DONOR-ACCEPTOR REACTIONS: GOOD BYE TO THE LABORATORY JARGON

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ABSTRACT

For chemistry education we are discussing mainly two concepts of acids and bases: theories of Arrhenius and Broensted. The first theory discusses the **dissociation** of molecules into ions: hydrochloric acid solution contains H^+ (aq) ions and Cl^-(aq) ions, sodium hydroxide solution contains Na^+(aq) ions and OH^-(aq) ions. This theory therefore deals with substances, which are acids or bases – it would be even better to take the logical names "acidic and alkaline solutions". If both solutions are mixed in equivalent quantities, the H^+ (aq) ions react with OH^-(aq) ions to form H_2O molecules, while the other ions remain in solution. The Broensted theory defines **protolysis** and proton transfers: a molecule or an ion transfers a proton (H^+ ion) to another molecule or ion; two conjugated acid-base pairs are involved. Thus, Broensted acids and bases are no more substances, but individual types of particles. Due to the autoprotolysis of H_2O molecules (not "autoionization of water"), the following equilibrium exists:

$$H_2O \quad + \quad H_2O \quad \leftrightarrows \quad H_3O^+(aq) \quad + \quad OH^-(aq)$$

Through this protolysis it is more advantageous to argue rather with H_3O^+(aq) ions than with H^+(aq) ions. In this theory there are still ampholyte particles which react as acid or as base particles – depending on the reaction partner: H_2O molecules, NH_3 molecules, HSO_4^- ions. Water, ammonia or sodium hydrogen sulfate cannot be regarded as ampholytes – pure water cannot be one time an acid and another time a base: with the pH of 7 it is always a neutral substance. The article will show misconceptions of students and point out the better terminology: reflecting this terminology, students should develop a better understanding of Chemistry! *[African Journal of Chemical Education—AJCE 6(1), January 2016]*

INTRODUCTION

The principle of "giving and taking" is well-known in every-day life – less known is the chemical donor-acceptor principle comprising the transfer of protons in acid-base reactions, of electrons in redox reactions, and of ligands in complex reactions. An atom, ion or molecule may give one or more protons, electrons or ligands, while other different particles receive them simultaneously.

At the end of the 17th century the German scientist Stahl designed the Phlogiston theory for explaining the well-observed combustion processes. He created a special definition of the donor-acceptor principle, transferring “phlogiston” from one substance to another one. Observing the combustion of carbon or metal, he suspected the "escape of phlogiston":

Coal → ash + phlogiston, metal → metal ash + phlogiston.

After further observations of the emanation of zinc and lead out of ores and the mysterious appearance of silvery molten metals during the heating of ore-coal mixtures, Stahl concluded the “transfer of phlogiston” from the burning coal to the ore (“metal ash” – today: metal oxide):

Coal (phlogiston) + ore (metal ash) → metal

At that time Stahl didn’t know about gases like oxygen or carbon dioxide being involved in combustion processes – it was the French scientist Lavoisier (with the help of Priestley and Scheele) who proved the existence of oxygen, defined the oxidation theory and described the generation of metals by “transfer of oxygen”: metal oxide + carbon → metal + carbon dioxide.

Even today we use this historical idea to introduce the oxidation theory to our beginners in chemistry before later teaching the concept of redox reactions by electron transfer. But the “escape of invisible fire substances" or parts of the Phlogiston theory are often still in mind of young students: empirical surveys prove that – alternative ideas can be found at any time [1].

To transmit the scientific idea and to realize a conceptual change, today's chemistry class should incorporate a series of experiments to detect the invisible oxygen, and also to demonstrate the escaping colorless gases like carbon dioxide and water vapor [1]. From the experimental results simple equations can be derived, i. e. for the reaction of copper oxide with iron:

copper oxide + iron → copper + iron oxide

The oxygen seems to be "transferred" from copper oxide to iron in order to produce copper and iron oxide – but you will find neither O atoms, nor oxide ions or O_2 molecules which are emitted or received. Only the redox reaction in terms of an electron transfer offers an appropriate interpretation: one Fe atom emit two electrons that are transferred simultaneously to a Cu^{2+} ion: the formation of Cu atoms is explained. The oxide ions are spectator ions which are incorporated into the new ionic lattice:

Fe atom $\rightarrow$ Fe^{2+} ion + 2 e^- (loss of two electrons, oxidation of the Fe atom)

Cu^{2+} ion + 2 e^- $\rightarrow$ Cu atom (gain of two electrons, reduction of the Cu^{2+} ion)

Fe atom + Cu^{2+} ion $\rightarrow$ Cu atom + Fe^{2+} ion (redox reaction and electron transfer).

