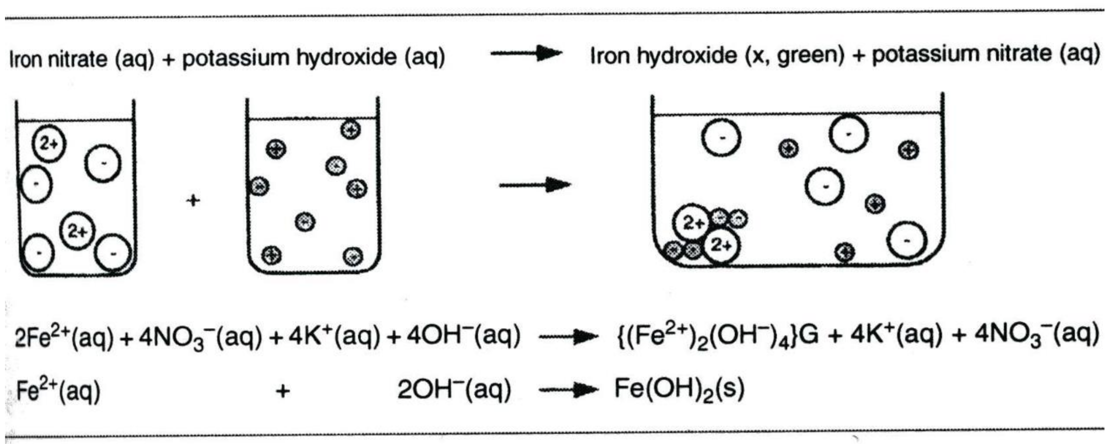

Fig. 1: Beaker model; example iron(II)-hydroxide precipitation [2]

But there are misconceptions of „partner change" and some curricula explain the precipitation as "double replacement reaction" [3]: "Barium and magnesium are changing partners". Taking ions into account it is easy to write: Ba^{2+} (aq) + SO_4^{2-} (aq) $\rightarrow$ $BaSO_4$(s). One should point out that those ions produce crystals with the $Ba^{2+}SO_4^{2-}$ ionic lattice, that other ions are "spectator ions" [3] in the sense of not reacting particles: Mg^{2+} (aq) and Cl^-(aq) ions remain. The best way is to draw a concrete model of a precipitation (see Fig. 1) and discuss this beaker model with the aim to develop a scientific mental model on the Submicro level.

EMPIRICAL RESEARCH ACCORDING TO THE SUBMICRO LEVEL

Author Wisudawati developed a questionnaire to give university students the usual chemical equation of acid-base and redox reactions and asked questions according to the involved atoms, ions or molecules, according to particles which do not react, according to the decision if there is an acid-base or redox reaction, and the connected transfer of protons or electrons (see questionnaire in the appendix of this article). Barke gave the same questionnaire to chemistry teachers during a teacher-training seminar in Tanzania, and Hassan created a questionnaire in German language to test students at University of Muenster in Germany.

Asih Wisudawati. At universities of Yogjakarta and Bandung she used the questionnaire (see appendix). During a 60-minutes period students should solve 10 tasks, and about 75 answer sheets have been returned. She got the following results:

- Most of the tasks 2, 5 and 6 are answered in a right way and interpreted as redox reactions. But not in all cases students could mark those particles which are giving electrons, and particles which are taking electrons.
- Reactions 1, 3, 4 and 7 are interpreted in a right way as acid-base reactions – but nearly no student can mark particles which give protons or take protons. In task 3 "weak acid HAc molecule", it is mostly interpreted as completely protolized into ions without explaining weak acids by equilibria between molecules and ions. Task 8 gives problems: the acid-base reaction of oxide ions with water molecules is interpreted as redox reaction without explaining.

- Solid salts are often described without ions: "Molecular symbols like Na_2CO_3, $CaCO_3$ and MgO" are taken for interpretation. By this misunderstanding metal ions couldn't be mentioned according to the question which ions are not involved in the reaction.

