BASIC DEFICIENCIES IN THE TEACHING OF BASES. IMPACT ON GREEK UNDER-GRADUATE CHEMISTRY STUDENTS.

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Abstract

Electrolyte solutions are discussed in every chemistry educational program whether it is destined for secondary education or university courses. However, among the sub-topics taught, acids occupy by far the most space in the text and vastly more time in classroom discussion than bases. As a consequence, several misconceptions emerge concerning the nature and behaviour of bases, mostly relating them to acids through the neutralization procedure. The impact of the above teaching scheme is accompanied, within the Greek secondary education program, by initially discussing Arrhenius theory, introducing Brønsted theory in the last year of secondary education level and providing only a hint about Lewis theory. Consequently, first year undergraduate students are confused about the validity and utility of the corresponding theories, often considering them alternative approaches to the description of the same property of an electrolyte. Furthermore, the undergraduate Chemistry curriculum does not appear to amend the problem as investigation involving third- and fourth-year student reveals. Less than ¾ of those students who recall a name of a theory can provide the correct definition of a base according to the theory and less than 1/3 can write the appropriate chemical equation to justify it. No general substitution of a theory for another one is apparent indicating confusion rather than misconception in the understanding of the fundamental properties of bases. However, several minor changes in teaching and tutoring maybe of help towards the goal of enhancing better overall understanding of the above among students majoring in Chemistry.

Keywords: *ammonia, acid-base theories, undergraduate course*

1. INTRODUCTION

It is sad to be stated that there exists no topic to be taught that is free of misconceptions. It appears that this statement is very true and furthermore, misconceptions arise and usually are retained throughout any course, however organized and sophisticated the teaching methods applied to it. Misconceptions may be introduced into the classroom even on the part of the teacher since it has been verified that mental models formulated early in one\s life tend to follow one until maturity (Kontopoulou et al 2017). Furthermore, the construction of the course itself or even the textbook used may act as a source of misconceptions through the implication of simplifications or incorrect matches between abstract ideas and observable quantities.

Chemistry especially, is full of misconceptions which possess a varying degree of origin as well as an even wider arsenal of factors influencing their accumulation and retention (Kind 2004; Horton 2007). This is based on the fact that, beyond the typical difficulties in understanding and developing of the scientific procedure by young students, Chemistry is involved in the study of the sub-micro realm which is not directly accessible and conceivable especially during infancy. Furthermore, both the teacher and the students are required to balance their thoughts and discussions among the three distinct ways of describing and understanding chemical phenomena, namely the macroscopic, sub-microscopic and symbolic (Johnstone 1991). Understanding the difference between chemical reaction and chemical equation and especially the description of the former through the latter, aided by the requirement that the equation has to be balanced according to Lavoisier's principle of mass conservation proves to be a major obstacle in the above understanding process (Papadopoulos et al 2022).

Electrolytes form a large group of compounds attracting considerable interest in their study since they compromise a wide range of compounds related to the human body and immediate environment.

Among electrolytes thee exist several groups of compounds the main ones being acids and bases. Acidic and basic behaviour has been identified and studied at an early stage of the genesis and maturation of the science of Chemistry, initially more descriptive and more recently founded on measurements and arguments derived from the knowledge and application of the atomic theory. Consequently, acids and bases are presented to the high school students and their properties are discussed in detail. The ionization of these groups of compounds in aqueous media is also discussed and represents in itself one of the major aspects of Chemistry taught at the secondary education level. The Greek secondary level education system, in its uniqueness in the introduction and deal of the sciences (Karageorgiou et al 2015) and its ever-changing nature regarding the chemical context of the educational program (Vandoulaki et al 2016) incorporates discussion of both acids and bases and their properties in solution. Following the traditional scheme, the more simple, Arrhenius model of acids and bases is taught (Arrhenius 1884). The Lewis model (Lewis 1923), although referred to in the final year of the six-year curriculum is never actually taught in the classroom.

