



Learners Ideas, Misconceptions and Challenge

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“Look to the East – the sun is rising”. One can hear that statement around the world – even if adults and educated persons know about the rotating earth and the fixed sun, no one is telling: “look how nice the earth is rotating to the East – just showing our sun”!

Even our scientists until the 16th century observed the same phenomena and were seriously thinking that the sun is rotating around the earth. Copernicus was the first who interpreted the movement of our planets and published his heliocentric mental model in 1543: “the earth is rotating around his axis in one day, and rotates around the sun in one year”. It took decades and decades after more and more scientists and citizens accepted that thinking – in opposite of their everyday observations according to the “rotating sun”.

So we cannot blame our children when they observe very carefully and derive the thinking of the geocentric model of earth. The physics teacher has to discuss intensively those observations, and with a good spatial model of the sun in the middle, of rotating earth and moon, of all the other planets, he can start to teach the heliocentric idea. The young students may realize a conceptual change and develop that idea – but at home with their family and friends they will not stay with that idea and will go on to describe their observations with the “rotating sun”. They still keep both mental models in mind: for everyday life they talk about the “rising sun”, for the physics teacher or for the written test in science they will shift to the “rotating earth”.

1. Preconcepts and school-made misconceptions

In chemistry we have the same experiences according to the transformation of substances, to the explanation of combustion and to the nature of gases. The students are observing very well but cannot develop the

scientific interpretation – they stay with pre-scientific ideas, with alternative ideas or with preconcepts. Those ideas which derive from everyday life and which students are bringing into science lectures should be called **preconcepts** [1].

If the science lectures are going on to the second and third year one can experience that students – not knowing topics like equilibrium or donor-acceptor-reactions from everyday life – do not develop scientific interpretations offered by the teacher, but are often staying with mistakes, with alternative ideas. Because those mistakes are mostly “school-made” we will call those ideas **school-made misconceptions** [1]. They can be explained by the difficulties of the topic or by not sufficient teaching – but there is a chance to change the teaching process and to successfully prevent misconceptions. The preconcepts are developed by everyday life, one cannot prevent young students from those ideas: you have to accept them, to discuss and try to correct them to realize a conceptual change. But school-made misconceptions should not appear automatically – there is a chance to prevent students from misconceptions by good teaching.

2. Preconcepts of children and challenge

There are listed and discussed a lot of preconcepts from young students concerning

- concrete-pictural and magical-animistic ways of speaking [1]
(pieces of wood *don't want* to burn, acids *attack* other substances, rust *eats up* iron, etc)
- substance as a carrier of properties [1]
(heated iron wool *turns* black, red-brown copper *changes* to green copper after time, etc)
- mixing and unmixing elements in compounds [1]

(silver sulfide contains silver and sulfur, water *consists* of hydrogen and oxygen, etc.)

- destruction theory versus conservation of mass [1]
(water from puddles *is gone*, removing stains from clothes – *the fat is away*, etc)
- combustion and destruction theory ([1] – [4])
(after burning on a grill charcoal *is away*, wood and paper *are gone* after combustion, etc.)
- air and other gases ([5] – [6])
- (gases weigh *nothing*, hot air *raises even up*, water evaporates *to form air*, etc).

In many publications ([1] – [10]) those precepts are reflected and the challenges discussed. Those concepts are not avoidable – they are appearing with every new generation of kids. The school-made misconceptions are avoidable – therefore they are more important to discuss: in the following chapters they are reflected, challenges are proposed.

3. School-made misconceptions and challenge

“Without explicitly abolishing misconceptions of students it is not possible to integrate sustainable scientific concepts” [3]. For advanced topics in science e.g. acid-base reactions and proton transfer students have hardly any precepts or misconceptions. The students know phenomena like sour taste of juices or acidic chemicals in the bathroom, but there is no knowledge of protons being transferred from molecules or ions to others. It is remarkable that teachers may teach the proton transfer even with some key experiments – but empirical research shows that students mostly don’t grab the idea

sufficiently. Reasons and challenge are shown.

School-made misconceptions can be found in the following topics:

- Ions as smallest particles of salt crystals and solutions,
- Chemical equilibrium,
- Acid-base reactions and proton transfer,
- Redox reactions and electron transfer.

3.1. Ions as smallest particles in salt crystals and solutions

With Dalton’s atomic model mostly atoms and molecules are introduced and teachers like to work with molecular symbols like H_2O , NH_3 or CH_4 – the whole organic chemistry can be described by those or structural molecular symbols. If later ions are presented it seems hard to handle ionic symbols – for the composition of salts and salt solutions, students tend to write molecular symbols as they are already used to: Na^+Cl^- , $Cl^-Mg^+Cl^-$, $Mg=O$, etc. The following empirical research will show it.

Symbols representing ions in a salt solution (see figure 1, “before evaporation”) were given to senior class students. Afterwards, students were asked to describe what happens to the ions when the water evaporates. Apart from several correct answers regarding ions by crystallization of sodium chloride, a large percentage of answers were given based on the existence of $NaCl$ molecules in crystals. These students started with ions in the solution, however when developing mental models for the evaporation of water they argued with the “neutralization” of ions [4] and the continuous fusion of ions into molecules, and finally they imagined “ $NaCl$ molecules” as particles of solid sodium chloride crystals (see figure 1).

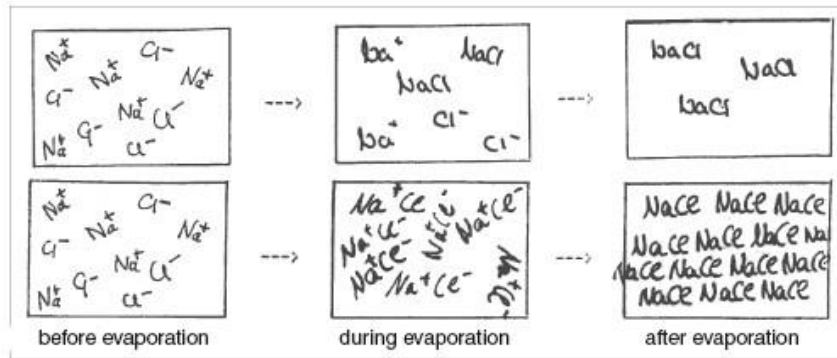


Fig. 1: Two examples for misconceptions concerning crystallization of sodium chloride [4]

Questionnaire:

BONAQA mineral water contains water, carbon dioxide, sodium bicarbonate, calcium chloride, magnesium chloride and sodium chloride.

Mark your answer:

- (x) the water contains CO₂ molecules
- () the water contains small salt crystals
- () the water contains molecules of various salts
- (x) the water contains ions of various salts
- () Your answer:

(marked answers are the expected ones)

Draw your mental model:

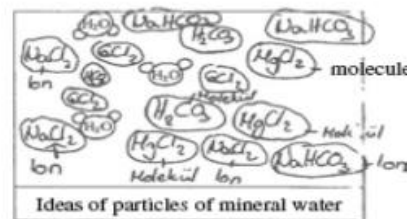
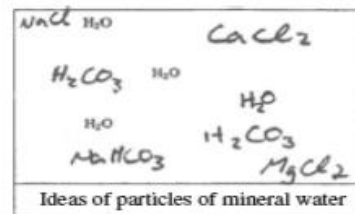


Fig. 2: Examples for misconceptions regarding particles in mineral water [4]

In a questionnaire regarding the label on a bottle of “BONAQA” mineral water, students in upper grades were shown the names of salts contained in that water: calcium chloride, magnesium chloride, sodium chloride and sodium bicarbonate [4]. The point of the questionnaire was to test their knowledge of existing ions in mineral water. In order to note correct ion symbols like Na⁺, Cl⁻, Ca²⁺, Mg²⁺ or HCO³⁻, most of the students suggest “salt molecules” (see figure 2): by drawing their mental models many students wrongly preferred “NaCl or MgCl² molecules” – even “NaCl² ions or molecules” (see figure 2).

Despite the fact that all students had dealt with the ion term in class, only 25 % of them recognized “ions of various salts” as the

correct alternative answer, about the same number of students chose “salt molecules”. If one looks at the model drawings, a mere 4 % of students actually included ion symbols in their drawings. Many of the test persons who, although they crossed off the ions as the correct answer, chose symbols for molecules (see figure 2).

