Misconceptions in Chemistry

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Addressing Perceptions in Chemical Education

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We would like to dedicate this book to Chemistry students everywhere. May their quest to full understanding of this subject lead them to the discovery of the truth and the beauty of Chemistry.

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October 2008 Hans-Dieter Barke, Al Hazari, Sileshi

Contents

Introduction

"At last I found a lecture worth getting up early in the morning for; excellent examples and experiments of teaching chemistry; now I know what chemistry education means and why it is so important for my studies; good to have the clear concept of the 'pie-chart' at the beginning of all lectures" [1]. These comments from would-be-chemistry teachers show that the lectures of chemistry education in our Institute of Chemistry Education at University of Muenster are extremely beneficial in assisting them in their approach to teaching chemistry at school.

The most important subjects of 15 lectures in chemistry education can be presented in a kind of "pie-chart" (see Fig. 0.1): "Learners ideas and misconceptions; experiments; structural and mental models; terminology, symbols and formulae; every-day-life chemistry; media; motivation; teaching aims" [1]. Because we want to put a lot of emphasis on the learner, she or he is therefore placed at the centre of the diagram. Secondly, "scientific ideas" should be reflected in association with appropriate "teaching processes" for the learner. Finally there should be reflections on the "human element" or "context" to each subject as Mahaffy [2] has proposed. There are free sectors in that diagram – for more chemistry education subjects to reflect upon. In this book emphasis is given to students' preconceptions and misconceptions; experiments; structural and mental models; terminology, symbols and formulae.

In our experience of beginning of courses in chemistry education, would-be-chemistry teachers are often not clear about their own or students' "Preconcepts" or "misconceptions". They are not aware of how important it is to know more about these concepts and how to integrate them into chemistry education at school. Our reason for publishing this book is to assist those studying to become chemistry teachers and those already teaching chemistry at school. We also support professor Jung's comments, a physics teacher in Germany: "One should really write a book on diagnosing misconceptions and give it to all teachers". The psychologist Langthaler made similar comments: "If you, as a teacher, would have more diagnostic abilities and tools, many problems with your students would never even arise".

In planning coursework in the past few decades, teachers were under the impression that young pupils had hardly any knowledge of science. Therefore,

H.-D. Barke et al., *Misconceptions in Chemistry*, DOI 10.1007/978-3-540-70989-3_0,

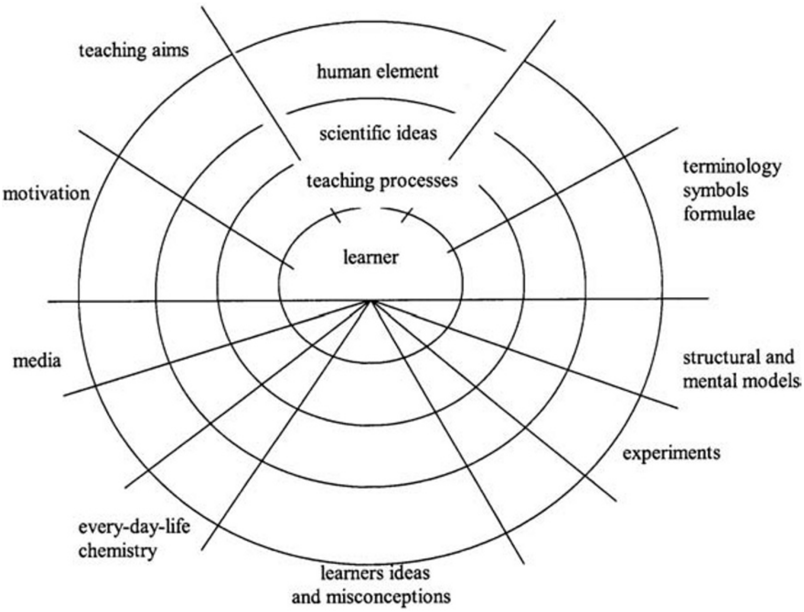

Fig. 0.1 Main subjects of a lecture in chemistry education, "pie-chart" metaphor [1]

teachers had only to decide how to plan a lecture in order to transmit scientific ideas to their pupils, perhaps incorporating laboratory experiments or new technology-based methods.

However, research has found otherwise. Latest studies in science education show that children and adolescents have many images and ideas about nature and their own surroundings. Nieswandt [3], for example, states according to her research: "Even from the very early days children are developing their own ideas about nature and every-day life. They are looking at cause and effect, at what happens if they let something fall to the floor, if they push, pull or throw things. By repeating these experiences, they develop a concept about the movement of things on the ground and in the air. Examination of these ideas and concepts shows that they are often in conflict to those that are typically accepted by the scientific community. Research in the field of pre-school knowledge has shown that these preconceptions of learning and comprehension tend to hinder the understanding of modern scientific concepts".

Research in students' conceptions in chemistry is based on the constructivist approach to learning, in which students construct their own cognitive structure. According to this approach of learning, learners generate their own meaning based on their background, attitudes, abilities, experiences etc, before, during and after instruction. Since students do construct or build their own concepts, their constructions differ from the one that the instructor holds and has tried to present.

These different concepts are variously described by different researchers as: misconceptions, alternative conceptions, naïve beliefs, erroneous ideas, multiple private versions of science, underlying sources of error, personal models of reality, spontaneous reasoning, developing conceptions, misunderstanding, mistakes, misinterpretation of facts, personal constructs and persistent pitfalls – to name just a few [4–10]. The authors will use the term “misconceptions” for the simple reason that researchers refer to it more often.

In order to promote successful learning or at least to simplify it, science educators should diagnose which preconceived images and explanations students hold. In this regard, Treagust [11] suggests using specific questionnaires to diagnose misconceptions of content and basic ideas: “By using a diagnostic test at the beginning or upon completion of a specific science topic, a science teacher can obtain clearer ideas about the nature of students’ knowledge and misconceptions in the topic” [11].

In this book, the authors present diagnostic instruments from scientific literature and from their own empirical research. They also want to propose strategies for teaching and learning chemistry, which may help to cure or even to prevent students misconceptions. Most of our basic research is done in Germany and has been published in the German book “Chemiedidaktik – Diagnose und Korrektur von Schülervorstellungen” [12] by Springer, Heidelberg, in the year 2006.