A quick survey of General Chemistry textbooks reveals that almost 4 times larger space is devoted to the discussion of acids and their properties, excluding acid-base reactions or the acidic behaviour of salt solutions, relative to the space allowed for the discussion of bases and their properties. In general, in the tables where the names of characteristic and well-known substances are classified as acids or bases, the latter only amount to 1/3 of the total number. A look at the Index of general chemistry textbooks also provide at least twice as many entries related to acids, relative to the entries related to bases, again excluding acid-base reactions. References to specific acids are ten-fold relative to references to specific bases, which almost exclusively belong to alkalimetal hydroxides. In Kind’s work (Kind 2004), is stated that (Cros et al 1986, 1988) investigated university science students' ideas about acids and bases, finding that the concept of bases was far less developed than that of acids. Many students gave the Arrhenius definition of bases being OH^- donors. Students could not name bases as easily as acids, giving only ammonia and sodium or potassium hydroxide as responses. Second year students showed no improvement on the first years in these respects. In a closely related topic, the pH scale is thought to be describing the acidity of a solution, with pH values larger than 7 being attributed to extremely small acidic content.

In advanced chemistry courses, acids and bases are redefined within the Brønsted-Lowry theory (Brønsted 1923; Lowry 1923) as "donors" and "acceptors", moving away from the Arrhenius definitions of an acid being a "substance which yields hydrogen ions" and a base producing hydroxide ion in solution. Hand suggests that presenting students with this new theory confuses them (Hawkes 1992). A major factor leading to this observation maybe lies in the acceptance of the various theories presented to the students as different proposals for the same phenomenon, which naturally directs them towards utilizing the most simple and straightforward between them or the first ever to be presented to them. As far as the undergraduate Chemistry curriculum is concerned, much less effort is placed in discussing pK_b relative to pK_a and in some courses even the trivial $pK_a + pK_b = pK_w$ is not explicitly mentioned or used in problem solving. Concerning tutorials, there is almost none related to the pH evaluation or utilization of a weak base solution and certainly none referring to buffer solutions containing weak bases. During the first year of studies in the Chemistry Department the Analytical Chemistry course deals with acid-base behavior in aqueous media and with weak acids (mainly) and bases without explicit reference to the fact that the electrolytes are discussed in relation to the Arrhenius or the Bronsted theory. Furthermore, in the Organic Chemistry courses reference to the essentially Lewis base character of electrophiles is not made and even clarification of the origin of DNA bases nomenclature is not performed. There exists a brief reference to Lewis acid and base behaviour in the 3rd year course in Coordination Chemistry where the metal cation to ligand reaction is described as a Lewis acid to Lewis base reaction.

2. DESCRIPTION OF THE STUDY

2.1 Initial stage

Serendipity played a major role in the initiation of the present survey as it emerged through a formal end-of-course examination of first year students in the local Chemistry Department. Placed in the frame of the typical questionnaire related to the General and Inorganic Chemistry course, a simple question was stated in the form of "Describe the reason for which ammonia is considered a base for each of the known electrolyte theories. Use a chemical equation to solidify your argument". The idea was to provide a "simple" question for the students but it appeared to act as a pit-hole instead. Following the initial data collection and evaluation it became apparent that the principles of acids and bases are not well understood by first year Chemistry students. It seemed therefore appropriate to investigate to some depth the factors leading to such a misconception. In fact there exist several sources for several misconceptions in the wrong answers to the above question since there are three known theories requiring citation and comment. Indeed very few are the surveys dealing with the complete set of acid-base models (Cyril and Coll 2016) whereas there exist several dealing with every specific model (Ouertatani et al 2007; Hawkes 1992; Drechsler and Schmidt 2005)

