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# "Acids are those dangerous green liquids, and what's a base?" – Evaluating upper secondary students' 'acceptance' of a learner-appropriate approach to teaching about acid-base reactions

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## Structured Abstract

**Background:** A central issue in chemistry education is the Johnstone triangle. The complexity of the chemical topic and the learners' propensity for conflating the levels of the chemical triangle show that using a conceptually coherent model on the submicroscopic level is indispensable for preventing learners from developing inadequate conceptions and helping them connect the macroscopic with submicroscopic properties (Taber, 2013). This is especially true for historically relevant topics such as acid-base chemistry (Häusler, 1987; Krebs & Hofer, 2022; Rychtman, 1979). Numerous proposals on how to teach the topic exist (Jiménez-Liso et al., 2020); however, focusing on the compatibility of acid-base reactions to other reaction types in the course of their introduction to learners has received less attention so far.
**Purpose:** This study aims at evaluating such an approach via a design-based research approach (Gräsel, 2010; Haagen-Schützenhöfer & Hopf, 2020). By delineating key ideas from the Brønsted-Lowry model of acid-base reactions and focussing on the donor-acceptor concept (Barke & Harsch, 2016) and electron transfers (Ghosh & Berg, 2014; Shaffer, 2006; Sieve & Bittorf, 2016), acid-base chemistry can be taught in a conceptually coherent and compatible manner.
**Sample/setting:** In order to evaluate this approach, 18 learners from several Austrian upper secondary schools (grades 10, 11, and 12) were interviewed using the method of probing acceptance (Jung, 1992) in three separate interview rounds. Due to restrictions imposed as a result of the Covid-19 pandemic, these interviews were conducted online using videoconference tools and collaborative word processors.
**Design and Methods:** In order to design learner-centred teaching materials appropriate for the target group, the learning environment was evaluated cyclically, and after each interview round and data analysis, a re-design followed. As the interview data showed learners' 'acceptance' of the presented learning environment, i.e. their level of agreement with the materials and terms introduced in the interviews, the data was analysed via evaluative text analysis (Kuckartz, 2014), and intercoder agreement assessed in percentual overlap.
**Results:** The results suggest that the teaching materials and the learning environment developed in the course of the study are received well by the intended target group. In the course of the interview rounds, acceptance increased from satisfactory to mostly successful, thus underlining the potential of the learning environment.
**Conclusions:** In conclusion, even though this study is very limited due to small sample size ($N$=18), the continuous effort we made to improve our learning environment according to the participating learners' offers a basis for larger-scale studies on the matter.
**Keywords:** *design-based research, acid-base chemistry, upper secondary school, method of probing acceptance*

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## 1 Introduction

Proposing how to teach acid-base reactions has a longstanding tradition in chemistry education research. Numerous ideas exist, offering a wide range of approaches. One of the reasons for this is that the topic plays such an essential role in our lives in everyday products, biochemical processes and the chemical industry (Bučková & Prokša, 2021). For example, acidic and alkaline solutions are found in numerous articles of food, cosmetics, and household products. Different terms associated with acid-base reactions, such as neutralization, have found their way into everyday language due to the historical development of acid-base concepts (Krebs & Hofer, 2022). References to acids and bases can also be found in advertisements, package leaflets and similar texts (Bučková & Prokša, 2021). In other words, acid-base chemistry is ingrained in everyday life and language, thus paving the way for students to develop prior knowledge and conceptions associated with what constitutes an 'acid' and, in some cases, a 'base' (Hoe & Subramaniam, 2016; Pan & Henriques, 2015). In addition, acid-base chemistry has been a focal point of chemistry as a science for hundreds of years, which led to the development of numerous oftentimes contradictory acid-base concepts (Häusler, 1987; Krebs & Hofer, 2022; Krebs, Hofer & Lembens, 2022; Rychtman, 1979). With the idea that an intrinsic component of acids must exist, a so-called *principe acidifiant*, numerous acid-base concepts were developed around specific features of what makes up an acid (e.g. oxygen, hydrogen, lone electron pairs, etc.; Häusler, 1987; Krebs & Hofer, 2022; Weyer, 2018). The prevalent acid-base concepts nowadays were introduced by Arrhenius, Brønsted-Lowry and Lewis over one hundred years ago (Arrhenius, 1907; Brønsted, 1923; Lewis, 1923; Lowry, 1923) and focus on hydron ions and hydroxide ions, transfer of hydrogen ions, and the formation of Lewis complexes to define acids and bases, respectively.