This book includes the translation of the German book on misconceptions and includes a lot of new supplements. Both books will give teacher educators, chemistry teachers and would-be-chemistry teachers various examples of students’ preconceptions and misconceptions, for consideration in their lessons. With this knowledge, teachers are better able to plan their own questionnaires and interviews in order to find out specific preconceptions and misconceptions of their students. Teachers become more aware of such misconceptions and are able to discuss them in their classrooms. Once the alternative conceptions of the students have been identified, the teacher has to decide how to deal with them:

– giving the scientific idea first and then discussing misconceptions, or
– go over students’ misconceptions first, make them uncomfortable with their own ideas and instruct the scientific concept afterwards.

Examples and proposals on how to deal with misconceptions during lectures and how to include convincing experiments are described in all chapters.

Gabel [13] found out that many teachers are not familiar with or do not acknowledge the science education research regarding misconceptions. Therefore, they do not intend to incorporate them into their lecture plan: “Probably nine out of ten instructors are not aware of the research on student misconceptions, or do not utilize ways to counteract these misconceptions in their instruction”. Gilbert et al. [14] calls upon all teachers not only to increase their awareness of the diagnostic methods available for finding misconceptions, but also to implement them in their lessons. They also suggested that teachers should be aware of these diagnostic tools during their teacher-training curriculum: “The pre-service and in-service education of prospective and experienced chemistry teachers can play a crucial role in bridging the gap between chemical education research and classroom practice" [14]. In this regard, they point out: "Increasing chemistry teachers' awareness of chemical education research, improving the use of chemical education research findings and involving chemistry teachers in chemical education research" [14].

The variety of subjects in chemical education automatically leads to a large assortment of misconceptions that are not possible to cover in one book. For this reason, in this book, an attempt will be made to address the most important concepts that arise in chemistry education: "We have examined the question extensively to see if it is possible to limit the relevant chemistry subject contents to superior central themes or scientific terms which are paramount for the comprehension of most chemical processes. We have discussed this issue with university professors along with experts in the field of teaching as well as with teachers at all levels. Because of this discussion, we have come up with the following consensus: an elementary understanding of basic principles of chemistry can be traced back to the command of a limited amount of principles – these principles are necessary for understanding chemistry. We call these principles, Basic Concepts" [15]. The following **basic concepts of chemistry** will be the foundation of this book: (a) Substances and Properties, (b) Particle Model of Matter, (c) Structure and Properties, (d) Chemical Equilibrium, (e) Donor–Acceptor Principle, and (f) Energy. The Donor–Acceptor Principle will be differentiated to Acid–Base Reactions, Redox Reactions and Complex Reactions.

Studying all the misconceptions, one would find parallels between the thinking of our students today and that of **ancient scientists of the last centuries**: As one would expect, all observations in our every-day life, which were carried out in a similar fashion throughout the ages, lead us to similar interpretations. In Chap. 1, some of the theories of the ancient scientists are described. These may help to show how misconceptions have been corrected in history. An example is the well-known **Phlogiston Theory**. Scientists of the 17th and 18th century assumed that all combustible substances contain some "invisible matter" and that upon burning, SOMETHING of the burning substances dissipates in the air. The German scientist Stahl called this "Phlogiston" and the Phlogiston Theory became highly accepted by scientists of these ages.

In Chap. 2 student's misconceptions and strategies for overcoming them will be discussed in the sense that young people have mostly observed their environment in a right and proper way, that they are not responsible for their "mistakes". An expansion on this idea will be presented that – besides the known **preconcepts** – there are also **school-made misconceptions** which arise in advanced science courses and which do not stem so much from the learners but rather from the teachers and the textbooks; or from the specific complexity of some subjects.

In Chaps. 3–10 preconcepts and misconceptions of the basic concepts and teaching and learning strategies will be reflected. In addition, since laboratory experiments and mental models are very convincing tools that could cure misconceptions in the cognitive structure of students, many experiments and structural models will be described following every chapter.

Children's preconcepts develop without a particle concept, hence the important "matter-particle concept" is divided in this book into two levels: "Substances and Properties" (see Chap. 3) and "Particle Model of Matter" (see Chap. 4).

Substances and Properties. In general, without having had a specific education in the particle concept, children tend to develop their original ideas based on properties of matter and their transformations. The well-known destruction concept concerning combustion is explained with the idea that "something is released into the air", or the properties of substances may change in their mind: "copper becomes green, silver becomes black". Along these lines, many explanations of other observations and phenomena will be discussed in Chap. 3.

Particle Model of Matter. "In chemistry, one goes with the premise that all matter is composed of submicroscopic particles, namely atoms or ions. They can appear isolated (atoms in noble gases), but mostly combined in groups of atoms or ions. They more or less form large aggregates with specific characteristics (e.g. metal crystals or salt crystals). The variety of matter is created by the many possible combinations and structures of a limited number of elements, of atoms and ions" [15]. With respect to this, misconceptions can only be school-made because one needs special lessons about the particle model of matter or Dalton's atomic concept before one develops misconceptions related to these concepts. These discussions will follow in Chap. 4.

Structure and Properties. "The properties of substances are directly dependent on the type of particles and on aggregates of particles, respectively chemical structures. Herein, it is more important to look at how atoms and ions are arranged in special structures than which kind of particles are involved" [15]. Chapter 5 will deal with this.

Chemical Equilibrium. "The exchange of matter and energy is basically possible in two directions at the same time, in forward and backward reactions. As a result, there exists under certain constant conditions a defined relationship between reactants and products which one describes as chemical equilibrium" [15]. In Chap. 6 misconceptions according to equilibria are reflected, teaching-learning suggestions are offered for every basic concept.