Most curricula introduce the ions with ionic bonding and ion formation from elements. In the famous experiment according the sodium-chlorine reaction to form sodium chloride teachers point out that sodium and chloride ions are formed by electron transfer, are filling outer electron shells like noble gas atoms, and are bonding in an ionic lattice by ionic bonds. All these new ideas are not easy to understand: different misconceptions arise

if one introduces ions by ion formation and asks: “what holds the ions together” (see figure 3)

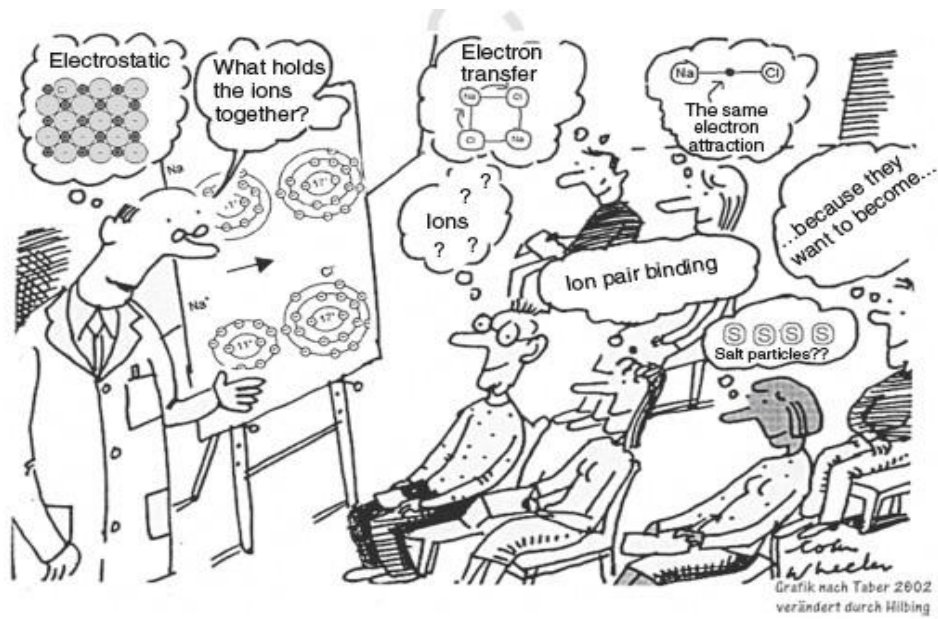


Fig. 3: Empirical findings concerning students’ misconceptions of ionic bonding [4]

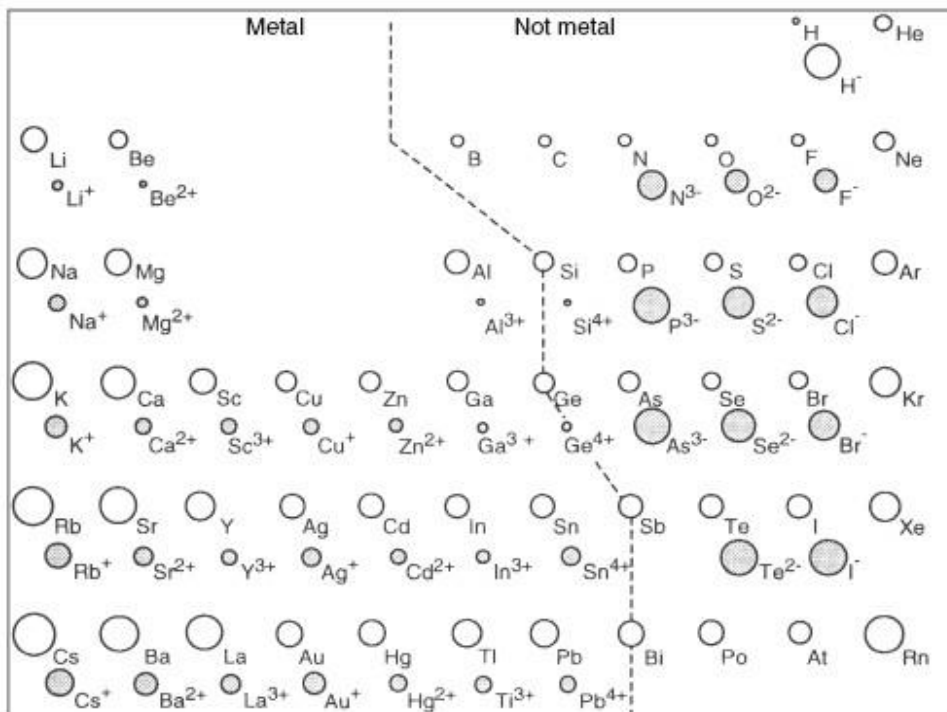


Fig. 4: PSE-depiction of a selection of atoms and ions and their spherical models [4]

Challenge of misconceptions.

Because of all new ideas about nucleus and shell, about electrons at different

energy levels, about outer electrons, about stable shells of noble gas atoms, many students are confused and it seems better to

introduce the idea about ions with the atomic model of Dalton. As soon as atoms and molecules are well known and visualized by their symbols also the third group of smallest particles should be introduced: the ions. One way is introducing the atoms of the Periodic Table with their atomic symbols and little spheres to visualize that every atom has a specific diameter. So it looks easy to symbolize also the according ions with symbols and their specific diameter (see figure 4): the charge number is given without comparing any protons in the nucleus and electrons in the shells – the ions are introduced without the differentiated atomic model! Remember: ions are discovered by Arrhenius in 1884 without knowing about electrons, the salts exist millions of years longer than sodium or potassium!

Analogically to point out the composition of a water molecule by the H_2O symbol, one may state that sodium chloride is composed of Na^+ ions and Cl^- ions in an ionic giant structure, that the ionic symbol for

sodium chloride can be shown as $(Na^+)_1(Cl^-)_1$ or for magnesium chloride as $(Mg^{2+})_1(Cl^-)_2$. To shorten those formulae it is possible to write $NaCl$ and $MgCl_2$ – but the involved ions should be the mental model of students!

The composition of important salt crystals can be visualized by 2D-drawings of layers of the ionic lattice (see figure 5), or by ionic symbols (see figure 6): formulae of salts are easy to find by calculating equal numbers of + and – charges. If salt solutions will be introduced in the same moment, the (aq)-symbol 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 (see figure 6). The (aq)-symbol seems important because the charge of ions is nearly compensated by H_2O molecules: hydrated ions are moving free without attraction in the solution. Ions in melted salts are attracting each other: beyond specific temperatures they are going together to form the ionic lattice in solid salt crystals.

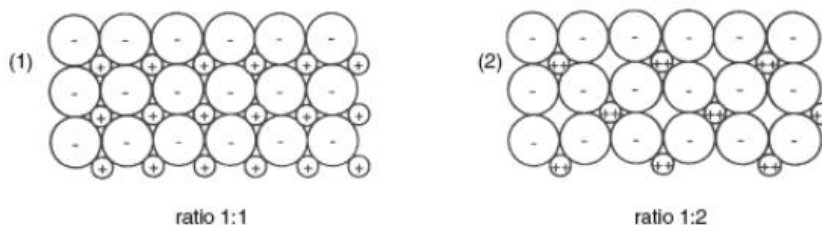


Fig. 5: 2D-models of ionic lattices in the ion ratio 1 : 1 (Na^+Cl^-) and 1 : 2 ($Mg^{2+}(Cl^-)_2$)

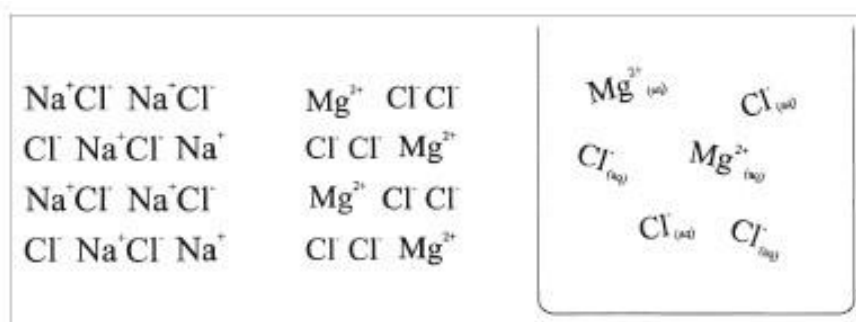


Fig. 6: 2D symbolic models of solid salt crystals and magnesium chloride solution

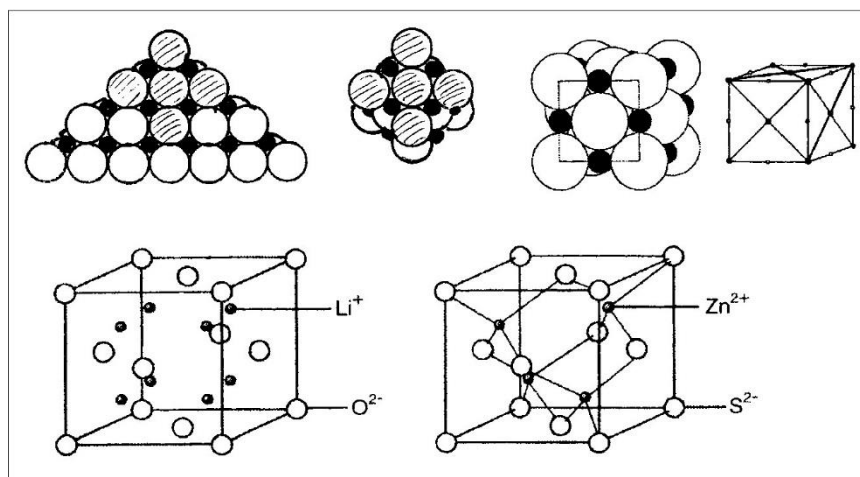


Fig. 7: 3D-structural models of the sodium chloride structure

It is advantageous for an understanding of the sodium chloride structure to build the spatial arrangement of ions by sphere-packing models (see figure 7, first packing left side): as a triangle of 30-mm balls the base layer should be glued together, other 30-mm balls are packed on top, finally 14-mm balls are filling all big wholes. The well known elementary cube is part of the giant structure: the cube should be glued, the ball in the middle of the first layer should be removed and the cube can be filled into the packing (figure 7, second and third model in the middle). It is also possible to build a crystal lattice model with balls and sticks (figure 7, right side): this model is built with sweet red and black candies and with tooth picks. This model shows only the arrangement of ions and the coordination number 6 in the sodium chloride structure but not the sizes of ions.