In the following paragraphs both electron transfer in redox reactions and proton transfer in acid-base reactions are explained in more detail. The explanation of complex reactions seems to be unnecessary since they are often lacking in the curricula.

PROTON TRANSFER

The Danish scientist Broensted defined that the term acid does not mean the substance, but rather an acid particle – the publication of Broensted from 1928 describes this clearly [2]. Examples of different acid particles are listed in Table 1.

Tab. 1: Examples of acid particles according to Broensted

Substances	acid particles	additional particles
Hydrochloric acid(aq)	H_3O^+(aq) ions	H_2O molecules, Cl^- (aq) ions
Nitric acid(aq)	H_3O^+(aq) ions	H_2O molecules, NO_3^- (aq) ions
Sulfuric acid(aq)	H_3O^+(aq) ions	H_2O molecules, SO_4^{2-}(aq) ions
Pure sulfuric acid(l)	H_2SO_4 molecules	
Sodium bisulfate(s)	HSO_4^- ions	Na^+ ions

Talking about alkaline solutions, it is necessary to differentiate between substances and particles. So caustic soda or sodium hydroxide solution are called substances, but bases are defined as particles to absorb protons: OH^- ions or NH_3 molecules. In the area of acids, it depends on the connection whether a substance or an acid particle is meant.

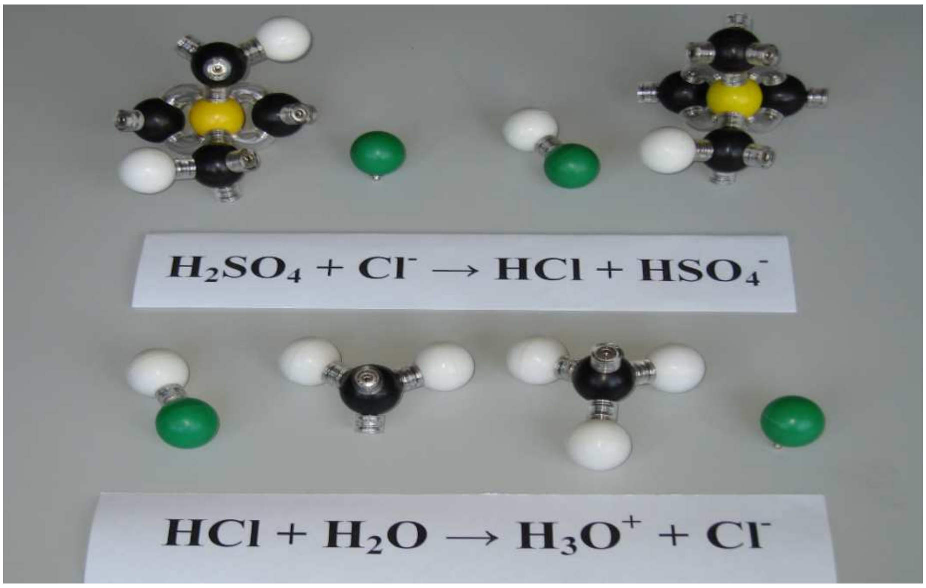

Fig.1: Molecular models for two acid-base reactions [3]