Question 9 asks about the most difficult alternative out of (a) – (d). Students are deciding mostly (d) according to the transfer of protons or electrons with following comments: „Proton or electron transfer confuses me; I need basic concepts of chemistry; we need to understand (a) – (c) for an answer; we need a lot of theory and more time to answer". Also (c) about "spectator ions" is confusing a lot of students.

Question 10 concerns students' wishes to go deep into the Submicro level. Many students answer: „Yes – because it is important to learn what particles are doing; to differentiate acid-base and redox reactions better; it helps to understand chemistry; it can support to be a better teacher; I can improve my understanding of chemistry".

Just the last answers may give an impression how much students will appreciate to get more information about atoms, ions and molecules which are involved in chemical reactions. As soon as he or she will interpret reactions on the Submicro level he or she understands the chemistry behind reactions; and chemical equations should not be memorized – they may be used as short information connected to mental models of those reacting atoms, ions and molecules. Especially the decision whether an acid-base or a redox reaction occur and which particle donates or takes a proton or an electron, can be completely understood.

Barke. He gave in September 2018 same questionnaire to 20 experienced teachers during a one-week-teacher-training seminar in Moshi, Tanzania. The results are very different: some teachers answered nearly perfect, the majority has big problems:

- Teachers cannot avoid the mixture of particles and substances: "H^+ ions and OH^- ions form water; H^+ ions and CO_3^{2-} ions form water and carbon dioxide gas". But we have this problem around the world: particles and substances are mixed (see later "Laboratory jargon").
- They also interpret reactions with „salt molecules". And if they want to show the chemical structure of compounds they cut into not existing ions: "$2H^+O^{2-}$, $Na^+O^{2-}H^+$, $2H^+S^{6+}O^{2}$" are some examples. Especially with combined ions like sulfate, nitrate or carbonate ions there are difficulties with indices and exponents in formulae.
- Redox reactions and the equivalence of electrical charges on both sides of equations are other difficulties. Concerning reactions of iron and copper chloride solution Fe and Cu atoms don't exist: "$Fe^{2+} + Cu^{2+}Cl^- \rightarrow Fe^{2+}2Cl^- + Cu^{2+}$". Charges are also misunderstood and wrongly calculated: "$Cu^{2+} - 2e \rightarrow Cu$ or $2Ag+ \rightarrow Ag + 2e$ or $Zn + 2e \rightarrow Zn^{2+}$" are examples.
- Acid-base reactions have been explained by "electron transfer" because teachers don't know proton transfers (this idea was given through the seminar): "$2\ H^+ + 2\ OH^- \rightarrow 2\ H_2O + 2e$ or $2\ H^+$ gain 2 e, OH^- loses 2e or H^+ is reduced, and OH^- is oxidized" are misconceptions.

Later after the seminar another Posttest has been performed – and the teachers could show their new knowledge concerning acid-base reaction and proton transfer, and redox reaction and electron transfer. So we have to admit that teacher education in science and especially in chemistry is so poor in Tanzania because lecturers at teacher colleges mostly hold only the Bachelor degree and have not studied those reactions on the Submicro level.

- Asking task 9 about the difficulties according to (a) – (d) all four alternatives have been irritating the teachers because they have never answered those questions – and have not really understood differences in acid-base and redox reactions. At the end of the seminar they were very thankful to get new insights in understanding chemistry and are now more sure how to explain those reactions scientifically, how to move successfully on the Submicro level.
- According to task 10 they want to go deep into the Submicro level: “Indeed – there is much knowledge in this topic which is very important for teaching; on this way we want to understand more chemistry”, have been some comments.

Mercedeh Hassan [5]. She created a questionnaire with some other problems as before, but with the same task to write down ionic symbols after offering common chemical equations. She gave her questionnaire to about 30 chemistry students in advanced semesters at Muenster University – and got the result that about 50 % of the answers are correct. But all the other answers show mistakes or even misconceptions:

- Instead of pointing out the involved ions students show molecular symbols for diluted solutions of acids and bases: “HCl(aq), H_2SO_4(aq), HNO_3(aq)”. For ionic solid salts they chose molecular symbols: NaCl, KI, $NaHSO_4$, K_2SO_4, FeO, CuO, CaO, $Ca(OH)_2$, $CaSO_4$, $Mg(OH)_2$, Mg_3N_2, $MgCl_2$, and others. So students are thinking like Arrhenius in 1887: Solutions contain the ions, but solid salts not. Are students really thinking of “molecules” in salt crystals? – or is the writing NaCl only an "abbreviation" for the name sodium chloride? Interviews should decide this in a following investigation.