Donor–Acceptor Principle. "Particle aggregates, but also the atomic units of matter themselves can interact or react with each other and can thereby develop attraction and repulsion forces, and can transfer particles or energy. These particles or energies are transferred from one partner to the other" [15]. The transmitted particles or energies can be (a) protons, (b) electrons, (c) ligands. In this respect, one can see school-made misconceptions with regard to (a) acid–base reactions (Chap. 7), (b) redox reactions (Chap. 8), and (c) complex reactions (Chap. 9).

Energy. "Energy is stored in all substances; the amount of stored chemical energy is a very characteristic property. In chemical reactions in which matter is transformed, chemical energies are also changing – matter either releases or absorbs energy" [15]. Chapter 10 will discuss this.

In order to identify the observational goal and to know the intention, the **experiments** will have the heading "Problem" with additional comments in the first paragraph; the second paragraph shows "Material, Procedure and Observation". The explanations of the observations are not written: they may be very different depending on the grade or progress of the specific class or student group. Because of short descriptions of all experiments only an experienced teacher may conduct the experiments – the descriptions are not for students or beginners.

Every chapter related to the basic concepts starts with a **"Concept Cartoon"** [16]: four students explain a special phenomenon from their view and present the correct answer and some misconceptions of the involved subject [16]. These cartoons summarize the most important misconceptions for the reader; they are also helpful in class to start the discussion about students' ideas. The students may find their own ideas among the cartoons or will get to know which other ideas are possible. In every case they can discuss ideas and misconceptions by asking the question "what do you think?" – and may find the scientific answer, with the help of their teacher or on their own. It is even possible to use the cartoons for assessment [16].

We hope that many teachers in the area of chemistry or science will be inspired to reflect misconceptions and related strategies for chemistry instruction. The authors wish everyone lots of success in their own studies and in educational ways to cure or prevent misconceptions – through suggestions and proposals for revising the curriculum and taking new roads. Thank you for teaching "modern chemistry" to our children and our future adults!

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Chapter 1
Perceptions of Ancient Scientists

Students' conceptions of combustion ("SOMETHING is going up into the air") amazingly account for parts of the historic **Phlogiston Theory**. Through identical observations, parallels have been noted between the beliefs of today's youth and many of the ancient scientists. It makes sense to study the development of some historic theoretical themes and examine how they are deep-rooted in science:

- theory of basic matter by the Greek philosophers,
- transformation concepts of the alchemists,
- the Phlogiston theory,
- historic acid–base theories,
- "horror vacui" and particle concept,
- atoms and the structure of matter, etc.

One should perhaps consider and use historic concepts to analyze historical conceptual changes, develop today's concepts of education and compare with those changes of the past. Moreover, the historical changes may be included in the teaching–learning strategies and materials; the students should talk about and realize that "their problems are similar to those of scientists of the past" [1]. Due to this, students would be more likely to let go of their own misconceptions: "If students are made aware of the misconceptions of earlier scientists, perhaps they might find their own misconceptions among them. If the teacher compares and contrasts the historical misconceptions with the current explanation, students may be convinced to discard their limited or inappropriate propositions and replace them with modern scientific ones" [2].

The above-mentioned themes can be thought through historical problem-oriented approach. According to Matuscheck and Jansen [1] it means: Students encounter difficulties of ancient scientists, they use similar explanations and approaches of the ancient scientists, and are led by teachers to the ways of scientific thinking of today.

H.-D. Barke et al., *Misconceptions in Chemistry*, DOI 10.1007/978-3-540-70989-3_1,

1.1 The Theory of Basic Matter

The ancient Greek philosophers have put a lot of thought into humanity and the world around them, they have come up with many recognized and accepted theories: Many of the current cultural and basic principles are based on these ancient Greek philosophies.

For instance, the basic questions that arose for these Greek philosophers are: "What is our world made of? What is the basic matter, material or substance? Just as important was the second basic thought that such basic matter must be eternal, that nothing can arise out of NOTHING and nothing can disappear to NOTHING – it is just the appearance of that basic matter which changes. With this realization, their attention was drawn to the following problems:

– the materials of the earth,
– the non-creationability and indestructibility of matter,
– the transformational ability of matter while retaining its basic substance" [3].

"Aristotle was the first to teach the difference between matter and property. This distinction of a thing being a 'carrier' of properties on the one hand, and on the other hand these properties themselves, were unknown to the Greek philosophers before Aristotle. Stemming from this knowledge, Aristotle discussed the theory that development and change, creation and destruction were nothing more than the transition from one essence to another" [4].

1.2 Transformation Concepts of the Alchemists

The age of the alchemists stretched from approximately the 4th to the 16th century, the Arabs being one of the main groups especially involved in this development. Alchemy, for them, was just another word for chemistry. This word is composed of the Arab word "al" and the Greek word "chyma" or metal production. This term shows the importance of metals for people and their wish to extract metals or even to transform non-noble metals into gold.

Many of the Arabs' writings even "provide directions for the artificial extraction of gold with the help of the 'Ferment of Ferments', the 'Elixir of Elixirs'. The correct mixture of the four elements is all-important and the 'spirit' (the heated, liquid quicksilver) has to permeate the 'matter' (lead, copper, etc.). The mysterious 'Elixir' itself is created through the correct fusion of the four elements, the body (metal) and the spirit (quicksilver), the male and the female. It assimilates these 'bodies' and colors them (therefore, they are known as 'tinctures') thereby transforming them to gold, causing them to multiply the amount thousand times" [5].

Also, the well-known scientist Albertus "believes in the possibility of creating gold, but he says, he knows of no alchemist who has succeeded in completely transforming metals" [5]. "Even up to the 18th century there was no lack of practical and witnessed alchemistic proof: there were examples of golden coins that supposedly were minted through alchemistic procedures, or nails made up of half of iron, and the other half of gold transformed from iron. Even court cases were sometimes ruled in favor of alchemistic operations, and last but not least, there were many swindlers who managed to show that through their 'successful transformations' it was indeed possible to transform metals into gold" [3].

In 1923, science was once again in a tizzy "when a Professor from a Berlin university reported that he had succeeded in transforming quicksilver into gold through treatment with electricity. The results were confirmed not only by various sides but there were several 'researchers' (even from Japan) who supposedly had made the same discoveries themselves. After a very thorough experimental examination, it was discovered a couple of years later that the minimal traces of gold came from the electrodes. This event finally banished the 'dream of gold' from the fantastic minds that had been pursuing it for centuries" [5].