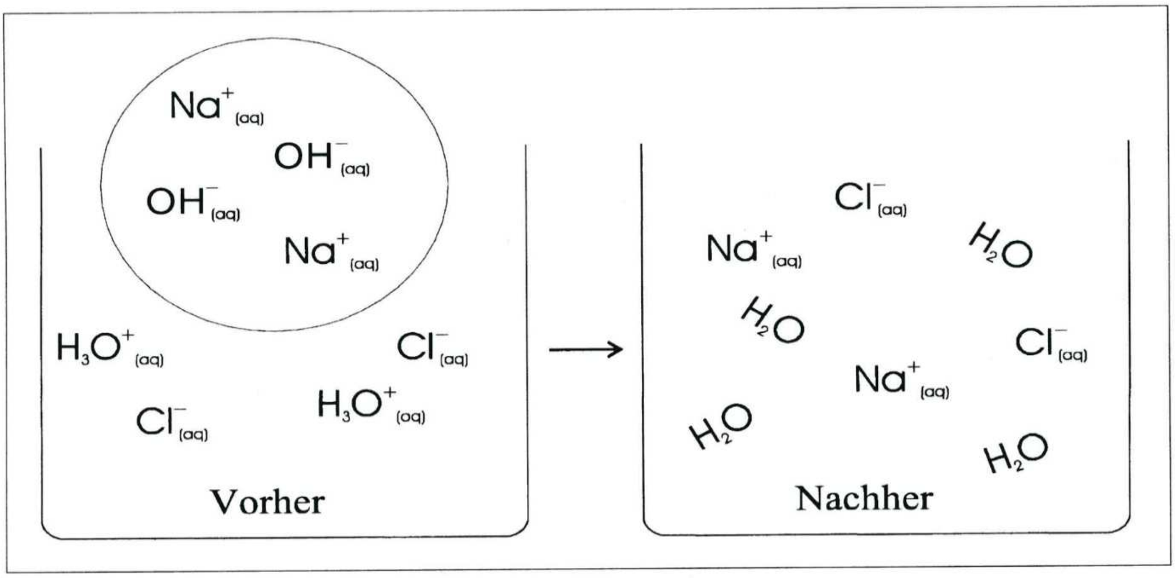

Fig. 2: Beaker model for neutralization of hydrochloric acid by sodium hydroxide solution [3]

However, particles cannot generally be divided into acids and bases – depending on the reaction partner, certain particles can react both, as an acid or as a base: H_2O or NH_3 molecules, OH^- ions or HSO_4^- ions – they are also called ampholytes. It is useful to indicate appropriate symbols for conjugate acid-base pairs: NH_4^+ / NH_3 or H_2SO_4/HSO_4^-. It is also beneficial to use molecular models (see Fig. 1) or beaker models (see Fig. 2) or sphere packing for crystals [1].

Terminology for proton transfer. In chemistry, it is common among experts to use a certain laboratory jargon to communicate quickly. For example, one speaks of sulfuric acid “which gives two protons" – and of course the H_2SO_4 molecule of pure sulfuric acid is meant; may be also the H_3O^+ (aq) ion of diluted sulfuric acid is regarded. The experts understand those statements in the laboratory jargon – the learner however cannot classify this and would ask: "Is 1 g or 1 mL of sulfuric acid gives away two protons"? The expert can alternate between the Macro-level, the

Submicro- and the Symbolic level of Johnstone [4] and knows what is meant – but not the learner. Some well-known expressions of laboratory jargon are listed and re-written with scientific formulations based on the Bronsted theory (see Tab. 2).

The last example of taking the involved molecules and ions shows that the function of a buffer can be explained optimally by mentioning the hydronium ions and hydroxide ions: both ions are converted into water molecules and the pH remains constant. Generally, applying Broensted's theory, one has to decide which molecule or ion reacts as an acid and which molecule or ion reacts as a base. This trains learners to interpretate chemical reactions on the Submicro Level [4] by using atoms, molecules and ions with molecular models (see Fig. 1) or beaker models (see Fig. 2). Finally they should describe and explain reactions on the Symbolic Level by using formulae and equations – they can then understand that all the chemical symbols are shortenings of molecular or crystal structures they know from the Submicro Level.