2.2 General considerations

Expectations were that some of the students might not remember all three of the formal acid-base theories, especially since they are introduced to them in several steps which are not simply and smoothly distributed within the Secondary Education Program. Indeed, reference to acids and bases is first made during the second year of junior high-school (student age 13-14 years) and only in general terms and without reference to any relevant chemical equation as the approach during this part of the education program is mainly descriptive and observational. Of course, following the Occam razor doctrine, the simple Arrhenius theory is the only one discussed. The content of the chemistry curriculum takes a drastic turn in senior high-school where acids and bases appear again in the third and last year (student age 17-18). The backbone of the course is chemical equilibrium and in this context introduction of the Brønsted theory seems appropriate aiming at the understanding of relative weak and relative strong acids and bases. Little effort is placed, however, in identifying Brønsted bases, especially when they cannot be considered as Arrhenius bases as well. Lewis theory is not described at all. However, Lewis theory is among the basic topics covered in the introductory undergraduate course of General and Inorganic Chemistry since it is prerequisite to the writing of molecular formulae and derivation of hybridizations and therefore local structures of simple compounds (Papadopoulos et al 2022).

The answering sheets collected for the study were assessed in a form typical of a end-of-course examination. The expected answers were divided in three parts, the first incorporating reference to the names of the three known electrolyte theories, the second related to the report of the key facts identifying a base for each theory and the third and more demanding one requiring a chemical equation where representation of the above key facts should be pictorially presented. Assuming that the first two steps only require the student to remember a name and a corresponding definition while the last one demands full understanding of the definition and further extend its abstract content into a symbolic representation (Johnstone 1991), a single point was assigned to each correct answer for the first two steps and two points for each correct equation giving a total of 12 points. Assessment is based on correct responses to any of the 12 points required for a complete answer. The presentation of the results in the following figures is therefore given in the form of 13 columns but distributed on a scale of 0 – 10.

3. RESULTS AND DISCUSSION

The study reported refers to a total of 435 answering sheets obtained from 1st (N=229), 3rd (N=84) and 4th (N=122) year students of the local Chemistry Department over a period of two years. The 3rd and 4th year participants had to answer at their own free will the question as part of their participation in a Didactics of Chemistry course, while the 1st year students had to answer it within the scheme of their General and Inorganic Chemistry course assessment.

The first general observation is that the results can be described as disappointing (Figure 1). The mean score obtained is 4.98 with a standard deviation of 2.51 The small percentage of totally correct answers (5.3%) is noteworthy, however, the most interesting and simultaneously most appalling result is the 3% that did not provide a single correct point.

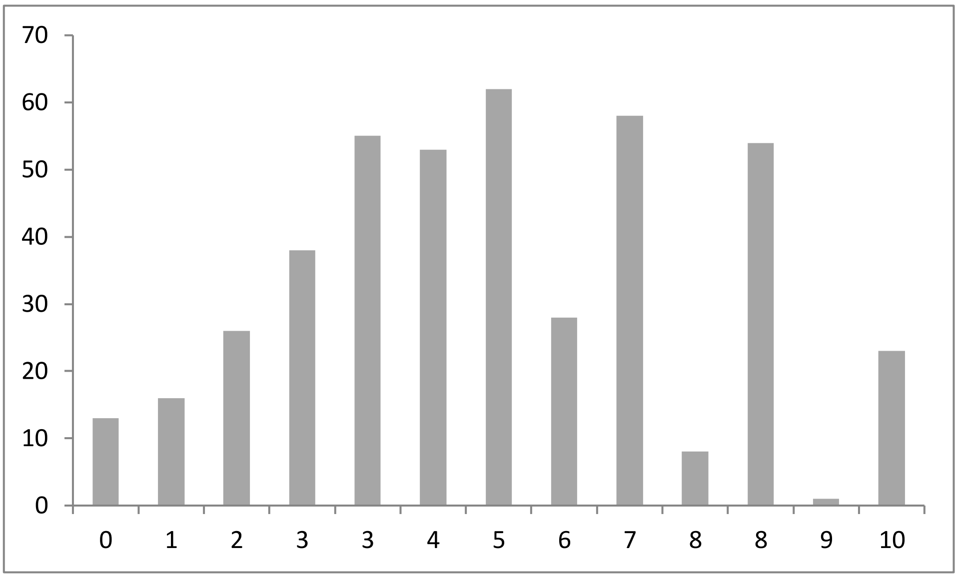

Fig. 1. Presentation of the overall student assessment. Thirteen discrete sets of scores are reported representing scores representing correct answer to 0-12 points required for a complete answer.