1.3 The Phlogiston Theory

As a fuel like coal or petrol burns, one apparently can observe that they disappear. German scientist Stahl published his interpretation of this observation in 1697 and introduced the term Phlogiston (gr.: Phlox, the flame): "He started off with the combustion of sulfur and assumed that the sulfuric acid which was produced through the combustion act was sulfur bereft of its own burning principle" [6]. Stahl claimed, "every combustible and calcifiable material contains phlogiston. The combustion is a process through which the phlogiston is released by the substance. He assumed that air played a certain role assimilating the phlogiston and transferring it into leaves of trees. Through the process of reduction (by heating of calcified metal on charcoal), phlogiston was transferred from the coal into the heated substance. From then on, the processes of oxidation and reduction were recognized as being linked to each other. Proof was given through experiments of calcification of a metal through heat and the reduction through carbon" [3]:

$$\text{Metal} \rightarrow \text{Calcified Metal} + \text{Phlogiston}$$
$$\text{Calcified Metal} + \text{Phlogiston (in Carbon)} \rightarrow \text{Metal}$$

However, Stahl had to state that pure metal was a compound of metal and phlogiston, and calcified metal – known today as metal oxide – was expected an element. In addition to this came the fact that known measurements of masses did not agree with the theory: "He didn't place much value on the increase in weight of calcified metal; in the end, he tried to pawn this off as an assumed 'negative weight' of the phlogiston. The chemists were very one-sided focusing only on qualitative appearance, the Phlogiston Theory served this purpose well" [3].

"One can better understand the point of view of the Phlogiston Theory followers if one does not approach it through the material process but rather through an energy approach. One does not just see the flame escaping in the burning process; heat energy is also created. This aspect is completely ignored when one looks at the subject from a purely material approach. In order to be fair, and by looking at this from a physical-chemical process, one must see and replace the phlogiston as a kind of energy" [5]. Oxygen, which according to Empedocles was known as "fire-stuff" later on became "phlogiston" (Stahl) and "fire-air" (Scheele). "For several decades the term 'heat-stuff' was commonly used for all of the above names until the cause of the heat energy was discovered in the movement of small particles" [3].

Lavoisier clarified these facts through the synthesis and the decomposition of mercury oxide. He discovered the Law of Conservation of Mass and the Oxidization Theory. With these discoveries, the long era of alchemy and Phlogiston Theory was laid to rest and chemistry came forward as a leading scientific discipline.

1.4 Historic Acid–Base Theories

People throughout the ages were well familiar with the acidic taste of many fruits and vegetables. In addition, it has been known that alcoholic drinks produce vinegar if these are in an open container and have air contact. This vinegar had been used for thousands of years as a preservative. "The Latin word *acetum* for vinegar (actually, *acetum vinum*, means gone sour from wine) stands, from an etymological point of view, for *acer* = acrid and for *acidus* = acid or sour. Hence, the English word acid and the French word l'acide derive from this" [7].

Many attempts were made to explain what the acid taste was like. French scientist Lémery, from the 17th century, tried in a most unusual manner to explain the effect of acid through the idea of particles. He theorized that this invisible substance, which makes up the acidic taste, consists of moving spiky particles, which cause the acidic taste on the tongue [8].

In the beginning, there were only general explanations for the acidic taste phenomenon; for instance, indicators can show the acid manner by its color. Later, there were explanations of acidic–alkaline definitions based on the structure of the material – they were, however, always based on acidic or alkaline solutions as chemical substances. Today, the most common definition for beginners is the Broensted–Lowery concept and the idea of a proton transfer from one particle to another particle. However, this definition is based more on the function of ions or molecules as acid particles – and not on acids as substances! The different historic acid–base concepts are briefly described in the following periods of time:

BOYLE. In 1663, Robert Boyle characterized all acids by using the plant coloring, litmus: a red litmus color shows acidic solutions, a blue color basic solutions. Boyle became the creator of today's indicator paper. Apart from the color reaction, he also observed that acidic solutions are able to dissolve marble or zinc.

LAVOISIER. After the fall of the Phlogiston Theory and the discovery of oxygen, Lavoisier studied the combustion of carbon, sulfur and phosphorus in 1777. By dissolving the resulting non-metallic oxides in water, he found that all these solutions show acidic effects. Based on these examples, he defined acids as substances composed of a non-metal and oxygen. In addition, he found out that acids, combined with the "bases", the metal oxides, result in well-known salts: carbon dioxide forms the carbonates, sulfuric acid the sulfates, phosphoric acid the phosphates – the combination system of "acids and bases" was discovered!

DAVY. The discovery of the element chlorine by Davy in the year 1810, resulted in the finding of the gaseous compound, hydrogen chloride (HCl), and its watery solution, hydrochloric acid. With the realization that hydrogen chloride is essentially an oxygen-free compound, the search went on for a method of describing acid solutions in a new manner. A little later, the discovery of hydrogen sulfide (H_2S) and hydrogen cyanide (HCN) and their acidic solutions meant that eventually hydrogen was associated with the "principle of acids". However, hydrocarbons, a class of known hydrogen-containing compounds, do not possess acidic properties.

LIEBIG. Through the analysis of many organic acids and the knowledge of reactions of these solutions with non-noble metals to produce hydrogen, Liebig pragmatically stated in 1838: "Acids are substances that contain hydrogen which can be replaced by metals". The CH_3COOH molecule, for example, contain different H atoms, only the one H atom of the COOH group was defined as "hydrogen which can be replaced by metals". These new findings led to an immense progress in chemistry because diluted solutions of organic acids and those of common mineral acids held up to that definition.