- If ions have been written compositions and charges are in many cases not correct: "instead of NH_4^+ it is written N^{3-} + 4 H^+; instead of 2 OH^- there is $(OH_2)^-$ or $(OH)_2^-$; instead of 2 Cl^- there is Cl_2^-; an H_2O molecule is written as 2 H^+ + O^{2-} or H^+ + OH^-; sulfuric acid solution is described by H_2^+ + SO_4^- " etc. So even in their higher semesters many students are not sure how to formulate scientifically ions for solutions of acids, bases and salts. In some cases, pure sulfuric acid is asked and offered as "$H_2SO_4(l)$" – but many students are taking ions and not realizing that this time the molecular model is asked as the right one.
- In redox equations the atoms and ions are not differentiated. For the famous reaction of iron with copper sulfate solution students are taking the ions instead of atoms: "Fe^{2+} ion gives two electrons and forms an Fe^{2+} ion"; „Fe^{2+} → Fe^{2+} + 2e or Fe + CuO^{2+} → Cu + FeO^{2+}" etc. Students have the idea to balance „atoms left and right of an equation" – but not the charges.
- By identification of redox reactions there are in average only 10 % mistakes, by acid-base reactions around 20 % of mistakes – redox reactions are more known than acid-base reactions. Some students even mark both redox and acid-base without a decision for one type. Mercedeh's analysis: Students may be confronted with two or three different mental models which are competing in their mind, i.e. mixing Arrhenius' and Broensteds terminology concerning acid-base reactions. Also Lavoisier 's oxidation theory and todays electron-transfer definition are competing mental models in students' mind.
- At the end of her thesis Mercedeh points out [5]: Misconceptions which are developed during childhood or during school time are taken into lectures of universities – and students

may realize conceptual changes to the scientific way by their studies. In case that they do not change their mental models those students as chemistry teachers will bring misconceptions into school and may transfer them to their pupils. Therefore, every chemistry teacher should integrate the idea of ions as smallest particles of acid, base and salt solutions as soon as those solutions are discussed. To avoid misconceptions regarding solid salts some crystal structures should be shown, and ionic lattices, for example calcium hydroxide, should be symbolized in formulae: $Ca^{2+} (Cl^{-})_2$. Especially crystal structures may be reflected to transfer the idea of giant structures into the mind of students – and differentiate from molecules.

LABORATORY JARGON AND MISCONCEPTIONS OF STUDENTS

According to the Submicro level we have in chemistry a special problem. Lecturers mostly use a "Laboratory jargon" in their lectures and the question comes up whether teacher students take this jargon for their own terminology, or develop "school-made misconceptions" [2] – or even transfer them later as teachers to their students. One example: „2 hydrogen react with 1 oxygen to form 2 water" is often stated by experts (and the experts know that the involved molecules are meant). If one points out that $2H_2$ molecules and $1O_2$ molecule are forming $2H_2O$ molecules (not water!), the explanation is totally clear and good to understand.

Joline Buechter [6]. A German empirical pilot study has shown first results: About half of the investigated participants at Muenster University could reflect and correct given jargon statements – but even after three years of studying chemistry the other students are staying with that jargon or other alternative conceptions. One example of the questionnaire [6]:

“2) Lab. Jargon: "Hydrochloric acid gives off a proton"

a) Hydrochloric acid can be deprotonated.

b) Hydrochloric acid can also absorb protons.

c) $H_3O^+(aq)$ ions are present in hydrochloric acid, they can emit protons.

d) HCl molecules are present in hydrochloric acid, they release protons” [6].