3.2 Chemical equilibrium

In order to understand most of the basic concepts in chemistry, chemical equilibrium is enormously important. In this sense Berquist and Heikkinen [11] state: “Yet equilibrium is fundamental to student understanding of other chemical topics such as acid and base behavior, oxidation–reduction reactions, and solubility. Mastery of equilibrium facilitates the mastery of these other chemical concepts”.

Unfortunately, it seems to be difficult to teach this topic. Finley, Stewart and Yaroch [12] studied the level of difficulty of

various themes in chemistry and reported the results of 100 randomly chosen teachers of chemistry from Wisconsin who chose chemical equilibrium as being clearly the most difficult theme overall. Berquist [11] noted: “Equilibrium, considered one of the more difficult chemical concepts to teach, involves a high level of students’ misunderstanding”. One can therefore expect a large variety of misconceptions because of the difficulties in teaching this subject as well as for understanding it.

Most common misconceptions.

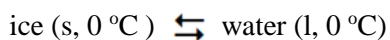
Tyson, Treagust and Bucat [13], Banerjee and Power [14], Hackling and Garnett [15] studied students’ comprehension of chemical equilibrium. The following misconceptions were discovered in these studies: “You cannot alter the amount of a solid in an equilibrium mixture; the concentrations of all species in the reaction mixture are equal at equilibrium” [13]. “Large values of equilibrium constant imply a very fast reaction; increasing the temperature of an exothermic reaction would decrease the rate of the forward reaction; the Le Chatelier’s principle could be used to predict the equilibrium constant” [14]. “The rate of the forward reaction increases with the time from the mixing of the reactants until equilibrium is established; a simple arithmetic relationship exists between the concentrations of reactants and products at equilibrium (e.g. concentrations of reactants equals concentrations of products); when a system is at equilibrium and a change is made in the

conditions, the rate of the forward reaction increases but the rate of the reverse reaction decreases (. . .) the rate of forward and reverse reactions could be affected differently by addition of a catalyst” [15].

Kienast [16] carried out tests on chemical equilibrium with over 12,000 students in four test cycles. The following misconceptions were observed: “In equilibrium the sum of the amount of matter (concentrations) of reactants is equal to the sum of the amount of matter (concentrations) of the products; in equilibrium the amounts (concentrations) of all substances which are involved in equilibrium are the same; the sum of the amounts of matter (concentrations) remain the same during a reaction” [16]. Another questionnaire of Osthues [17] is shown for diagnosis and interpretation of the understanding of chemical equilibrium [4].

Challenge of misconceptions.

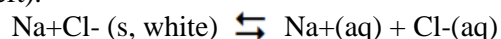
A first way to teach the equilibrium may be the melting of ice with the thermometer which shows 0 °C as long as a mixture of ice and water is present:



It doesn’t matter if there is much ice or more water: if both substances are there, equilibrium between solid and liquid water exists. During heating the energy is used to separate the water molecules from ice crystals – the temperature stays with 0 °C.

Another example shows the solubility of sodium chloride in water. If one observes a saturated sodium chloride solution together

with solid sodium chloride on the bottom of the flask, and adds an additional portion of solid sodium chloride to it, this portion sinks down without dissolving. If one measures the density of the saturated solution before and after the addition of salt portions, one gets the same measurements. The concentration of the saturated solution does not depend on how much solid residue is present; equilibrium sets in between the saturated solution and arbitrary amounts of solid residue (see figure 8 on the left):



Even if concentrated hydrochloric acid is added to the saturated solution, the equilibrium stays: because of the high concentration of chloride ions white solid sodium chloride crystals precipitate and decrease the concentration of sodium ions (see figure 8 on the right): an acidic sodium chloride solution remains.

One cannot see a *dynamic equilibrium*, reactions from saturated salt solution to solid salt and back. In order to have a better idea, it is possible to revert to a model experiment. Two similar measuring cylinders are prepared, 50 mL of water are placed in one of the cylinders, and the other one remains empty (see figure 9). Using two glass tubes of equal diameter to transport water back and forth, water is continuously transported between the two cylinders: after several transports, 25 mL of water remains in each of the cylinders, the water level does not change despite carrying constant volumes of water back and forth (not shown in figure 9).

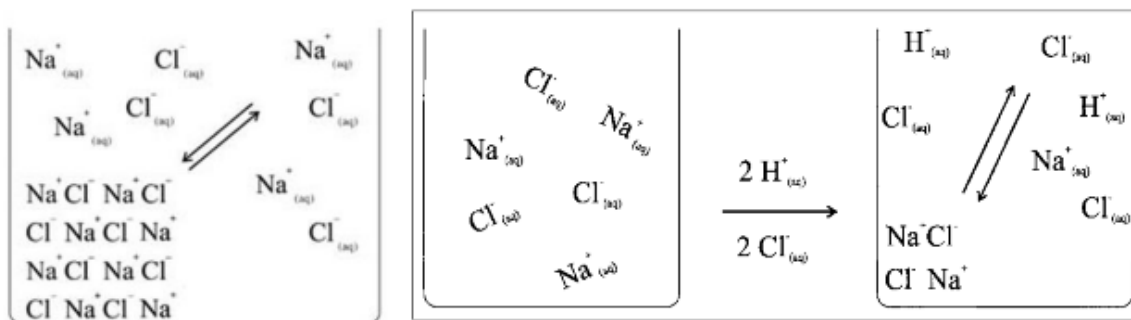


Fig. 8: Beaker models for the solubility equilibrium of saturated sodium chloride solution

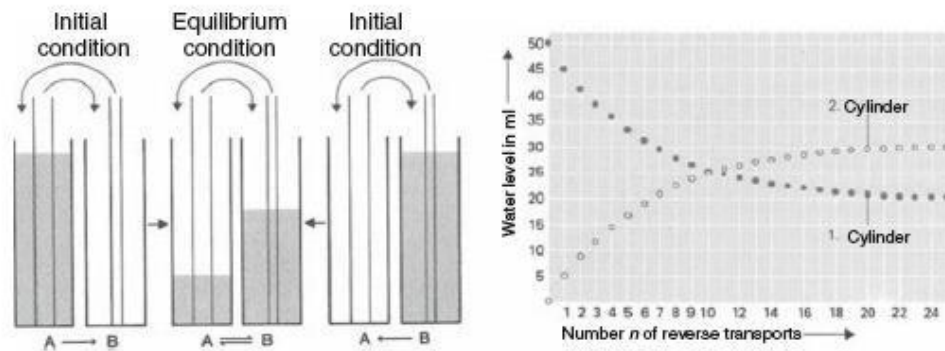


Fig. 9: Model experiment for the dynamic aspect of a chemical equilibrium [18]

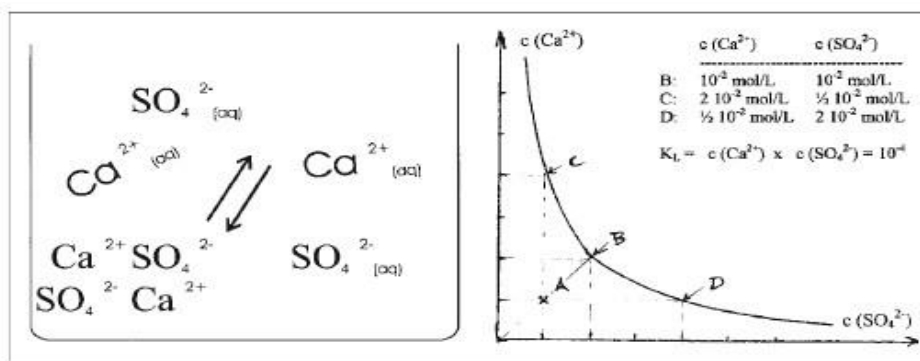
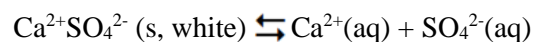


Fig. 10: Model drawing and mental model of solubility equilibrium of calcium sulfate

If two glass tubes with different diameters are used, then one cylinder would perhaps have the volume of 20 mL and the other would have 30 mL “in equilibrium”: the water level does not change because the same amount of water is continuously carried back and forth in the two different glass tubes (see figure 9, left side). If one records the number of transports and the measured volumes in both cylinders a special graph results (see fig. 9, right side).