ARRHENIUS. Upon examination of the electrical conductivity of many solutions, the term "electrolyte" for conducting substances was assigned. The acidic solutions also conducted electricity, and therefore belonged to the group of electrolytes. During additional freezing point depression experiments, it was discovered that electrolyte solutions showed a much greater effect than, for instance, sugar or ethanol solutions of the same concentration. Arrhenius was the first to interpret these experiences with "ions" and created the theory of electrolyte dissociation in aqueous solutions in 1884. In this way, the smallest particles of acidic solutions could be defined as hydrogen ions H^+(aq), and correlative remnant ions, the smallest particles of basic solutions as hydroxide ions OH^-(aq), and correlative remnant ions.

BROENSTED. After verifying the structure of atoms and ions by different models of nucleus and shell, hydrogen ions were classified as protons which do not exist freely and which connect with water molecules forming hydronium ions H_3O^+(aq). Based on this classification, Broensted and Lowery separately developed their own acid–base definition relating to protons in 1923. This definition proved independent of the aqueous solution and continued to expand more in the direction of particles (ions and molecules) rather than on substances: particles that give up protons (H^+ ions) to other particles are Broensted acids; they are also called proton donors. Particles that take protons are bases or proton acceptors.

Other definitions came next: concepts of Lewis, of Pearson and of Usanovich [7]. Because these concepts distanced themselves more and more from the classical acidic substances, they do not and should not play a significant role in the teaching–learning of chemistry for beginners.

1.5 “Horror Vacui” and the Particle Concept

Experiments with pipettes and wine siphons alerted the ancient natural philosophers to the fact that there are no air-free or other areas free of material on this earth, that as soon as a substance leaves a space it is replaced by another – mostly air. In this regard, Canonicus came up with a well-known formula, which states that “nature avoids empty space without any material, nature shows a horror vacui, a fear of empty spaces” [5].

Even Galileo Galilei knew of this phenomenon through the building of water wells and that it is impossible to pump water to the surface from a depth of over 10 m [5]. He attributed this depth as being the utmost power with which nature can prevent a vacuum. In 1643, Galilei created an experiment in order to measure the “resistenza del vacuo” or “resistance of vacuum” (see (a) in Fig. 1.1): The cylinder with a hook is filled with water, the moveable piston carries such a heavy mass that an empty space is created in the cylinder. One does not know “if this experiment was carried out or just described on paper” [5].

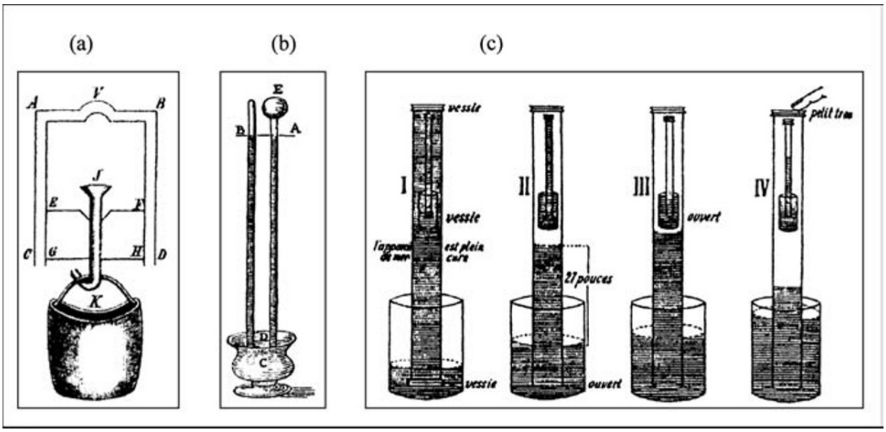


Fig. 1.1 Historical experiments to overcome the “horror vacui” [5]

This apparatus inspired his student Torricelli to replace the hard piston by mercury which is heavy and flows like a piston in a glass tube (see (b) in Fig. 1.1). With this experiment, first described in 1643, Torricelli was able to establish the rate of normal air pressure at 760 mm mercury. He was able to show the existence of a material-free zone: the vacuum [5] above the mercury column at the end of the glass tube.

Pascal established the final proof with his experiment "du vide dans le vide", the vacuum within the vacuum (see (c) in Fig. 1.1): in 1647 the Torricelli apparatus shows no evidence of gas pressure or no special "ether" above the mercury level [5]. Further experiments at various heights above sea level prove that the 20 km high column of air balances out a 760 mm elevation of a mercury column at sea level and by normal air pressure. This apparatus became useful for measuring air pressure, the first mercury barometer was built, and the unit of "1 mm Hg" got the unit 1 torr – due to the famous scientist Torricelli!

Because of this knowledge, Guericke developed efficient air pumps and demonstrated air pressure through spectacular experiments with the well-known "Magdeburger Halbkugeln": He took big half-spheres of metal which were joined together, he pumped them almost entirely free of air. Eight horses on one side and eight on the other pulled both half-spheres. It was only through using all their strength that the horses managed some times to overcome the air pressure and to separate the half-spheres with a big loud bang.

1.6 Atoms and the Structure of Matter

The old Greek philosophy offered at least two famous schools of thought. Some followers of Democritus and Leukipp were convinced that continual separation of a portion of matter must be finite and that matter contains atoms (gr.: atomos, indivisible). This idea postulates the concept of particles and the surrounding free space and was known as the **Hypothesis of Discontinuity**.

Aristotle and other philosophers claimed that the continual separation of matter was infinite. The idea of the impossibility of free space, which must separate particles from each other – the "horror vacui" – convinced them of the continual reconstruction of matter: **Hypothesis of Continuation.** The School of Aristotle had a huge influence and led to the suppression of the Hypothesis of Discontinuity for almost 2000 years [9].

After the vacuum was realized by the Torricelli experiments the "horror vacui" was hugely overthrown: one could conceptualize a vacuum. Gassendi developed on that base the particle concept from a sub-microscopic point of view, and in 1649 he rehearsed Democritus' idea of "atoms and empty space as the only principles of nature, apart from the complete full and complete empty space nothing else can be considered" [10]. After a two-thousand year interruption, scientists were finally able to embrace the Hypothesis of Discontinuity and to reconsider matter as being made up of smallest particles.