The right answer is of course (c): “$H_3O^+(aq)$ ions are present in hydrochloric acid, they can emit protons”. We took famous misconception (d) and were waiting of “HCl molecules in solution”. Because of the well-known idea of “deprotonation” we offered alternative (a), answer (b) is a fake [6]. The right answer (c) is chosen by 40 % of participants, the real misconception about “HCl molecules in hydrochloric acid” is fortunately taken by only 5 %. But answer (a) has reached the majority of 55 %: Many students are thinking of scientifically good sound of “deprotonation”. Other examples may be studied by Barke and Buechter [1].

Yuli Rahmawati [8]. She created the English version of Tab. 1: Correct answers of two groups Joline’s questionnaire and took it to students of UNJ University in Jakarta/Indonesia. Similar results have been obtained (see Table 1). In question 2 “Proton donor HCl” Indonesian students show lower results because they have not chosen H_3O^+ ions but mostly the alternative “HCl molecules release protons”. In question 7 “Neutralization” many students decided “salt formation” as right answer – and not the reaction of $H^+(aq)$ ions and $OH^-(aq)$ ions. Related to question 10 “Amphoteric H_2O molecule” most students

Questions	German	Indonesia	
1	68	92	84
2	40	15	19
3	90	54	50
4	77	63	59
5	55	48	45
6	22	25	33
7	50	15	22
8	82	83	65
9	64	79	87
10	55	23	31
	Year 3	Year 3	Year 1-4

don't look to the H_2O molecule as proton donor and acceptor, but chose the substance "water can be an acid or a base". In Indonesia most explanations are given related to substances – curricula must change to instruct also on the Submicro level for understanding chemistry.

CHALLENGING MISCONCEPTIONS

What shell we do to avoid those mentioned misconceptions with ions as important particles? As soon as atoms and molecules are well-known and metal atoms in metal structures are visualized by densest sphere packings, molecules by ball-stick models and their molecular structural symbols, also the third group of smallest particles should be introduced: the ions.

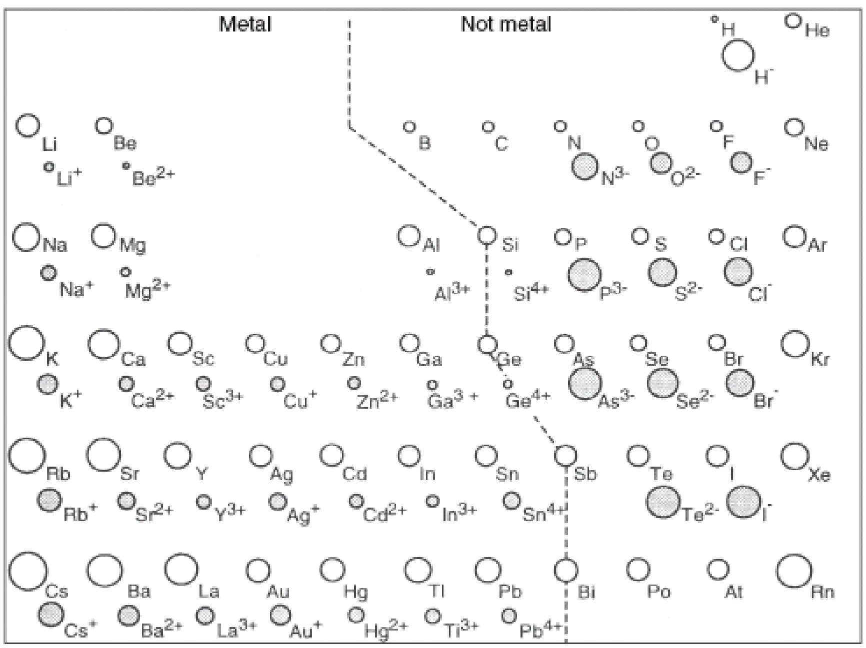

Fig. 2: PSE-depiction of a selection of atoms and ions and their spherical models [2]