Partition according to year of study reveals no statistically significant differences between students at various stages of their overall undergraduate program, although there is a slightly better performance by 3rd year students as their 5.53 average score indicates. The decline observed for the final year students may be attributed to the construction of the department's program with a single core up to the 6th semester making allowance for various "directions" composed mainly of non-compulsory courses during the final two semesters of the program. The construction of the last year courses focus on special topics involving more in-depth discussions of applied chemistry, therefore removing the students' interest from the more basic and general aspects of the science. Of course, a great part of the behaviour of smart materials depends on electrolytic or redox properties, however the advanced courses consider the knowledge of the basics for these properties as a concrete part of the students' background and no effort is made towards their repetition.

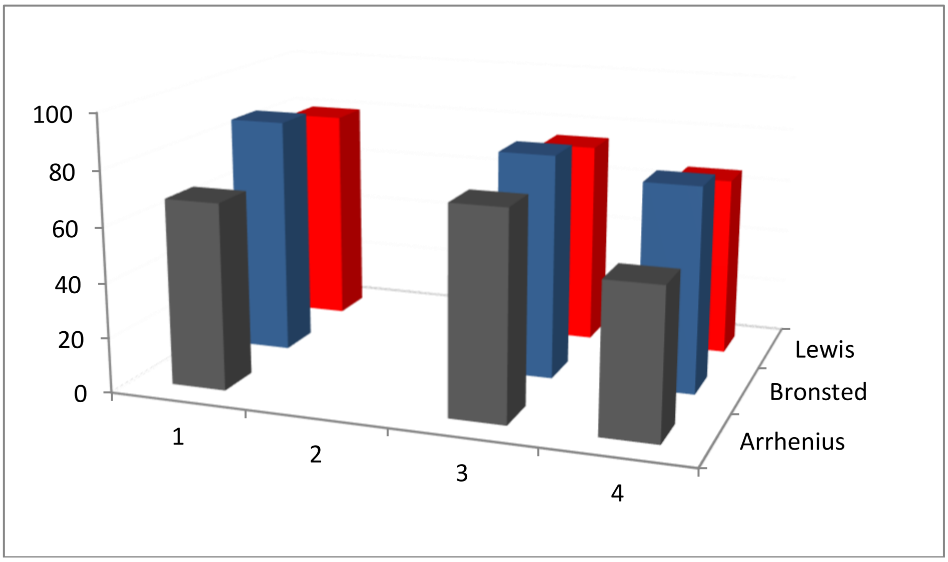

Fig. 2. Percentage of students correctly citing the names of the electrolye theories per year of study.

Bearing in mind the long-term acquaintance of the students with Arrhenius theory, dating back for more than 5 years, we expected that almost all of them should remember the name, the corresponding definition (Coll and Treagust 2003) and that they would be able to formulate a chemical equation where the hydrolysis of and not simple dissociation of ammonia (Hawkes 1992) would give rise to the OH^- ions required by the theory in order to classify ammonia as a base. We were also optimistic about the related answers regarding Lewis theory since it represents the most recent new addition to their background and is therefore expected to claim a large amount of their interest.