If calcium sulfate powder (gypsum) is mixed well with water and the suspension is left to stand, a white solid sinks down to the bottom. The question arising from the amount of solid substance is whether a part of the calcium sulfate dissolves or the substance is insoluble in water. Testing the electrical conductivity, however, shows a much higher value than with distilled water: calcium sulfate dissolves in very minute amounts; a dynamic equilibrium is formed between the solid residue and the saturated solution:



Magnesium sulfate and calcium sulfate solutions of equal concentrations show approximately the same electrical conductivity. If one compares electrical conductivity of the saturated calcium sulfate solution with the conductivity of various standard solutions of soluble magnesium sulfate, one can find the unknown concentration of the saturated calcium sulfate solution at 30 °C:

$$c(\text{calcium sulfate}) = 10^{-2} \text{ mol/L}$$

Accordingly, for saturated calcium sulfate solution we know ion concentrations (see figure 10):

$$c(\text{Ca}^{2+}) = 10^{-2} \text{ mol/L}$$

and

$$c(\text{SO}_4^{2-}) = 10^{-2} \text{ mol/L}$$

Now the solubility product can be defined in the following way (see figure 10):

$$K_{sp}(\text{CaSO}_4) = c(\text{Ca}^{2+}) \times c(\text{SO}_4^{2-}) = 10^{-4}$$

If one is dealing with a diluted calcium sulfate solution, saturation can be attained in three different ways (see point A in figure 10, right side): one continues to add solid calcium sulfate and reaches saturation (Point B). It is however also possible to add drop wise concentrated calcium chloride solution, thereby increasing the concentration of $\text{Ca}^{2+}(\text{aq})$ ions until the first calcium sulfate crystals precipitate (Point C). It is also possible to add concentrated sodium sulfate solution, thereby increasing the concentration of $\text{SO}_4^{2-}(\text{aq})$ ions until the first solid calcium sulfate precipitates (Point D). In each case, we have a pair of values for the saturation equilibrium on the hyperbolic curve (see table in figure 10), these pairs follow the solubility product. If one varies concentrations of ions involved in equilibrium by adding same kind of ions, then it is obvious that the product of ion concentrations is always constant, that this product has always, at constant temperature, the value $K_{\text{sp}} = 10^{-4}$. Tables and hyperbolic figures may demonstrate the concentration dependence of the related ions (see figure 10).

The solubility equilibrium of calcium sulfate can also be demonstrated by supplementing portions of sodium sulfate and calcium chloride solutions: using highly concentrated solutions solid calcium sulfate precipitates. In addition to $\text{Ca}^{2+}(\text{aq})$ ions and $\text{SO}_4^{2-}(\text{aq})$ ions, the solution also contains $\text{Na}^+(\text{aq})$ ions and $\text{Cl}^-(\text{aq})$ ions, the equilibrium can be approached from the side of the dissolved ions:



3.3 Acid-base reactions and proton transfer

Examples of misconceptions are described by many authors around the world. In our institute Musli [19] developed a questionnaire and gave it to about 100 students at senior classes of German high schools. Unusual and interesting statements from students have been quoted relating to acids, specifically on the differences between pure acids and acidic solutions, on neutralization, and on differences between strong and weak acids.

Acid concepts.

Astonishingly, only acids are accredited with an “aggressive effect”, although bases also have this attribute: “acids eat away, acids destroy, and acetic acid is a destructive and dangerous substance in chemistry, not used in normal everyday life” [19]. “An acid is something which eats material away or which can burn you; testing for acids can only be done by trying to eat something away, the difference between a strong and a weak acid is that strong acids eat material away faster than weak acids” [20]. Barker (Kind) [20] comments on these students’ statements as follows: “no particle ideas are used here; the students give descriptive statements emphasizing a continuous, non-particle model for acids and bases, some including active, anthropomorphic ideas such as ‘eating away’ “.

Regarding the question “what do you understand by the term acid or base?”, many students respond with a pH value (“acids have a small pH value”). Other statements describe acid concepts, which have been mainly learned and remembered: approximately 15 % of the answers show the Arrhenius concept (acids contain H^+ ions); approximately 30 % show the Broensted concept (acids release protons), whereby it is not certain if students correctly understand the notion of acids as acid particles. In the additional exercise, “give examples for atoms/ions/molecules that are acids or bases”, mostly formulas for hydrochloric acid, sulfuric acid and acetic acid are noted. Regarding the Broensted concept, the correct answers for base particles, i.e. the hydroxide ions have only been listed in about 15 % of the cases, at the same level as hydronium ions in diluted solutions of strong acids.

Sumfleth [21] shows that students accept the Broensted definition, but are interpreting bases mostly on Arrhenius’ idea. Therefore, the knowledge about Broensted’s concept cannot be transferred to new contexts: “most students cannot really apply acid–base theories, this is also evident for students who have chosen chemistry as their major”. Students also have a lot of difficulties with the idea of an acid. They tend to think in three directions:

1. acids as pure substances like the gas hydrogen chloride, HCl,
2. acids as solutions like hydrochloric acid, containing $\text{H}^+(\text{aq})$ ions and $\text{Cl}^-(\text{aq})$ ions,
3. acids as particles like hydronium ions, $\text{H}_3\text{O}^+(\text{aq})$.

Mostly, students mix up all three ideas. They speak of substances: “hydrochloric acid gives one proton”. They think protons come out of the nucleus of atoms

or ions: “the other particle should be radioactive”, etc. Students have problems switching from the level of substances to the level of particles and they like – even in advanced classes – to stay on the level of substances: “hydrogen chloride plus acid gives hydrochloric acid”. When discussing corresponding acid-base pairs, students do not deal appropriately with the level of particles, they prefer to state: “hydrogen chloride and water form the corresponding acid-base pair”.

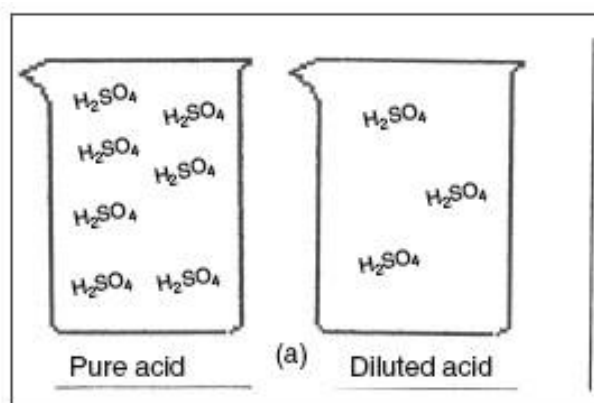


Fig. 11: Beaker models of pure and diluted sulfuric acid [4]

Pure acids and acidic solutions.

In another exercise [19], the students are supposed to state the similarities and differences between pure sulfuric acid and the 0.1 molar solution, and to schematically draw the smallest particles in two model beakers (see figure 11). Correct answers regarding hydronium ions and sulfate ions in dilute solutions can be found in 10 % of the answers or model drawings. Approximately 45 % of the answers approach it from the dilution effect: symbols for sulfuric acid molecules for the diluted solution are written with larger distances (see figure 11).

Many other answers offer different claims: “pH value of pure acid is less; pH values are different for acids and acidic solutions (without mentioning pH value or differences); the densities vary; pure acids are much more corrosive, are more amenable to reactions than the solution”. Only about 10 % of the students gave the correct verbal answers and included appropriate model drawings with the expected ion symbols for the diluted solution. A surprising fact is that two students who gave a correct verbal answer regarding

the “dissociation in diluted sulfuric acid solution” did not note any ion symbols.

Neutralization.

In this exercise [19], it was stated that “hydrochloric acid reacts with sodium hydroxide solution”. The students were asked first to show chemical equations using the types of involved particles. Approximately 80 % of the students were able to write the common equation: $\text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O}$. Half of the students noted the reaction equation with ion symbols and expressed that the $\text{H}^+(\text{aq})$ ions and the $\text{OH}^-(\text{aq})$ ions react to produce H_2O molecules. Most of the students stated, that “NaCl” is formed without showing sodium ions and chloride ions; some even offer “NaCl molecules”, “solid NaCl” or “NaCl crystals” as reaction products. Sumfleth [21] found that students think along the lines of acid–base equilibrium: “after neutralization, sodium chloride solution contains the same amount of hydrochloric acid and sodium hydroxide solution; with neutralization there exists equilibrium of acid and base”.