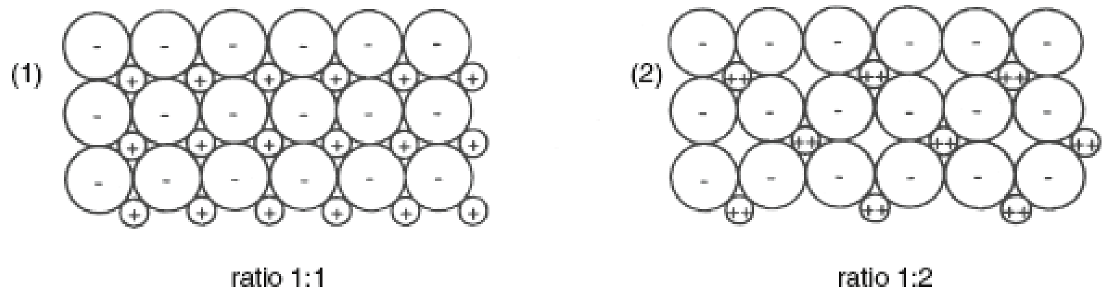

Fig. 3: 2-D models of ionic lattices in the ion ratio 1:1 (NaCl) and 1:2 ($MgCl_2$) [2]

Usually, during the introduction of atoms the Periodic table is shown with all atomic symbols, numbers and atomic masses. If one takes spheres to visualize that every atom has a specific diameter, it is easy to symbolize also the corresponding ions with their specific diameter (see Fig. 2): Charge numbers are given without comparing any protons in nucleus and electrons in shells – the ions can be introduced without the differentiated atomic model! Later during higher classes students may work with the nucleus-shell model of atoms and ions and the number of electrons can be discussed for explaining ion charges.

Analogically to the composition of a water molecule by two H atoms and one O atom, one may state that sodium chloride is composed of Na^+ ions and Cl^- ions in an ionic giant structure (see Fig. 3): the ionic symbol for sodium chloride should be shown as $(Na^+)_1(Cl^-)_1$ or for magnesium chloride as $(Mg^{2+})_1(Cl^-)_2$ (see Fig. 3). On this way students have chances to know that ions are composing those salts – and may avoid misconceptions of “salt molecules” [2]. After discussing those ionic symbols can be shorten to NaCl and $MgCl_2$ – but the involved ions should be in the mind of learners, in their mental model of the composition of salt crystals!

The composition of salt crystals can be visualized by 2D-drawings of layers of ionic lattices (see Fig. 3). If afterwards salt solutions will be introduced, (aq)-symbols should be added: $Na^+(aq)$

ions and Cl^-(aq) ions for sodium chloride solution, Mg^{2+}(aq) and Cl^-(aq) ions in the ratio 1:2 for magnesium chloride solution. Even the neutralization of acid and base solutions should be visualized by beaker models (see Fig. 4). The (aq)-symbol is important because the learner knows that different charged ions are attracting and would go together. The (aq)-symbols show hydrated ions: 4, 5 or 6 surrounding water molecules are avoiding the strong attraction of ions.

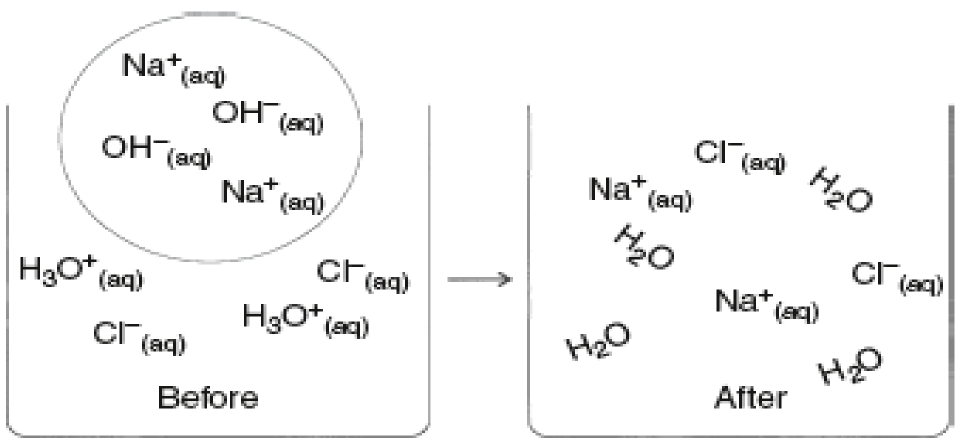

Fig. 4: Beaker model for neutralization of hydrochloric acid by sodium hydroxide solution [2]