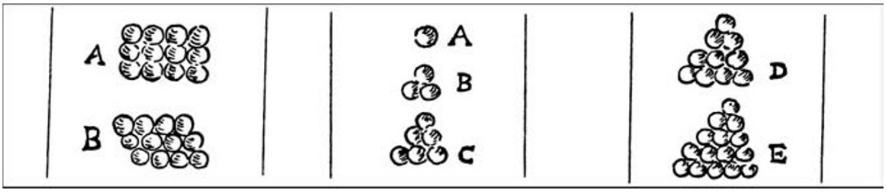


Fig. 1.2 Structural models of ice created by Kepler in the year 1611 [11]

Years before Gassendis' publications, Kepler through his observation of "six-sided snow crystals" reported in the year 1611: "There must be a reason for the fact that whenever the first snowflakes fall, they are always shaped in the form of a six-sided star, why don't they form a five-sided or even a seven-sided star?" [10]. Kepler assumed that steam contains "steam balls" and discussed condensation to snowflakes through various model-ball arrangements (see Fig. 1.2): "If one pushes similar-sized balls together so that they touch one another on a horizontal level they form either triangular or square shapes; a middle ball is surrounded by six other balls in the first model and four balls in the second model. The five-sided shape cannot provide a balanced coverage, and the six-sided shape can be reduced to a triangular form" [11].

In addition, Kepler spoke of the layering of closest packed balls in triangular patterns. He discovered the most compact ball set-up with coordination number of 12: "Again one ball is touched by 12 others – six neighboring balls at the same level, three on top, and three on the bottom". By assuming spheres as models of the smallest particles of water and in discussing their closest hexagonal order, Kepler was able to explain the permanent recurring six-sided snowflake shape. He thereby discovered the connection between the outer crystal shape and the inner arrangement of the smallest particles in the crystal, he postulated a first idea of the "chemical structure of ice".

Haüy [12] also contemplated arrangements of the smallest particles; however, he did not use balls as their models, but was thinking of "smallest portions of matter" and took "smallest crystals" as the same form of particles as in the big and visible crystal. Concerning the calcite crystal, he made the comment: "These rhomboids are what we would call integral particles (molécules intégrantes) of the calcite in order to differentiate them from the elementary particles (molécule élémentaires): one part is made of calcium, and the other part of carbon dioxide" [12].

Wollaston [13] went back to the ball-shape and backed it up with non-directed bonding of the smallest particles in crystal: "The existence of atoms merely requires mathematical points endowed with powers of attraction and repulsion equally on all sides, so that their extent is virtually spherical" [13]. In addition to this, he accented the closest packings of balls as models for crystal structures, but Wollaston was aware of the speculative nature: "It is probably too much to expect that we will ever find out the exact structure of any crystal" [13].

In 1808, from his observations, the English scientist Dalton was able to add a very important general theory on particles. In his work, “A New System of Chemical Philosophy” [14], he combined the idea of elements and the atomic concept and created the first table of atomic masses:

1. Every element consists of finite particles, the atoms.
2. Each atom of a given element has the exact same size and mass.
3. There are exactly as many types of atoms as there are elements.
4. Atoms can neither be created nor destroyed through chemical processes [14].

Dalton used different labeled spheres and, even if they were not always correct, came up with first models for compounds (see Fig. 1.3). He assumed, for instance, that the water molecule should be described by one H atom combined with one O atom, thinking of today’s symbol HO (see Fig. 1.3, Number 21).

This incomplete concept delayed the correct Atomic Mass Table for quite some time. Later, with the concept of H_2O molecules, the suitable atomic masses were put in place. Many of Dalton’s “elements like magnesia or lime” later proved to be compounds. Dalton’s atomic theory was so fruitful that many organic substances could be successfully analyzed, especially with Liebig’s combustion analysis. The only problem remaining was how to express the analytical results using chemical symbols, i.e. the different formulas for acetic acid molecules (see Fig. 1.4). For this reason, Kekulé initiated the Congress of Karlsruhe, which was held in 1861 in order to discuss the differentiation of atomic and molecular concepts. In other words, the first concepts regarding the structure of substances were defined as “atoms in elements” and “molecules in compounds”. These definitions were just taken in textbooks on chemistry education until the middle of the 20th century.

Regarding the carbon–hydrogen compounds, Kekulé [16] published the theory of the connectivity of C atoms with four bonding units each and the structure of benzene molecules: “One can now assume that several carbon


[219] Erklärung der Tafel.

1.	Wasserstoff; rel. Gewicht	1
2.	Stickstoff	5
3.	Kohlenstoff	5
4.	Sauerstoff	7
5.	Phosphor	9
6.	Schwefel	13
7.	Magnesia	20
21.	Ein Atom Wasser oder Dampf, bestehend aus 1 Sauerstoff und 1 Wasserstoff, in physischer Berührung gehalten durch eine starke Affinität und angesehn als umgeben von einer gemeinsamen Wärmesphäre; sein relatives Gewicht	8
22.	Ein Atom Ammoniak, aus 1 Stickstoff und 1 Wasserstoff	6
23.	Ein Atom Salpetergas, aus 1 Stickstoff und 1 Sauerstoff	12
24.	Ein Atom ölbildendes Gas, aus 1 Kohle und 1 Wasserstoff	6
25.	Ein Atom Kohlenoxyd, aus 1 Kohle und 1 Sauerstoff.	12
26.	Ein Atom Salpetergas, aus 2 Stickstoff und 1 Sauerstoff	17
27.	Ein Atom Salpetersäure, aus 1 Stickstoff und 2 Sauerstoff	19
28.	Ein Atom Kohlensäure, aus 1 Kohle und 2 Sauerstoff	19
29.	Ein Atom Kohlenwasserstoff, aus 1 Kohle u. 2 Wasserstoff	7

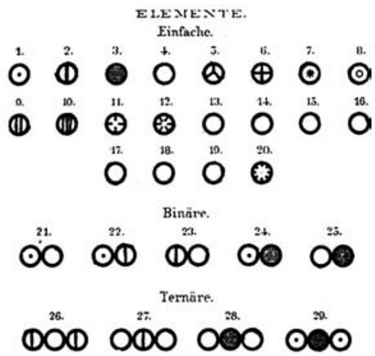


Fig. 1.3 Dalton’s first Atomic Mass Table and first models in 1808 [14]