The findings were once more not in line with the general expectations (Jabot and Henry 2007). Concerning the facts required to be cited for each theory, a completely correct answer there appears to be a wide variation between remembering the name of a theory, citing the key characteristic of bases within the theory and finally presenting a balanced chemical equation to account for it. For the Arrhenius theory a 65.8% of the participants remembered the name but only a 72.7% of them (or 47.8% of the population) gave the correct key feature of an Arrhenius base and of these only a 72.6% (a total of 34.9%) provided the typical hydrolysis chemical equation. For the Brønsted theory the corresponding percentages obtained are 83.2% for reference of the name, 71.3% (59.3%) for additionally citing the appropriate chemical behavior and finally 55.0% (32.6%) for adding the correct chemical equation. For the recently presented and discussed Lewis theory the relative percentages were 75.4%, 83.5% (63.0%) and 16.4% (10.3%). It becomes evident from the above results that short term memory is utilized most by students since a considerably larger percentage of those remembering the name of Lewis theory were able to provide the correct basic statement of the theory although the same is true for about ¾ of those citing any theory. Long term memory, on the other side, would account for a drastically larger percentage in both use of the name of Arrhenius and provision of the corresponding statement, which was not observed in our case. A point of interest which requires further investigation is the relation of the knowledge of a specific theory to the overall achievement of the participants. Taking into consideration only those who gave a fully correct answer for each theory, their average scores per theory are obtained as 7.52 (1.64) for Arrhenius, 7.17 (1.99) for Brønsted and 8.61 (1.89) for Lewis theory respectively, with the corresponding standard deviations given in parentheses. This again argues for a stronger cohesion of the newly acquired knowledge into the scientific background of the students as far as theoretical considerations are taken into account.

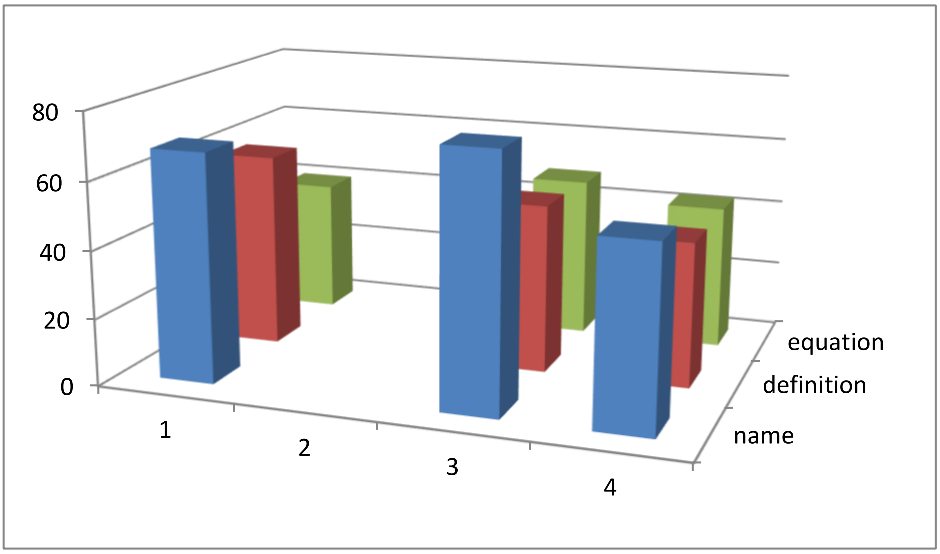

Fig. 3. Variation per year of study, of the percentage of correct statement of the name and definition of the Arrhenius theory as well as of presentation of a suitable chemical equation to account for the basic character of ammonia according to the theory.

The initial expectations were not high concerning the presentation of relevant chemical equations to account for the basic character of ammonia, because although it is widely understood that the balanced chemical equation is a major tool for connecting the various levels of describing a chemical phenomenon (Taber 2009) stoichiometry understanding has yet to be developed within the undergraduate education program. One out of three undergraduates were able to present a balanced chemical equation to account for the basic character of ammonia for the first two theories and only one out of ten in the case of Lewis theory. Furthermore, a dramatic 16.6% did not attempt to formulate a single chemical equation in order to account for at least one of the theories and a further 10.1% only reported the hydrolysis of ammonia without any comment. The relevant chemical equation is

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$$

and one might argue that it is adequate for the justification of the basic character of ammonia beyond the Arrhenius theory, however, in such a case the participant to the survey should have indicated that for the Arrhenius theory it is sufficient to observe the resulting formation of the hydroxide anion, OH^-, while for the Brønsted theory the formation of the ammonium cation through the abstraction of a proton from the water molecule is the central argument. In the absence of such a statement we chose to consider the equation for Brønsted theory as missing.