Strong and Weak Acids.

Sumfleth [21] describes the common misconception, that for most students acid strength is solely based on the pH value of solutions. Thus, it is possible for them to determine the acid strength in an experiment by using acid–base indicators. Students overlook that by taking a 1M hydrochloric acid solution with a pH value of 0, one can dilute to every larger pH value up to almost 7. The acid strength as equilibrium and as different concentrations of molecules or ions and mixing those ideas, causes confusion.

In our questionnaire [19], students were asked to compare and contrast 0.1M solutions of hydrochloric acid (HCl) and acetic acid (HAc); and in addition students were requested to draw schematic beaker

models of involved atoms, ions or molecules. Approximately half of the students gave no answers concerning similarities and differences, 20 % mentioned the acid strength, and 10 % noted the pH value as differences. Acetic acid was regarded as “the stronger acid because a larger I-effect of the methyl group can be registered at CH₃COOH molecules and therefore the proton can more easily split off”. This quotation shows that the treatment, which coincidentally took place in the half year of the studies in organic chemistry, lead the students to associations on arbitrary contents, which they did not properly understand. Only to 15 % of the students showed appropriate acetic acid molecular models and the related ions in their model drawings (see figure 12 up left).

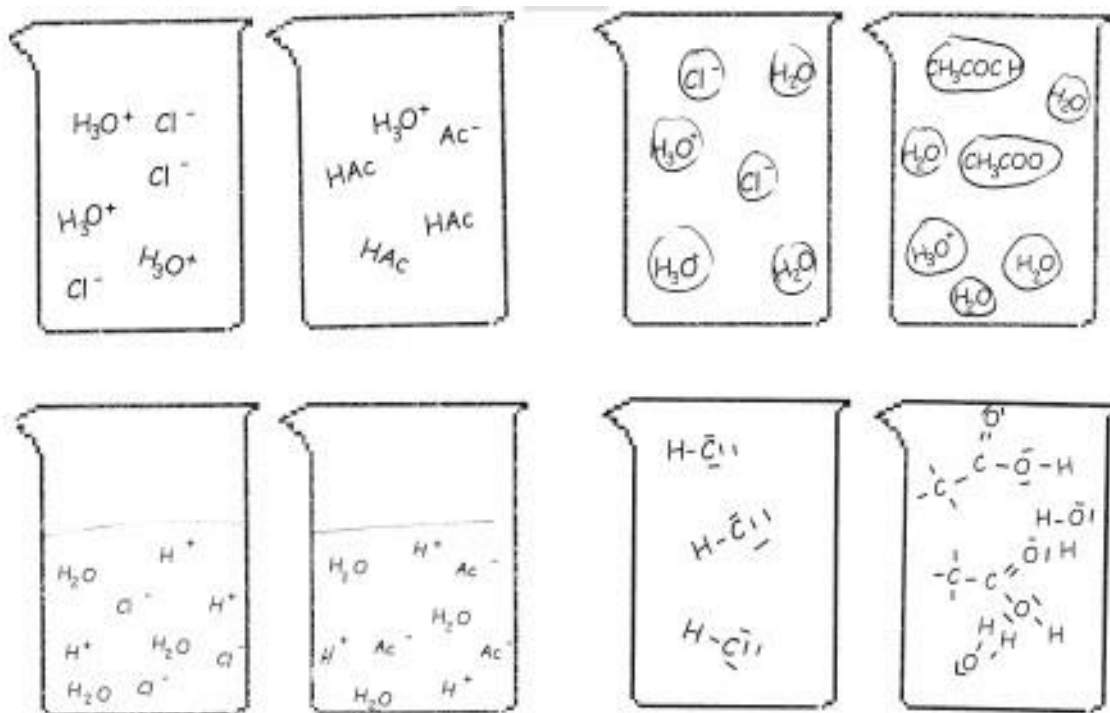


Fig. 12: Examples for appropriate and inappropriate mental models on weak acids [4]

To the same degree, students have drawn correct ion symbols but no molecule symbols, or they merely imagine only molecules and no ions (see figure 12). From this data one can easily conclude that these students have not understood the differences between strong and weak acids, they know about equilibria but do not apply the

knowledge on the equilibrium of molecules and ions in weak acids.

Challenge of misconceptions.

Because acids are known as solutions which are “destroying other material” those statements support the destruction concept of students. To challenge this misconception one

can show that acidic household cleaners remove lime deposits, but produce salt solutions and carbon dioxide: all changes of material by acids or bases are chemical reactions producing other special products. But the most important challenges are misconceptions according the Broensted concept, neutralization and weak acids.

Broensted concept.

After knowing some phenomena and the facts that acidic solutions contain $H^+(aq)$ ions and

basic solutions $OH^-(aq)$ ions, it is important to convince learners that the proton-transfer idea is the broader concept for acids and bases. Because one proton can only go from one particle to another one, this Broensted idea is based on acidic particles which give protons like HCl molecules, H_2SO_4 molecules, $H_3O^+(aq)$ ions or $HSO_4^-(aq)$ ions.

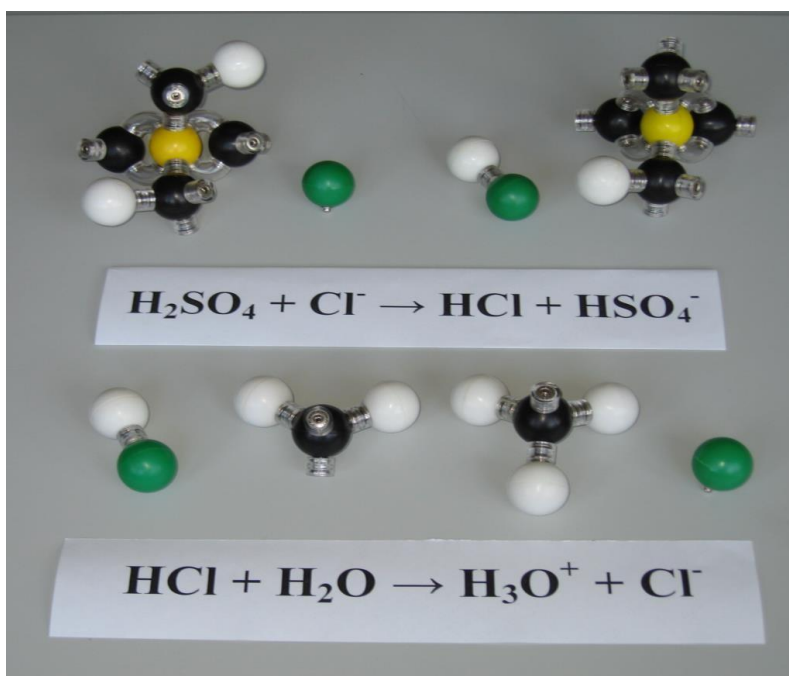
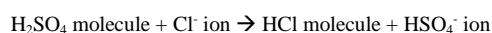


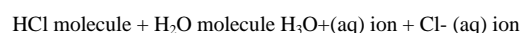
Fig. 13: Visualization of two acid-base reactions in the sense of Broensted's theory [19]

One example for a typical proton-transfer reaction is the formation of hydrogen chloride gas by sodium chloride and pure sulfuric acid. Both are given into a gas developer, the acid is dropped to the salt: gaseous hydrogen chloride can be filled into a gas syringe or a cylinder. By this reaction H_2SO_4 molecules donate protons (H^+ ions) to Cl^- ions of sodium chloride to form HCl molecules and HSO_4^- ions, sodium hydrogensulfate remains (see figure 13):



The produced hydrogen chloride gas can be mixed with water: the indicator changes colors, electric conductivity raises. This well known reaction forms hydrochloric

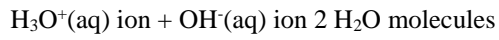
acid solution, HCl molecules give protons to H_2O molecules, the following ions are obtained (see figure 13):



In both cases molecules are acids or acidic particles which donate protons, Cl^- ions and H_2O molecules are bases or basic particles which accept protons. In hydrochloric acid the $H_3O^+(aq)$ ion reacts as a proton donor, also in diluted sulfuric acid the $H_3O^+(aq)$ ion is the acidic particle – not the H_2SO_4 molecule. For all acid-base reactions one has to look at those particles which give protons, and at those which take protons.

Neutralization.