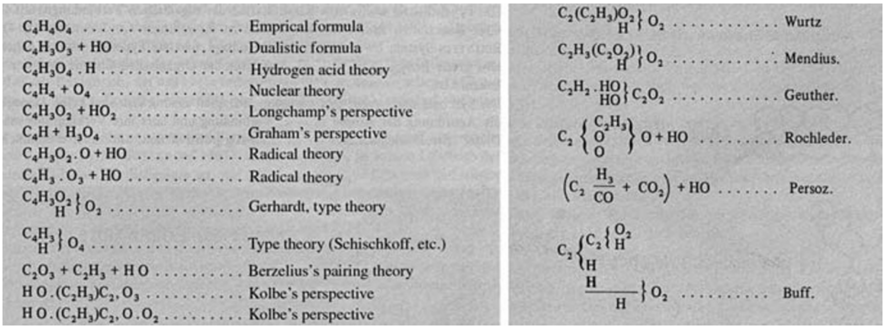
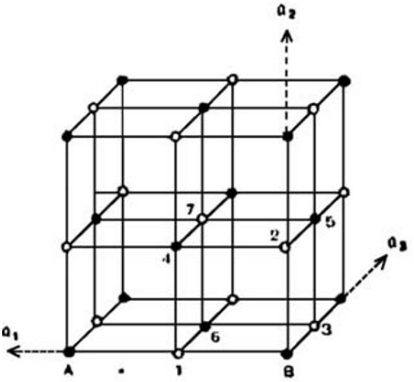


Fig. 1.4 Mental models of acetic acid molecules in the year 1861 [15]

atoms form a chain and are connected through bonding units. Furthermore, the connectivity always alternates through one or two bonding units. If we assume that the two C atoms, which close the chain, are connected through a single bonding unit, we will obtain a closed ring, which offers another six bonding units" [16]. Chemical symbols like C_6H_6 were established bit by bit. Only through overcoming the Oscillation Theory for single and double bonds in benzene molecules, the ring symbol for the benzene molecule could be developed: this is the most common symbol today.

After initial ideas of atoms and molecules, there was only one remaining kind of particle missing in order to complete the basic kit: ions. Arrhenius [17] observed variations on the electrical conductivity of different salt solutions and related his observations to decreasing freezing points and increasing osmotic pressures compared to usual solutions of sugar or ethanol. In 1884, he postulated the Dissociation Theory and the ions as being the smallest particles of all solutions of salts, acids and bases. Initially, this first concept for ions was not really understood by his colleagues, so that Arrhenius stated: "How can one think of free sodium in a sodium chloride solution knowing how sodium behaves in water, and that free chlorine should exist in the colorless and odorless sodium chloride solution knowing that a chlorine water solution is yellow and smells strongly… The fact that I believed in the destruction of salt molecules to form ions was considered a problem and opposed by members of the faculty. Knowing that most chemists would strongly reject, I tried to avoid emphasizing the Dissociation Theory. This delayed the publication of the theory for three additional years" [18]. It took a long time to introduce the idea of ions in chemistry lectures and textbooks, and misconceptions regarding "salt molecules" continued to exist way into the 20th and 21st century.

In 1912 the German scientist Laue [19] discovered the new interference pattern through X-ray radiation of crystals and finally confirmed that molecules are not the smallest particles of salt crystals: "The term molecule no longer plays a role regarding NaCl and KCl. Each Cl atom touches six metal atoms with an exact distance between them" [19]. However, it became obvious that the



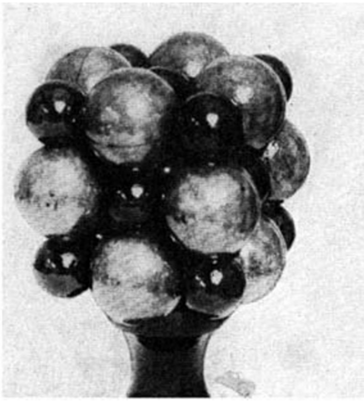


Fig. 1.5 Structural models of sodium chloride by Laue [19] and Bragg [20]

salt molecule model no longer made sense especially since Laue's model of the sodium chloride structure became more and more popular (see Fig. 1.5).

The English researcher Bragg [20] stated this also: "For instance, chemists had talked of common salt, sodium chloride, as being composed of 'molecules' of NaCl. My very first determination showed that there are no molecules of NaCl consisting of one atom of sodium and one of chlorine. The atoms are arranged like the black and white squares of a chessboard, though in three dimensions. Each atom of sodium has six atoms of chlorine around it at the same distance, and each atom of chlorine has correspondingly six atoms of sodium around it" [20]. He even constructed a spherical packing model for his concept (see Fig. 1.5).

Roelleke [21] discussed the historical development of structural X-ray analysis and, using an X-ray machine for classrooms, he obtained interference patterns according to Laue and Debye–Scherrer. He proposed ways to introduce X-ray analysis in chemical education.

Until way into the middle of the 20th century, one was not willing to let go of the trusted concepts of salt molecules. Bragg was even asked by other colleagues to save the molecule concept: "Some chemists at that time were very upset indeed about this discovery and begged me to see that there was just a slight resemblance of one atom of sodium to one of chlorine as a properly married pair" [20].

Even up until now, the misconceptions of molecules in salt crystals are so strongly anchored that even in scientifically trained circles one is not using the correct mental model of ions or ion grids according to salt crystals. The historical development of models concerning structure of matter and the big number of misconceptions can be read more precisely in other places ([22, 23, 24]) and in Chap. 5.

Conclusion: When we consider "historical misconceptions" and "scientific errors", which intelligent scientists have produced over the ages in their attempts to discover how matter is structured, we must show appreciation to our students who may, in their attempts, stumble across similar misconceptions as in the history. For this reason, it is important that each educator should be aware of the history in chemistry and physics in order to appreciate mental models of students today. It may also be appropriate to teach first the historical ways of discovering particles and chemical structures, before the most valid concepts of today are introduced.