Tab. 2: Examples of the laboratory jargon concerning acids and bases and scientific terminology by the Broensted theory (proton = H^+ ion, **H**Ac = **H**OOCCH$_3$, Ac^- = acetate ion)

Laboratory jargon (misconceptions)	**Appropriate terminology (Broensted)**
1. Acid-base definitions (also historically) Acids contain hydrogen, by neutralization it can be replaced by a metal: from CH_3COOH the composition CH_3COONa can be derived (Liebig 1824)	Acid molecules or ions are proton donors. HAc molecules contain H atoms which can be donated as H^+ ions to H_2O molecules to form H_3O^+ ions. By neutralization an HAc molecule or an H_3O^+ ion gives a proton to an OH^- ion: $HAc + OH^-(aq) \rightarrow H_2O + Ac^-(aq)$ $H_3O^+(aq) + OH^-(aq) \rightarrow 2\ H_2O$, $Na^+(aq)$ ions remain
Hydrogen chloride dissociates into ions to form hydrochloric acid: $HCl \rightarrow H^+ + Cl^-$ (Arrhenius 1887)	HCl molecules are protolyzing: they are giving protons to H_2O molecules, H_3O^+ (aq) ions and Cl^-(aq) ions are formed and are the main particles of of hydrochloric acid (see Fig. 1),

	H_3O^+ (aq) ions are the proton donors
Sulfuric acid dissociates into ions: $H_2SO_4 \rightarrow 2\ H^+ + SO_4^{2-}$ (Arrhenius 1887)	In pure sulfuric acid H_2SO_4 molecules are the proton donors, in diluted sulfuric acid the H_3O^+(aq) ions are the proton donors (partly HSO_4^- (aq) ions too)
Sodium hydroxide dissociates into ions: $NaOH \rightarrow Na^+ + OH^-$ (Arrhenius 1887)	Na^+ ions and OH^- ions form in solid sodium hydroxide an ionic lattice. Dissolving in water they are separated by H_2O molecules into hydrated Na^+(aq) ions and OH^-(aq) ions
The self-dissociation of water incorporates the equilibrium by ions: $H_2O \leftrightarrows H^+ + OH^-$	The autoprotolysis of H_2O molecules provides an equilibrium with ions: $H_2O + H_2O \leftrightarrows H_3O^+ + OH^-$
Water is an ampholyte: it can be an acid or a base	H_2O molecules are ampholytes: the molecule can either give a proton (as an acid) or may take a proton (as a base) – depending on the partner
The concentration of water is calculated: c = 55.5 mol / Liter	The concentration of H_2O molecules in water is: c = 55.5 mol H_2O molecules / Liter
Strong acid means low pH, weak acid means relatively high pH	Strong acids are completely protolyzed, weak acids are partly protolyzed, an equilibrium between molecules and ions exists: $HAc + H_2O \leftrightarrows H_3O^+(aq) + Ac^-(aq)$
Acetic acid is a weak acid with low concentration	The HAc molecule is a weak acid, HAc molecules exist in equilibrium with corresponding ions
Neutralization makes HAc and NaOH a conjugated acid-base pair	Conjugated acid base pairs differ by one proton and are HAc / Ac^- and H_2O / OH^-
2. Examples for carbonate-acid reactions	
Sodium carbonate reacts with hydrochloric acid: $Na_2CO_3(s) + 2\ HCl(aq) \rightarrow 2\ NaCl(aq) + H_2CO_3(aq)$ $H_2CO_3(aq) \rightarrow H_2O + CO_2(aq, g)$	Carbonate ions are the proton acceptors: $CO_3^{2-} + 2\ H_3O^+(aq) \rightarrow 2\ H_2O + H_2CO_3\ (aq)$ $H_2CO_3(aq) \rightarrow H_2O + CO_2(aq, g)$ Na^+(aq) ions and Cl^-(aq) ions don’t participate in the reaction, they remain as “spectator ions”
Calcium carbonate reacts with citric acid: $CaCO_3(s) + 2\ HCit(aq) \rightarrow CaCit_2(aq) + H_2CO_3(aq)$ $H_2CO_3(aq) \rightarrow H_2O + CO_2(aq, g)$	HCit molecules are the proton donors: $CO_3^{2-} + 2\ HCit(aq) \rightarrow H_2CO_3\ (aq) + 2\ Cit^-(aq)$ $H_2CO_3(aq) \rightarrow H_2O + CO_2(aq, g)$ Ca^{2+}(aq) ions are spectator ions