Taking solutions of strong acids and bases, the $\text{H}_3\text{O}^+(\text{aq})$ ions are the acidic particles and $\text{OH}^-(\text{aq})$ ions the basic particles, both react to form water molecules:



After their reaction the other ions remain: in case of the reaction of hydrochloric

acid and sodium hydroxide solution $\text{Na}^+(\text{aq})$ ions and $\text{Cl}^-(\text{aq})$ ions remain as “spectator ions”, they are no reacting partners. No “solid salt” or “ NaCl molecules” are produced but sodium chloride solution remains – it is good for understanding to visualize this by ion symbols (see figure 14).

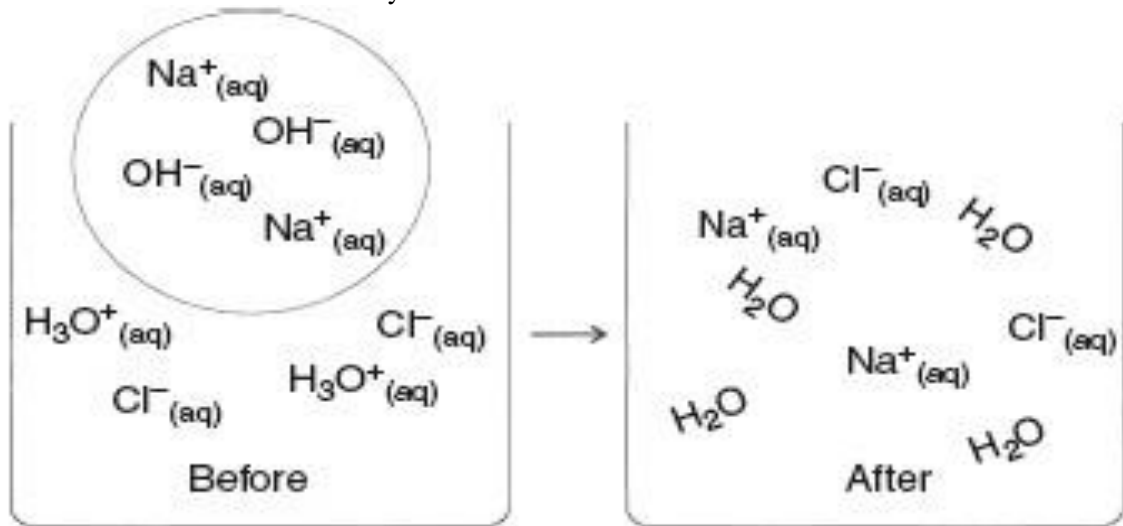


Fig. 14: Beaker model of the neutralization of hydrochloric acid by sodium hydroxide

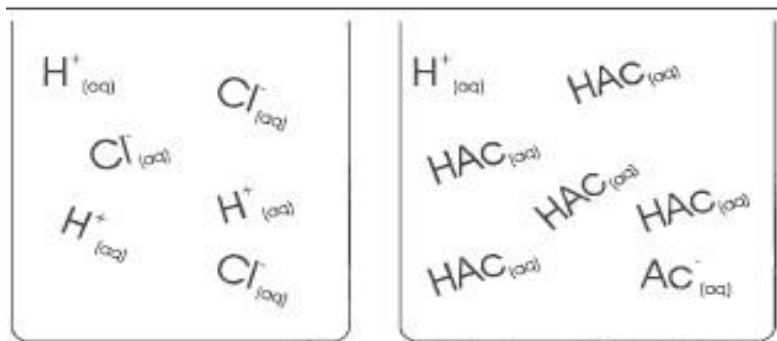


Fig. 15: Beaker models of a strong and a weak acid

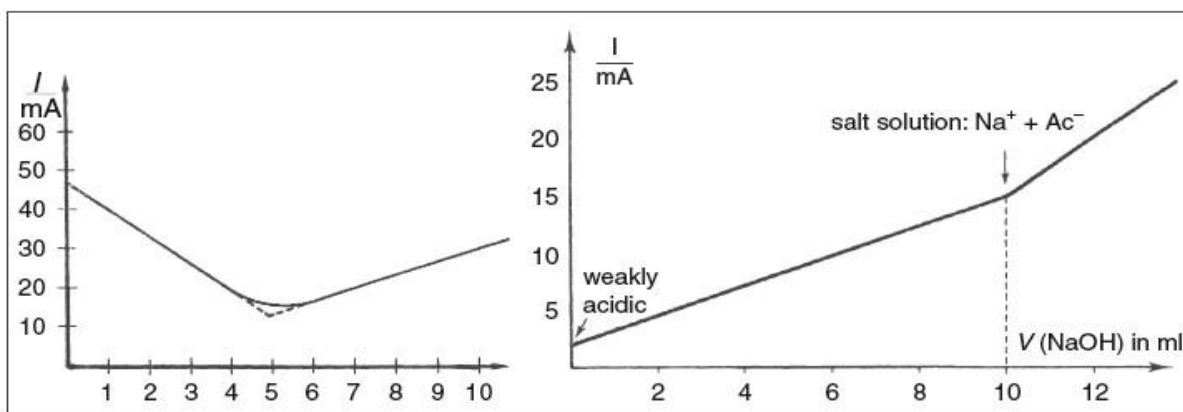


Fig. 16: Diagrams of conductivity titrations of hydrochloric acid and acetic acid [18]

It is also advantageous to visualize that the number of ions is the same before and after neutralization: four ions in this model (see figure 14) are there before neutralization, four ions are there afterwards. So the $\text{H}_3\text{O}^+(\text{aq})$ ions are replaced by $\text{Na}^+(\text{aq})$ ions, and the electric conductivity goes down during neutralization because $\text{H}_3\text{O}^+(\text{aq})$ ions have a higher specific conductivity compared to the $\text{Na}^+(\text{aq})$ ions after neutralization.

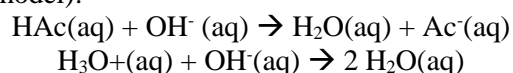
Weak acids.

The term “weak” suggests itself the following most common misconception: weak acids are “weakly concentrated”. It may well be that during students’ lessons, protolysis equilibrium of acetic acid was used as an example, may be even equilibrium constants came into play, and pH values of specific acetic acid solutions were measured or calculated – however, only a few students are able to comprehend and connect all these facts to develop the scientific idea about weak acids. In order to look at the degree of protolysis, it is advisable to use convincing experiments. If the pH values of 1.0 molar and 0.1 molar solutions of two acids, hydrochloric acid and acetic acid, are measured with a calibrated pH meter, one gets the expected pH values of 0 and 1 for hydrochloric acid solutions – but not for the acetic acid solutions: approximately pH values of 2.4 and 2.9 can be measured

When this happens, a classic cognitive conflict arises: “what is so different about acetic acid”? If the 0.1 molar acetic acid solution shows a pH of nearly 3, the concentration of the $\text{H}^+(\text{aq})$ ions should be

10^{-3} mol/L. Because the concentration of HAC molecules starts with $c(\text{HAc}) = 10^{-1}$ mol/L, only 1 % of the HAC molecules protolyse into ions. In a beaker model one should draw 99 models of HAC molecules compared to only 1 $\text{H}_3\text{O}^+(\text{aq})$ ion and 1 $\text{Ac}^-(\text{aq})$ ion – in every case the number of molecule models must be higher than the number of ions (see figure 15, right model). If the aspect of a dynamic equilibrium is connected and K_S constants are discussed carefully, the understanding will rise.

Additionally, electrical conductivity measurements help in the understanding of protolysis equilibrium for weak acids. The comparison of equally concentrated strong and weak acids supplies the much lesser conductivity for weak acid solutions. If one carries out a conductivity titration one gets very different forms of conductivity curves in comparison to the titration of strong acids (see figure 16). Titrating with sodium hydroxide solution, the measured values do not decrease but they rather increase. In this titration, a very low concentration of hydronium ions reacts with hydroxide ions, but mostly the large number of HAC molecules is transferring protons to $\text{OH}^-(\text{aq})$ ions: HAC molecules are replaced by $\text{Ac}^-(\text{aq})$ ions and therefore the increase in conductivity is explained. Later, after the equivalent point is reached and an excess of hydroxide ions appears, the curve increases more steeply. For the description of this neutralization, there are two kinds of acid-base reactions (see also figure 15, right model):



If all acid-base reactions are interpreted consequently with atoms, molecules or ions as acidic and basic particles students may get a scientific understanding of the Bronsted concept and will not develop misconceptions as presented.

3.4 Redox reactions and electron transfer

As in the historical development, the Lavoisier definition of oxygen transfer is often used in beginners' lessons ("metals take oxygen, metal oxides are formed"). Later, as soon as the differentiated atomic model is introduced, the redox reaction regarding electron transfer is applied in advanced lessons. Knowing the oxygen transfer and the idea of the redox reaction there is often the belief that oxygen has to be involved in *every* redox reaction. The reason for this may be the syllable *-ox*, which is semantically strongly associated with the name oxygen (oxidation, metal oxide or nonmetal oxide).