Neutralization. Students know the common equation for neutralization, in case of hydrochloric acid and sodium hydroxide solution: HCl + NaOH → NaCl + H_2O. Asking about the particles which are reacting often HCl and NaOH molecules are mentioned. So it is important to point out that H_3O^+(aq) ions and OH^-(aq) ions are reacting in the sense of Broensted's theory [6]:

$$H_3O^+(aq)\text{ ion} + OH^-(aq)\text{ ion} \rightarrow 2\ H_2O\text{ molecules}$$

With the help of the beaker model (see Fig. 4) one can understand that other ions are not reacting: Na^+(aq) ions and Cl^-(aq) ions remain as "spectator ions", they are not reacting partners. No "solid salt" or "NaCl molecules" are produced – but sodium chloride solution *remains*. It is also good to visualize that the number of ions is the same before and after neutralization (four ions in the beaker model of Fig. 4): H_3O^+(aq) ions are replaced by Na^+(aq) ions.

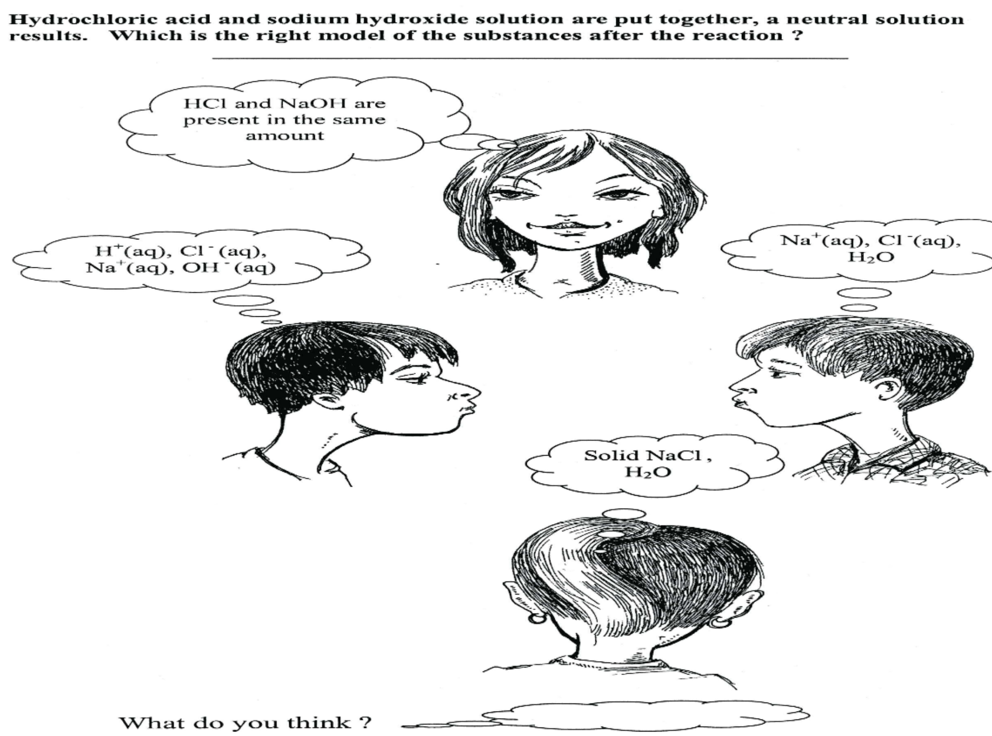

Fig. 5: Concept cartoon concerning the neutralization [4]

CONCLUSION

In older times, teachers liked to perceive students as “blank pages” and thought that they only have “to fill blank pages” with contents of science. Today we know that at early stages, boys and girls develop their own preconcepts [2]. Empirical studies show that we have more success in teaching and learning when we integrate those alternative models into instruction and after discussing those preconcepts to come up to consolidate the scientific explanation.

Also school-made misconceptions [2] should be mentioned for a special topic to show the right answer between some alternatives. Especially Concept cartoons [4] are suitable to analyze misconceptions of students and discuss those ideas with the goal of scientific explanation (see Fig. 5). By this way teachers may challenge those misconceptions and may convict students additionally by experiments, concrete models and problem-solving teaching.