3. Neutralization of acid solutions by sodium hydroxide	
Example hydrochloric acid: molecules are reacting, salt and water are being produced: HCl + NaOH → NaCl + H_2O	$H_3O^+(aq)$ ions and $OH^-(aq)$ ions react to form H_2O molecules: $H_3O^+(aq) + OH^-(aq) \rightarrow 2\ H_2O$ $Na^+(aq)$ ions and $Cl^-(aq)$ ions don't participate in the reaction, they remain (see Fig. 2):
Example acetic acid solution: molecules are reacting, salt and water are being produced: HAc + NaOH → NaAc + H_2O	In weak acetic acid, two acid particles exist and react with $OH^-(aq)$ ions: 1. $HAc + OH^-(aq) \rightarrow H_2O + Ac^-(aq)$ 2. $H_3O^+(aq) + OH^-(aq) \rightarrow 2\ H_2O$ $Na^+(aq)$ and $Ac^-(aq)$ ions don't participate
4. Acetic acid-acetate buffer	
By adding an acid to the buffer solution, sodium acetate reacts: NaAc + HCl → NaCl + HAc By adding hydroxide, acetic acid reacts: HAc + NaOH → NaAc + H_2O	In buffer solution with pH about 4.7, the HAc molecules and $Ac^-(aq)$ ions exist in equal concentrations. By adding hydronium ions, acetate ions react, water molecules are produced: $H_3O^+(aq) + Ac^-(aq) \rightarrow H_2O + HAc$ By adding $OH^-(aq)$ ions, HAc molecules react and also water molecules are being produced: $OH^-(aq) + HAc \rightarrow H_2O + Ac^-(aq)$

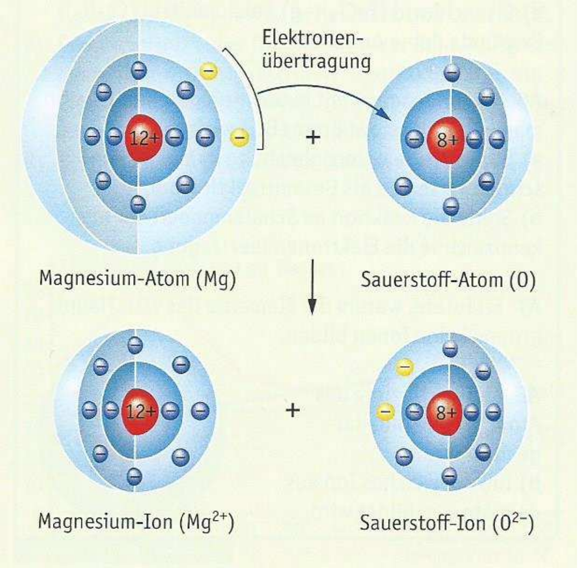

Fig. 3: Mental model according to electron transfer of two electrons [5]

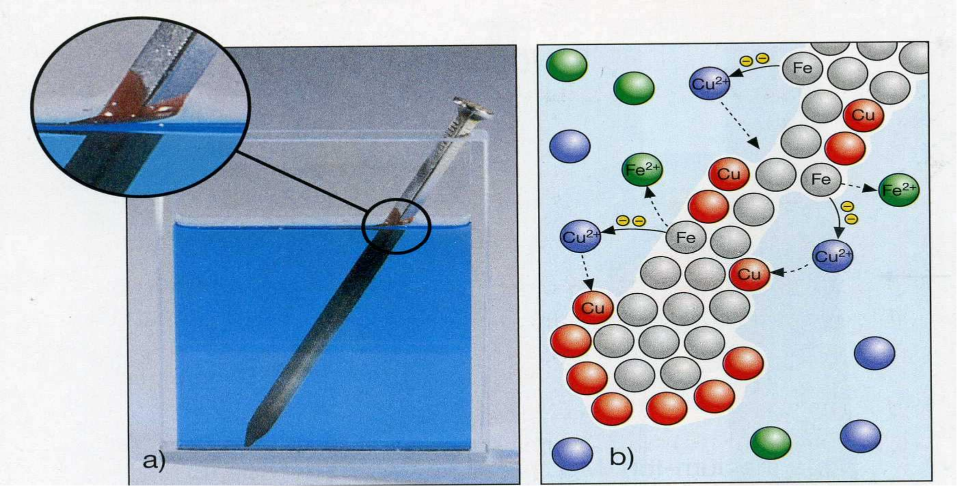

Fig. 4: Mental model according to the reaction of iron with copper sulfate solution [5]