The most common foci for teaching acid-base chemistry are introducing different macroscopic properties of acidic and basic substances in a learner-centred or inquiry-based setting (Jiménez-Liso et al., 2018; Jiménez-Liso et al., 2020), applying specific acid-base models because of their usability in a particular context (Bretz & McClary, 2015; Jiménez-Liso et al., 2018), or using historical acid-base models to teach about Nature of Science (NoS) (Erduran & Kaya, 2019; Jiménez-Liso et al., 2020; Krebs & Hofer, 2022). For example, existing teaching-learning sequences and teaching materials focus on introducing macroscopic properties of acidic and basic substances such as inducing colour changes in pH indicators (Jiménez-Liso et al., 2018, 2020). Others introduce models such as the Lémery concept (explaining acidity and basicity to be caused by a constituent particles' shape, i.e. that an acid particle is pointy and a base has a pore to neutralise the acid with) to explain the one specific acid-base reaction, in this case the reaction occurring between acetic acid and sodium bicarbonate in an aqueous solution (Jiménez-Liso et al., 2018). Different acid-base models and concepts were also adapted to form digital learning environments, such as simulations and computer animations, which represent the reaction process on the submicroscopic level (González-Gómez et al., 2015; Watson et al., 2020).

Whilst the relevance of the topic both for chemistry as a scientific discipline and a school subject is indisputable, acid-base reactions prove to be highly complex for both learners of chemistry (Carr, 1984; Hoe & Subramaniam, 2016; Paik, 2015) and chemistry teachers and student teachers (Alvarado et al., 2015; Barke, 2015; Lembens et al., 2019). One of the factors contributing to this complexity can be explained with the Johnstone triangle, i.e. how to understand the submicroscopic level in connection with the macroscopic properties of the corresponding substance by use of different representations and symbols (Johnstone, 1991; Reid, 2021; Taber, 2013; Talanquer, 2011). 'Switching' between its different levels (macroscopic, submicroscopic and representational) poses a high cognitive load and demands a 'multi-level thought' that learners oftentimes have not yet developed (Taber, 2013). In addition, conflating different and especially contradictory historic models and concepts can lead to alternative conceptions (Alvarado et al., 2015; Hoe & Subramaniam, 2016; Pan & Henriques, 2015), model/concept confusion (Carr, 1984; Damanhuri et al., 2016) and the emergence of hybrid models (Justi & Gilbert, 1999).

Overall, most studies have been content to either focus on what teachers and learners of chemistry confuse or misunderstand about the topic, or how acid-base reactions can be taught to reflect their macroscopic properties or their history in the field of chemistry. Conversely, few attempts have been made to focus on how acid-base reactions can be taught as a subtype of chemical reactions. In other words, there is a need for research on how the topic can be taught in a way that is adaptive, linguistically and conceptually appropriate, and compatible to other reaction types. We intend to address this issue by focusing on highlighting the donor-acceptor concept (Barke & Harsch, 2016) as a main part of acid-base reactions, as well as utilizing the Electron Pushing Formalism to explicate the reaction mechanism of Brønsted-Lowry acid-base reactions (Krebs, Hofer & Lembens, 2022; Sieve & Bittorf, 2016). Stemming from organic chemistry, curved arrows drawn upon lone electron pairs of structural formulae to illustrate the movement of electrons in the course of a reaction (equation) (Ghosh & Berg, 2014). We argue that an adaption of the Brønsted-Lowry acid-base concept with a focus on the donor-acceptor concept (Barke & Harsch, 2016) and the illustration of bond breaking and forming via Electron Pushing Formalim (EPF) (Ghosh & Berg, 2014; Shaffer, 2006; Sieve & Bittorf, 2016) can be used to adequately model acid-base reactions on the submicroscopic level and explain properties such as acid and base strength (Krebs, Hofer & Lembens, 2022). Additionally, the concept can be extended to broader acid-base concepts such as those of Lewis and Ussanovich (Fleischer, 2020; Reiners et al., 2020), thus increasing its upward compatibility.

The purpose of this paper is to detail first steps in our development of such a learning environment for upper secondary students. The study presented here was designed to assess the learners' 'acceptance' of the explanatory framework, or the comprehensibility, plausibility and applicability (Posner et al., 1982) of the design to problems and tasks. These three features of 'acceptance' were chosen to aim at learners undergoing at least partial conceptual change concerning their naïve notions of acid-base chemistry, as Posner et al.'s (1982, p. 214) prerequisites for conceptual change include the following four conditions:

1. Learners must experience dissatisfaction with an existing explanation or concept, for example, by identifying its boundaries.
2. They are offered a new concept or explanation which is intelligible for the learners.
3. The new concept or explanation appears plausible to the learners in that it better explains a problem than the existing explanation or concept.
4. This concept or explanation offers the possibility of fruitfulness, or applicability, to other areas of interest.

Consequently, we give results of the assessment of our explanations and representations of acid-base reactions, referred to subsequently as *key ideas*. The research question discussed in this paper is, therefore, the following:

*To what extent are our explanations of acid-base reactions understandable and plausible for the learners and applicable to more advanced tasks and problems?*

As a response to this research question, the remainder of the paper is divided into four sections: The theoretical background offers more insight into the connection of the Johnstone triangle and difficulties in teaching and learning about acid-base chemistry. Subsequently, we describe our methodology, i.e. the method of probing acceptance (Jung, 1992). Here, learner acceptance of a new or different explanatory framework or smaller learning environment can be evaluated in accordance with Posner et al.'s (1982) steps of conceptual change. Finally, we will give insights into our results of whether the participating learners found our explanations understandable, plausible and applicable to more advanced tasks and discuss these results within the context of the Johnstone triangle.