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Chapter 2
Students' Misconceptions and How to Overcome Them

Misconceptions are not only to be observed in today's children or students – even scientists and philosophers developed and lived with many misconceptions in the past (see Chap. 1). Historical concepts and their changes are very interesting because similar ideas can help our students today: just like early scientists did they develop their own concepts by similar observations e.g., in regard to combustion. Ideas that are developed without having any prior knowledge of the subject are not necessarily wrong but can be described as **alternative**, **original** or **preconcepts** [1]. Every science teacher should know these preconcepts for his or her lessons – this is why many empirical researchers are working all over the world.

Increasingly however, researchers are also finding chemical misconceptions in advanced courses. Because they cannot be only attributed to the students but mainly caused by inappropriate teaching methods and materials, they can be called **school-made misconceptions**. They are clearly different from preconcepts that tend to be unavoidable. Inappropriate teaching methods can be stopped by keeping teachers up-to-date in their subject through advanced education.

One should attempt to find as many preconcepts and school-made misconceptions and discuss them with pre-service and in-service teachers. Another important task is to make suggestions of instructional **strategies to improve lessons,** which will lead to challenge preconceptions and school-made misconceptions: recommending alternative strategies to the traditional approaches, setting up convincing laboratory experiments, using more structural models or new technology-based methods etc.

2.1 Students' Preconcepts

Self-developed concepts made by students do not often match up with today's scientific concepts. One fails to take into account that these young folks have often, through observation, come up with their own mostly intelligent ideas of the world. In this sense, they are in good company considering that ancient

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scientists and natural philosophers also used their power of observation and logic in order to shape their ideas. Often, these scientists and philosophers did not use additional experiments to back up their theories (see Chap. 1).

When students talk about combustion, saying that "something" disappears and observe that the remaining ash is lighter than the original portion of fuel, then, they have done their observation well and have come up with logical conclusions. This is why we cannot describe their conclusions as incorrect but rather as:

– original or pre-scientific ideas,
– students preconceptions or alternative ideas,
– preconcepts.

It is common to come across several preconcepts at the beginning stages of scientific learning at the elementary, middle and high school levels of chemistry, biology and physics. Before conclusions are systematically made regarding the important issues of chemistry in the following chapters, three general examples of a student's **preconcepts** will be presented:

– the sun revolves around the earth,
– a puddle is sucked up by the sun's rays,
– the wood of a tree comes from the soil.

Sun and Earth. Most children's first experiences regarding the sun are accompanied by comments made by their families and neighbors: "Look, the sun will rise in the morning, at midday it will be at its highest point and in the evening it will set". Observations regarding sunrise, sunset, its own cycle and the common manner of speech regarding this subject must lead the child to the idea: "The sun cycles around the earth". In some of her interviews, Sommer [2] even comes across the idea of the earth as being a disc: "Children imagine the earth to be a disc over which the sky stretches parallel. The sun, the moon and the stars are to be found in the sky; there is no universe" [2].

Greek natural philosophers developed their ideas 2000 years ago. Ptolemy especially imagined the earth to be at the center of everything and pondered: "The sun moves around the earth". It was at the end of the 16th century that Copernicus, after exact observation of the movement of the planets, came up with the heliocentric image of the earth: "The earth is one of the sun's many planets, like these planets, the earth is revolving in a particular pathway around the sun and it also revolves on its own axis". Considering the uproar of the church at that time and the ensuing Inquisitions, one can imagine how stable Ptolemy's theory was present in the minds of people of the time. It was the real wish of the church to keep people in this ignorance: The earth was supposed to be the center of the universe.

Children and adolescents often, through their own observations, come up with similar concepts like Ptolemy, of course – there is no way to make discoveries like Copernicus' and to develop the heliocentric view of the earth. Teachers have to use the best methods and technology, e.g. a planetarium, in order to convince the kids to free themselves from their original ideas and to accept that the earth is revolving around the sun.

In order to have convincing lessons, it is important that young people have enough opportunities to first express and compare their ideas of the universe. Only after children feel uncomfortable with their ideas, the new and current worldview should be introduced. The children should realize that their view of the world is also quite common and even scientists in the past believed that "the sun moves around the earth". Good teaching with models like moving spheres in a planetarium should finally convince children of the revolving earth.

Puddles and Sun Rays. Through conversations with elementary school children regarding the disappearance of puddles on a sunny day, it is obvious that they believe that the sunrays "soak up the water", that "water disappears to nothing". When asked, many teachers admit that they find this explanation "cute" and often do not bother to correct or discuss it: they let the children be with their "sunray theory" and their view of the "elimination of water".

If, on the other hand, the teachers would carry out experiments showing the vaporization of water and the resulting condensation of the steam to liquid water, the scientific view could be started. If one also introduces the idea of particles and the mental model of increasing movement of the water particles through heat, a child would much better understand that the water particles mixes with air particles and therefore remain in the air.

They, furthermore, would understand that particle movement and diffusion of energy-rich particles are responsible for the evaporation of water. This would also lead the children to a logical understanding of the conservation of mass for later science lessons and understanding chemical reactions, especially regarding combustion. It is necessary however, that children can express their own view about the "disappearance of water" before they learn the scientific concept. To be convinced by the scientific concept they should look to demonstrated or self-done experiments and compare with their own view. Following these discussions, after more experiences with evaporation and condensation of water, children or students may realize their conceptual change (see Sect. 2.3).

Wood and Earth. "When people are given a piece of wood and asked how the material got into the tree they commonly reply that most of it came from the soil" [3]. Even though, in biology, the subject of photosynthesis is taught with the use of carbon dioxide, water, light and heat for the synthesis of sugar and starch, still many students when asked where wood comes from, reply: "from the soil". Most students seem to have their knowledge of biology lectures in special "compartments" of their brain. They do not link them to their every-day life understanding: "Presumably most of the graduates would have been able to explain the basics of photosynthesis (had that been the question), but perhaps they had stored their learning about the scientific process (where carbon in the tree originates from gaseous carbon dioxide in the air) in a different compartment from their 'everyday knowledge' that plants get their nutrition from the soil" [3].