ELECTRON TRANSFER

Talking about electron transfer, the same question should be asked: from which atom, ion, or molecule is an electron coming, and to which particle is it being transferred? The example of the magnesium-oxygen reaction clarifies this perfectly (see Fig. 3): the Mg atom emits two electrons and is thus converted into an Mg^{2+} ion, the O_2 molecule is split into O atoms, each O atom absorbs two electrons and is converted into an O^{2-} ion. According to the used definition of “oxidation of magnesium" we also say: the Mg atoms is being oxidized, the O atom is being reduced (see Fig. 3):

Mg atom → Mg^{2+} ion + 2 e-   oxidation = electron emission from a particle

O atom + 2 e- → O^{2-} ion   reduction = electron reception of a particle

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Mg atom + O atom → Mg^{2+} ion + O^{2-} ion   redox reaction = electron transfer

Likewise, for the well-known reaction of an iron nail in copper sulfate solution (see Fig. 4), one has to argue: not “iron” but Fe atoms are being oxidized, and Cu^{2+} (aq) ions are being reduced [7]. The sulfate ions remain completely uninvolved: they are "spectator ions".

Terminology for electron transfer. Concerning redox reactions the common laboratory jargon one states often: “iron gives two electrons” – and a mixture of substances and particles is used. This unconscious mixing confuses the learner and provides unclear facts. Table 3 shows examples of incorrect statements and their corrections. Likewise reaction equations, in which only “numbers of atoms on the left and on the right hand side of the arrow" are compensated, are part of the laboratory jargon: they don’t serve to explain redox reactions in an understandable way (see Tab. 2 with respect to acid-base reactions). For clarity, we select the symbol H^+(aq) for redox reactions – and not, as previously, the symbol H_3O^+(aq): for the explanation of the proton transfer, this symbol is easier to understand.

Tab. 3: Examples of the laboratory jargon for redox reactions and appropriate terminology

Laboratory jargon (misconceptions)	**Appropriate terminology**
1. Redox definitions (also historically)	
Magnesium is being oxidized taking oxygen: $2\ Mg\ (s) + O_2\ (g) \rightarrow 2\ MgO\ (s)$ (Lavoisier 1784)	Mg atoms are being oxidized, O atoms are being reduced: 2 Mg atoms → 2 Mg^{2+} ions + 4 e- O_2 molecule + 4 e- → 2 O^{2-} ions (see Fig. 3)
Copper oxide reacts with magnesium: copper oxide is being reduced, gives off oxygen, magnesium oxidizes and takes oxygen: $CuO\ (s) + Mg\ (s) \rightarrow Cu\ (s) + MgO\ (s)$ (Lavoisier 1784)	Mg atoms are being oxidized, Cu^{2+} ions are being reduced: Mg atom → Mg^{2+} ion + 2 e- Cu^{2+} ion + 2 e- → Cu atom O^{2-} ions merely change the ionic lattice