Other challenges are working with acids and bases, and with related ions. Following Broensted's theory acids and bases are molecules or ions – not substances [7]. For working with related ions the special Periodic system of atoms and ions (see Fig. 2) may help. Understanding compositions of salt crystals is easier if involved ions are taken from the Periodic table and combined to models of ionic lattices (see Fig. 3), or even visualized by sphere packings [2]. For visualizing acidic, alkaline or salt solutions one should create and discuss beaker models (see Fig. 4). Students should develop accurate mental models – and misconceptions may be challenged!

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Appendix: Asih W. Wisudawati June 2018

Questionnaire "Redox or Acid-base reaction?"

For understanding Chemistry, we need three levels of reflection:
1. **Macro level** of observations according to substances and chemical reactions,
2. **Submicro level** with interpretation of all observations with mental models by particles of matter like atoms, ions, molecules and by chemical structures,
3. **Symbolic level** with shortenings of mental models by chemical symbols like atomic, ionic, molecular symbols, and chemical equations. In following problems the macro and symbolic level is presented in this questionnaire, the submicro level is asked by participants.

One example for the wanted answers in the following eight problems:
Macro level: Magnesium reacts with hydrochloric acid, gaseous hydrogen is observed.
Symbolic level: Mg(s) + 2 HCl(aq) → $MgCl_2$(aq) + H_2(g)
Submicro level: **a) Which particles (atoms or ions or molecules) are involved?**
Answer: Mg atoms / H^+ ions, Cl^- ions / Mg^{2+} ions Cl^- ions (1:2) / H_2 molecules
b) Write down equation of those atoms, ions or molecules which react!
Mg atom + 2 H^+ ions → Mg^{2+} ion + H_2 molecule
c) Which atoms, ions or molecules are NOT involved in the reaction?
Cl^- ions are „spectator ions"
d) Redox or acid-base reaction? Explain transfer of electrons or protons.
Redox: Mg atom gives two electrons: Mg atom → Mg^{2+} ion + 2 e- (oxidation)
2 H^+ ions take two electrons: 2 H^+ ions + 2 e- → H_2 molecule (reduction)

Try to solve the next eight problems in this way!
Take a blank white paper and write down your answers according to (a) – (d).

1. Solid sodium carbonate reacts with hydrochloric acid, gaseous carbon dioxide is observed:
Na_2CO_3(s) + 2 HCl(aq) → NaCl(aq) + H_2CO_3(aq) (H_2CO_3 → H_2O + CO_2)
2. Zinc reacts with diluted sulfuric acid, gaseous hydrogen is observed:
Zn(s) + H_2SO_4(aq) → $ZnSO_4$(aq) + H_2(g)
3. Acetic acid solution reacts with sodium hydroxide solution, small heat is observed:
HAc(aq) + NaOH(aq) → NaAc(aq) + H_2O (**H**Ac = **H**OOCCH_3)
4. Hydrochloric acid reacts with sodium hydroxide solution, big heat is observed:
HCl(aq) + NaOH)aq) → NaCl(aq) + H_2O
5. Iron reacts with blue copper chloride solution, brown copper develops on iron:
Fe(s) + $CuCl_2$(aq) → $FeCl_2$(aq) + Cu
6. Copper reacts with silver nitrate solution, silver crystals are growing on copper:
Cu(s) + 2 $AgNO_3$(aq) → $Cu(NO_3)_2$(aq) + 2 Ag
7. Solid calcium carbonate reacts with acetic acid, gaseous carbon dioxide is observed:
$CaCO_3$(s) + 2 HAc(aq) → $CaAc_2$(aq) + H_2CO_3(aq) (H_2CO_3(aq) → H_2O + CO_2)
8. Solid magnesium oxide reacts with hydrochloric acid, magnesium oxide dissolves:
MgO(s) + 2 HCl(aq) → $MgCl_2$(aq) + H_2O
9. Let us know which of alternatives (a) – (d) was the most difficult for you. Explain.
10. Do you like to go with (a) – (d) so deep into the Submicro level? Explain.