Schmidt [22] described studies with almost 5000 students which were asked to decide on which of his listed reactions belonged to redox reactions: the reaction of diluted hydrochloric acid with (1) magnesium (Mg), (2) magnesium oxide (MgO), and (3) magnesium hydroxide (Mg(OH)₂). We know of course that (1) is to be identified as a redox reaction, that (2) and (3) are acid-base reactions: in (2) H₃O⁺(aq) ions react with O²⁻ ions of magnesium oxide, and in (3) H₃O⁺(aq) ions react with OH⁻ ions of magnesium hydroxide.

Approximately half of the students in advanced courses chose the correct answer. The remaining students marked one or both oxygen-related reactions and gave explanations like: "(2) and (3) contain oxygen, which is absolutely necessary for redox reactions; oxygen is necessary for every redox reaction, so (1) cannot be a redox reaction; (2) and (3) are redox reactions because in both cases oxygen and electron transfer takes place; oxidation means: a reaction in which oxygen is involved. The ending 'oxide' shows that (2) as well as (3) are redox reactions" [22].

According to the oxygen concept Schmidt [22] cited the following study about a typical acid-base reaction: "Garnett and Treagust, in 1992, asked senior high school students whether or not the equation

$\text{CO}_3^{2-} + 2 \text{H}^+ \rightarrow \text{H}_2\text{O} + \text{CO}_2$ represents a redox reaction. All students with correct answers used the oxidation number method. Those who answered incorrectly had two reasons. One was to assume that the carbonate ion donates one oxygen atom to form carbon dioxide and was, therefore, reduced. The other was to assign the oxidation number to polyatomic species by using their charge number. CO₃²⁻ was given the oxidation number negative 2, and CO₂ the oxidation number 0. Consequently, the reaction CO₃²⁻ → CO₂ was identified as an oxidation. In a similar manner, the reaction H₃O⁺ → H₂O can be identified as a reduction: the hydronium ions must have gained electrons and so should have been reduced" [22].

Sumfleth [21] asked students in grades 6 - 12 in Germany to provide an explanation regarding the popular reaction of an iron nail in copper sulfate solution. She found incorrect answers, which could be traced back to precepts, as well as school-made misconceptions.

Especially, students in grades 6 – 8 described the formation of a copper-colored coating with "sedimentation, clinging to, sticking to, or color fading of a material on an iron nail" or "the copper sulfate colors the iron nail, the copper sulfate sticks on to it, like when a piece of wood is placed in a dye and is then dried". Half of the 7th grade students guessed "an attraction of the substances" as the reason, the other students mentioned a pre-existing magnetism – probably because of the iron nail. These students however, only described their observations with words, one cannot admonish them for their preliminary ideas. Even in senior high school classes, these discussions remain: "copper sulfate is reduced; copper atoms attract electrons; iron nails can absorb ions from the solution" [21].

Heints [23] carried out new studies in grades 10 – 12 at German high schools where redox reactions have been introduced as electron transfer, the found school-made misconceptions are similar to those which are mentioned already. Many other references show misconceptions in the area of redox reactions, especially with the interpretation of voltage and electric current in electrolysis or Galvanic cells. Marohn [24] looked for the mental models that students develop by

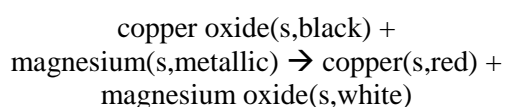
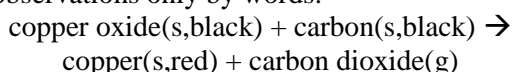
discussing Galvanic cells. In addition, Garnett and Treagust discovered conceptual difficulties in the area of electric circuits [25] and electrolytic cells [26], the same with Ogade and Bradley working on electrode processes [27], Sanger and Greenbowe investigating common misconceptions in electrochemistry [28] or current flow in electrolyte solutions and the salt bridge [29].

Challenge of misconceptions.

Nevertheless, these topics are so difficult to understand that misconceptions can hardly be avoided – especially concerning the nature of electrons as waves and/or particles, concerning the electromagnetic fields and their forces. Therefore, the only challenge is to look to the basic definitions of the redox reaction and to discuss common experiments, to gain scientifically accepted mental models of redox reactions.

Oxygen transfer.

If the students in beginner classes of chemistry should know about the production of iron, copper or other metals from ores and metal oxides, one can demonstrate the reaction of copper oxide with carbon or with magnesium. One should stay on the macro level of substances and their reactions and describe the observations only by words:



It can be stated that copper oxide is reduced to copper, that carbon is oxidized to the compound carbon dioxide – but perhaps one can avoid to call this reaction redox reaction. Because of all misconceptions mixing the oxygen and electron definition one can wait and name in higher classes of chemistry only the electron transfers with the idea of redox reaction.

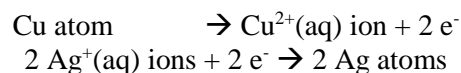
Electron transfer.

For the same reason, one starts that topic with reactions where no oxygen is involved, for example with the cementation of copper from a copper sulfate or better a copper chloride

solution. Because some students argue with “iron takes oxygen from sulfate ions” [23] it seems more acceptable to use copper *chloride* solution. A prerequisite for the interpretation of metal precipitations is the term “ion” and the atomic structure by nucleus and differentiated electron shells. So the blue color of a diluted copper chloride solution can be explained by the presence of $\text{Cu}^{2+}(\text{aq})$ ions. Armed with this information, there are good ways for the problem-oriented interpretation of the following experiments.

An iron nail is dipped into copper chloride solution and taken out after 20 seconds: a copper-colored coating appears on the iron nail. If iron wool is placed in copper chloride solution, the wool turns red, the solution warms up, the blue color of the solution disappears. The discoloration of the solution almost forces an interpretation, that $\text{Cu}^{2+}(\text{aq})$ ions from the solution “disappear”, or have reacted. This question leads to the supposition that they have deposited as Cu atoms on the iron and have formed copper crystals.

If a helix-shaped copper wire is placed into diluted silver nitrate solution and one waits a few minutes, then the development of silver crystal needles can be observed and also the change in the color of the initially colorless solution to blue. With this reaction one observes that $\text{Cu}^{2+}(\text{aq})$ ions appear and that copper metal has partially dissolved. From this reaction, one concludes that, with experiences gathered from the first experiment, metal atoms dissolve as ions, accompanied by the release of electrons. Along with this, metal cations of the salt solution take electrons, forming metal atoms and crystallizing to needles of pure silver:



Describing the half reactions, it should be made apparent to the students that the term “+ 2e⁻” should be placed on the correct side of the equation: one Cu atom can become one Cu^{2+} ion only if it simultaneously releases two electrons. It is advisable to suggest to students that the number of atoms and the number of charges should be the same “left and right of the arrow”. In the given

examples, the number of the charges on both sides is zero in each case.

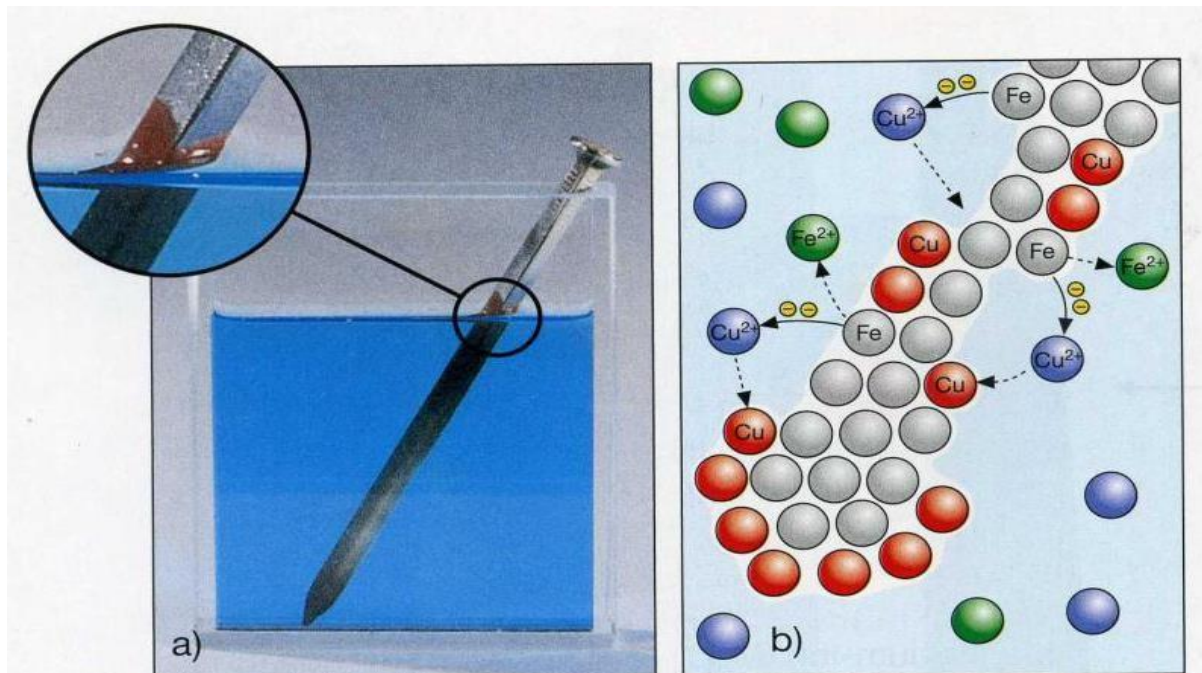
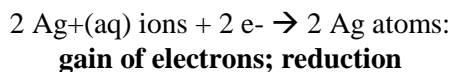