2. Metal-acid reactions	
Magnesium reacts with hydrochloric acid, gaseous hydrogen escapes: $Mg(s) + 2\ HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$	Mg atoms are being oxidized, H^+ ions are being reduced: $Mg + 2\ H^+(aq) \rightarrow Mg^{2+}\ (aq) + H_2$ $Cl^-(aq)$ ions of hydrochloric acid solution don't participate in the reaction: "spectator ions"
Magnesium reacts with diluted sulfuric acid, magnesium is being oxidized: $Mg(s) + H_2SO_4\ (aq) \rightarrow MgSO_4\ (aq) + H_2(g)$	Mg atoms are being oxidized, H^+ ions are being reduced: $Mg + 2\ H^+(aq) \rightarrow Mg^{2+}\ (aq) + H_2$ $SO_4^{2-}(aq)$ ions don't participate in the reaction
Magnesium reacts with pure sulfuric acid, gaseous hydrogen sulfide escapes: $4\ Mg(s) + 5\ H_2SO_4(l) \rightarrow H_2S(g) + 4\ MgSO_4(s) + 4\ H_2O$	Mg atoms are being oxidized, S atoms of H_2SO_4 molecules are being reduced to S atoms in in H_2S molecules (oxidation number +VI to -II): $4\ Mg$ atoms $\rightarrow 4\ Mg^{2+}$ ions $+ 8\ e-$ H_2SO_4 molecule $+ 8\ H^+ + 8\ e- \rightarrow H_2S + 4\ H_2O$
3. Reactions of metals with salt solutions	
Iron reacts with copper chloride solution, iron is being oxidized, copper chloride reduced: $Fe(s) + CuCl_2(aq) \rightarrow Cu(s) + FeCl_2(aq)$	Fe atoms are being oxidized, Cu^{2+} ions reduced: $Fe + Cu^{2+}(aq) \rightarrow Cu + Fe^{2+}(aq)$ (see Fig. 4) $Cl^-(aq)$ ions are spectator ions
Copper reacts with silver nitrate solution, copper is being oxidized, silver nitrate reduced: $Cu(s) + 2\ AgNO_3(aq) \rightarrow 2\ Ag(s) + Cu(NO_3)_2(aq)$	Cu atoms are being oxidized, Ag^+ ions reduced: $Cu + 2\ Ag^+(aq) \rightarrow 2\ Ag + Cu^{2+}(aq)$ $NO_3^-(aq)$ ions are spectator ions
4. Permanganate-hydrochloric acid reaction	
In this reaction gaseous chlorine is formed from hydrochloric acid: $KMnO_4\ (s) + 4\ HCl\ (aq) \rightarrow 1.5\ Cl_2(g) + MnO_2(s) + KCl(aq) + 2\ H_2O$	Mn atoms of MnO_4^- ions are being reduced (+VII to +IV), Cl^- ions are oxidized to Cl atoms: $3\ Cl^-$ ions $\rightarrow 3\ Cl$ atoms $+ 3\ e-$ MnO_4^- ion $+ 4\ H^+(aq) + 3\ e- \rightarrow MnO_2 + 2\ H_2O$
5. Oxygen corrosion	
Iron corrodes in moist air forming iron hydroxide, Iron is thereby being oxidized: $2\ Fe(s) + 2\ H_2O + O_2(aq) \rightarrow 2\ Fe(OH)_2(s)$	Fe atoms are being oxidized, O atoms of O_2 molecules are being reduced: $2\ Fe$ atoms $\rightarrow 2\ Fe^{2+}$ ions $+ 4\ e-$ $2\ H_2O + O_2 + 4\ e- \rightarrow 4\ OH^-$ ions $2\ Fe^{2+}$ ions $+ 4\ OH^-$ ions $\rightarrow 2\ (Fe^{2+})_1(OH^-)_2$

6. Daniell cell Zinc and copper are dipped in their 1-molar solutions, the voltage of U = 1.1 V occurs: $Zn(s) + CuSO_4 (aq) \rightarrow Cu(s) + ZnSO_4(aq)$	The equilibria shift to the right, when Zn atoms are being oxidized and Cu^{2+} ions reduced: Zn atom ⇆ Zn^{2+} ion + 2 e- Cu^{2+} ion + 2 e- ⇆ Cu atom