In a more detailed investigation of the data retrieved, the misconceptions and misinterpretations concerning the three electrolyte theories is attempted. In this respect, Arrhenius theory is given in general a relatively high percentage of the correct definition, however there are minor deviations from the ideal situation as 3.1% for 1st year students, a 2.4% of 3rd and a 7.4% for 4th year students erroneously provide the definition of Brønsted base instead. Smaller percentages of 2.4% for both 3rd and 4th year students mistake the Lewis base definition for the Arrhenius one. This observation is accompanied by a progressive substitution of the Arrhenius definition for the Brønsted one, giving percentages of 2.2%, 7.1% and 15.6% for 1st, 3rd and 4th year students respectively. Interestingly enough, the Lewis theory does not interfere with the Brønsted one as the respective percentages are 0.0, 2.4% and 5.7%. Lewis theory appears to be more concrete, to the extent that it is identified, since it bears only minor "contamination" from the other theories concerning its definition, the largest by far being a 3.3% from Brønsted theory at the 4th year of studies.

As a general overview of the above results, we are led to believe that the long-term acquaintance of the students with the Arrhenius theory of electrolytes elevates it to the status of the only theory present and renders obsolete the need to remember the name of its originator. This proposal is based mainly on the unexpectedly low percentage of the name citation as well as of the decline of this percentage with the year of study. The most concrete understanding of Lewis theory reflected in the larger percentage of correctly stating its key definition is in line with the proposal that newly acquired knowledge is most appealing for citation. The general inability to present a suitable chemical equation in order to justify a chemical property is a persisting problem within the Greek educational program and cannot be confronted through some local actions on specific topics like the one discussed in the present study.

4. CONCLUSIONS AND PROPOSALS

Knowledge assimilation is not propagated by the simple addition of newly acquired facts into a pre-existing database, as it is the case for artificial intelligence machines (Lefkowitz and Lesser 1988). Even in that case the intervention of experts is required for the correct fitting of the new data and the identification of the correspondence towards previously acquired information and classified data. It has to be made clear to the students that acid-base phenomena cannot be described by a single and simple model as well as that the various models discussed in the classroom find application under differing circumstances and have to be treated accordingly although knowledge of their key characteristics should be kept in mind (Coll and Lajium 2011). Special care should be given, in our belief, to the indication that each theory is expected to treat uniformly with its predecessor the compounds, processes of phenomena treated by both theories, providing extension and expansion to new ones. Therefore, an Arrhenius base cannot be considered as non-basic or as acidic by more recent and more general theories, although the reasoning for considering it a base should be different and the realm of Lewis theory, for example, could be different from the aqueous medium required for Arrhenius theory.

A major obstacle in the diminished degree of understanding of base properties arises from the considerably larger amount of information available (and subsequent discussion time) on acids rather than bases. It has been pointed out that a more even-handed process would involve an alongside introduction to the chemistry of acids and bases (Kind 2004) and it should be considered in constructing the corresponding curricula. A further action that can be relatively easily carried out under the Greek educational system is to drop the generally used “acids and bases” headline for the electrolyte chapter since in Greek the terms for the two families of compounds can be arranged in the opposite way relative to the English sequence. In this way the two terms are arranged in the correct Greek alphabetical order (βάσεις και οξέα, bases and acids) and the heading of the chapter implies that bases are going to be treated first, although not to as great length as acids which will follow. For the undergraduate courses involving General Chemistry lectures and tutorials, care should be taken to introduce at least some problems dealing with the dissociation and performance of base solutions. For example, derivation of the Henderson-Hasselbalch equation for ammonia containing buffers could be given as an exercise to first year students who are currently confined to acid-containing buffers.

Introductory remarks or short appendices referring to chemistry basics like bond energy, reaction energetics and, of course, definition of bases and acids could be easily incorporated into existing undergraduate text books or provided as internet links to the students for almost every course taken throughout the four-year studies aiming for a Chemistry major. This supplementary information would provide a suitable means of reorganizing pre-existing data in the minds of students and help to consolidate newly acquired information rather than substituting it for some earlier taught topic.

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