Fig. 17: Reaction of an iron nail with copper chloride solution and mental model [18]

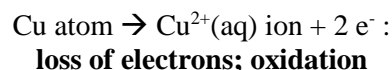
It should be concluded that the ions from the more noble metals are changed into atoms and crystallized from the solution. Simultaneously, due to electron transfers, the atoms of active metals dissolve through the formation of ions. This hypothesis can systematically be tested with other metal pairs; the observations are noted by the precipitation sequence of metals.

Of course, those reactions should be visualized, for example by a beaker model (see figure 17): each Cu^{2+} ion from the solution is taking two electrons, an iron atom of the nail is delivering them, dissolving as an Fe^{2+} ion. The chloride or sulfate ions are not reacting, they can be called “spectator ions”.

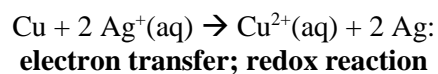
The conversion of metal compounds to pure metals is historically known as reduction; so the reduction of metal ions with the gaining of electrons is thereby explained:



The gained electrons stem from the reacting metal atoms, which form ions by losing electrons:



Altogether, an electron transfer takes place from Cu atoms of copper to Ag^{+} ions of the solution:



The term oxidation can now be associated with well-known metal-oxygen reactions; also in these reactions, metal atoms are oxidized into their corresponding metal ions, oxygen atoms are taking electrons and are reduced into oxide ions. Oxygen reactions can be called special types of redox reactions – but most other redox reactions deal without oxygen as a reaction partner!

If one argues consequently by all further redox reactions with the atoms, ions and molecules, this topic can be understood and the definition by “oxygen transfer” should not interfere with the the idea of “electron transfer”. Later, redox reactions can be explained by oxidation numbers too – but pay attention: by this mental model the oxidation

number of *atoms* or of *atoms in molecules* is involved, not any oxidation number of *substances*.

4. Best practice to challenge misconceptions

Acid-base reactions and proton transfer can only be explained if consequently the atoms, ions or molecules are pointed out which give or take a proton. With redox reactions and electron transfer it is the same:

atoms, ions or molecules are giving or accepting one or two electrons – not substances! Johnstone [30] created a “Chemical Triangle” with three corners (see figure 18): The macro level shows phenomena like substances and reactions, the submicro level shows the involved atoms, ions, molecules and chemical structures, the representational level formulae, equations, stoichiometric calculations, etc.

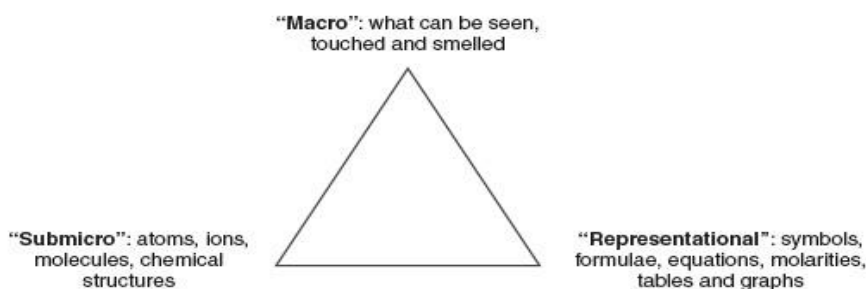


Fig. 18: “Chemical Triangle” for teaching chemistry according to Johnstone [30]

He points out that chemistry is hard to understand if one switches from the macro level just to the representational level: students are memorizing formulae and equations, and don't have the chance to understand. Instructing first – after showing some phenomena – the submicro level and the involved atoms, ions, molecules and chemical structures of involved substances, the learners will understand in a better way. One example: conducting titrations in the neutralization topic, one shows and discusses the beaker model first (see figure 14), and after that one can develop equations to show the reaction of hydronium ions with hydroxide ions to water molecules. Going this way, students will accept that formulae and reaction equations are shortening models of all theoretical explanation, also of the shown beaker models.

Misconceptions

Many misconceptions are appearing when the “submicro level” [30] is introduced: Students are transferring properties of substances to properties of particles [4]:

- S atoms are yellow, Cu atoms are red,
- P atoms are poisonous, they ignite themselves,

- one Cu atom is the smallest portion of copper,
- sugar molecules are sweet,
- sugar molecules disappear by dissolving sugar in water, but the water tastes sweet,
- particles can disappear by dissolving crystals, they appear again by crystallization,
- water has an angle of 109 degrees,
- water molecules are liquid,
- O atoms have two arms, H atoms only one arm,
- C atoms are destroyed by combustion of charcoal,
- magnesium contains of two kinds of particles: one kind evaporates by combustion, the others remain as ashes,
- between molecules of gases there must exist some invisible material, there cannot be a vacuum (horror vacui),
- gas molecules have no mass.

Teachers and students can avoid the mixture of those misconceptions if they differentiate three levels of terminology concerning the three levels of Johnstone's triangle (see fig. 18):

- macro level (reality): substances and their properties like density, melting temperature, boiling temperature, electric conductivity, pH values, etc., chemical reactions, substances before and after reactions, energy changes, etc.
- submicro level (mental and concrete models): experts investigate substances and get mental models about chemical structures by their measurements and scientific theories; learners cannot go this way – they need sphere packing and lattice models for giant structures or molecular models for the structure of involved molecules as concrete models concerning the arrangement of atoms, ions or molecules; by those models they can develop suitable mental models,
- representational level (symbolic level): formulae, chemical equations, mole idea, stoichiometric calculations, equilibrium constants and their use, calculations of pH values or redox potentials, thermodynamics and calculations of energy changes, etc.

Besides all “preconcepts” brought from everyday life [4] and those misconceptions concerning the chemical terminology students are developing “school-made misconceptions” by not sufficient teaching in the area of difficult topics [4]:

- chemical equilibrium and the use of equilibrium constants,
- acid-base reactions and proton transfer from one particle to another one,
- redox reactions and electron transfer from one particle to another one,
- complex reactions and ligand transfer from one particle to another one,

- energy transfer, specially concerning chemical energy.

If teachers know those misconceptions they can plan all instruction on base of this knowledge and can prevent students from school-made misconceptions or can even integrate misconceptions into instruction for a better understanding.

Integrating misconceptions into instruction.

In older times, teachers perceived the students like “blank pages” and thought that teachers only have to fill the “blank pages” with contents of science. Today we know that at a very early stage, students develop their own preconcepts about properties of substances and their changes, about combustion processes and the role of gases. Today empirical studies show that we have more success in teaching and learning when we integrate those alternative models into instruction: the **conceptual change** seems more realistic if students discuss their conception, feel uncomfortable with it, feel that the new scientific concept can explain better, and can do a conceptual change more successful [31]. Also school-made misconceptions should be reflected and compared with the scientific explanation.

One way for the comparison of own concepts and scientific ones are **concept cartoons** [10]: the right answer is shown by a statement of a boy or girl – and a lot of alternatives are shown too. In an example (see figure 19) students are asked: “what species are present in hydrochloric acid”? By this way the teacher may diagnose misconceptions about the composition of the acidic solution and will find how students are thinking.

What species are present in hydrochloric acid ?



Fig. 19: Concept Cartoon concerning the composition of hydrochloric acid [10]

With the preparation of this topic the teacher can challenge those misconceptions by convicting experiments, suitable models and problem-solving teaching. After finishing the topic the teacher may show the same cartoon another time: students will discover the right answer and will explain what is wrong with the other alternatives. With this knowledge students will write a better test or will give the correct answer more easily.

The American scientist Ausubel [32] has written a big book about educational psychology. In an interview he was asked to mention only one sentence which seems the most important for education. Ausubel stated: "Ask your students what they know about a topic. Take those answers and plan your instruction on the base of that knowledge" [32]. Also the reflected misconceptions are part of the knowledge that students are bringing to class: teachers should know this knowledge and should integrate it in his lectures!

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