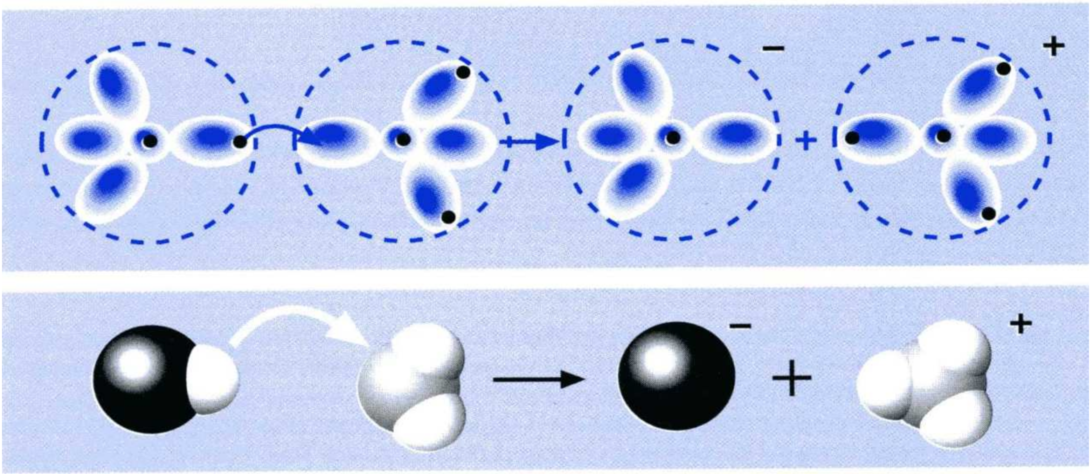

Fig. 5: Mental model of proton transfer between electron clouds [9]

ALTERNATIVE MENTAL MODELS OF DONOR-ACCEPTOR REACTIONS

The figures 1-4 suggest independently co-existing protons and electrons that move from one particle to another. This mental model should be preliminary for the learners in Piaget's development stage of concrete operations. In further lessons this concept can be extended by describing atoms, ions and molecules with electron clouds. Using the example of reacting HCl and H_2O molecules, a mental model is proposed with the transfer of protons from one electron cloud to the other (see Fig. 5). Christen and Baars [9] state: "There are no free, self-existing H^+ ions (as it was postulated in 1883 by Arrhenius); the proton which is initially bound to the chlorine atom by a pair of electrons, separates from these electrons, shifts then in one of the two electron clouds of the oxygen atom, and is finally bound by these electrons" [9].

Due to the wave-particle duality, electrons can be regarded as particles, but they should be also seen as standing waves or elementary electric charges. These charges are discharged from the electron clouds of atoms, ions or molecules and absorbed by electron clouds of other particles. The electron clouds can be measured today by electron density – they are never punctate structures.

In many cases, electrical charges are not being transferred, but only postponed: "The redox process often consists of an electron shift" [9]. For example, hydrogen and oxygen react to form water, the reaction is called a redox reaction: $2\ H_2 + O_2 \rightarrow 2\ H_2O$. According to the oxidation states, an electron transfer can be presumed, but actually the electron pairs or electron clouds of the O atoms are merely shifted: from non-polar covalent bonds in the O_2 molecule to strongly polar covalent bonds in the H_2O molecule: the result is an electron shift, not an electron transfer. But learners in the development stage of concrete operations may perceive protons and electrons as tiny particles and describe still proton or electron transfers. Later in advanced classes it is up to the teacher to switch to explanations on the abstract level of electron clouds or wave-particle duality.

CONCLUSIONS

Learners in chemistry classes should firstly work on the Macro Level of substances and reactions [4], without using models and chemical symbols: many experiments and chemical reactions can be observed and described with reaction symbols in words. Once the Submicro Level of smallest particles starts, the learner should consistently argue with smallest particles: the level of substances and the level of particles should not be arbitrarily mixed [4]. In particular, with the introduction of atoms and molecules, it would be desirable, to introduce also the ions – even without differentiated atomic models [10]. Thus, the structure of salt crystals and of salt solutions can be described scientifically correct with ions – without provoking misconceptions [1]. In particular, a "structure-based chemistry education" would be advantageous with the use of simple models such as sphere packing, space lattices, molecular models and beaker models [10]: they lead to appropriate mental models of the structure of matter and to the model of regrouping atoms, ions and molecules in chemical reactions on the Submicro Level [4]. And finally, they are the prerequisite for the successful introduction and use of formulae and equations on the Symbolic Level [4]: formulae should never be abbreviations – they should be shortened models of the structure of matter!

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