## 2 Research Background

A central obstacle in learning chemistry is understanding and working with the three levels of the chemistry 'triplet', or Johnstone triangle (Johnstone, 1991; Reid, 2021; Taber, 2013; Talanquer, 2011). Whereas the macroscopic level refers to learners' experiences with chemical substances by seeing, smelling, feeling, and the like, the submicroscopic level refers to entities and processes that are not accessible to direct observation, i.e. molecules, ions, bonds, energy, etc. We gain knowledge about the submicroscopic level through experiments and measurements; the representational level includes every form of representation with which we communicate on the macroscopic as well as the submicroscopic level (word equations, chemical symbols, models, flow diagrams, etc.) (Talanquer, 2011). This 'multi-level thought' leads to difficulties in connecting the three levels of the triangle and thus grasping chemical subject matter in its technical and linguistic complexity (Taber, 2013). Consequently, topics such as acid-base reactions are difficult to teach and learn about, as they demand an understanding of the topic on all three levels of the Johnstone triangle (cf. Fig. 1).

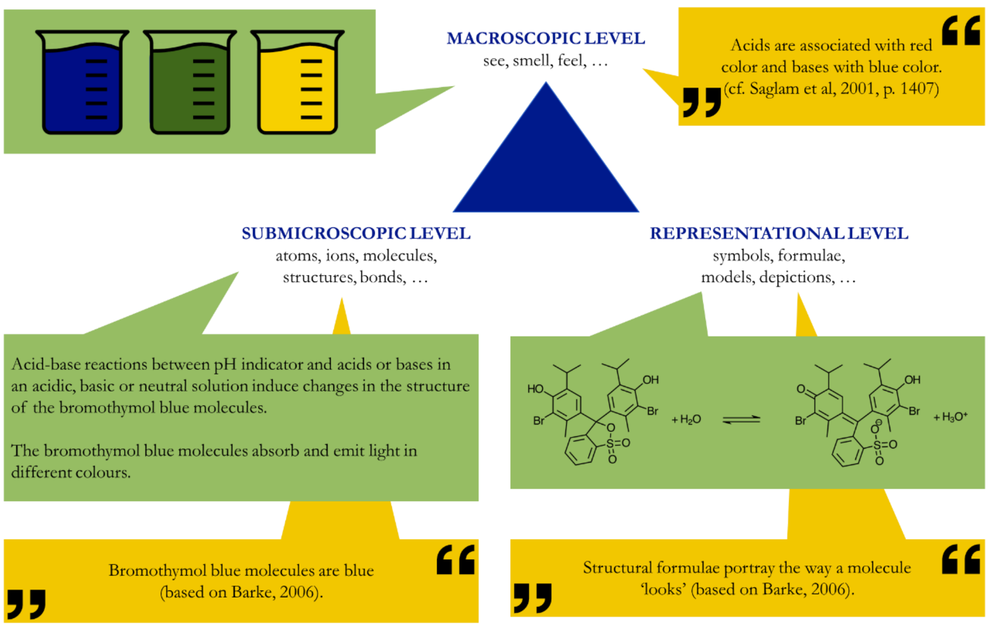


**Fig. 1.** Acid-base chemistry examples (green) for the three levels of the Johnstone triangle (based on Johnstone, 2000) supplemented by learners' alternative conceptions (yellow, in quotation marks).

Regarding the learners' perspective on acid-base chemistry, it appears that their "knowledge is a fragmented accumulation of bits and pieces containing conflicting and naïve notions" (Lembens et al., 2019, p. 1). Alternative conceptions about this reaction type span all levels of the chemistry 'triplet', with learners presenting ideas such as acids always being corrosive (macroscopic level, Hand & Treagust, 1988; Kind, 2004; Özmen et al., 2009), or conflating different acid-base models (symbolic level; Carr, 1984; Hawkes, 1992). Concerning the submicroscopic properties of 'acids' and 'bases', we have previously discussed (Krebs, Hofer & Lembens, 2022) that learners might even believe that the properties particles exhibit in the course of an acid-base reaction are features that the particles themselves 'have', i.e. that being an acid is an ingrained feature of these particles. This belief has been observed in other regards as well (e.g. students believe that sulfur atoms are yellow), thus posing a general cognitive challenge regarding teaching and learning chemistry (Barke, 2006). Moreover, conceptual uncertainties and ambiguities about the topic have been identified among (future) teachers as well (Alvarado et al., 2015; Barke & Büchter, 2018; Lembens & Becker, 2017). Consequently, an approach to teaching about acid-base chemistry must include the learners' perspectives and alternative conceptions, and thus conceptual change theory (Posner et al., 1982; Vosniadou, 2013).

## 3 Methods

In order to develop and evaluate a learner-centred approach to teaching about acid-base reactions, our research followed the design-based research (DBR) paradigm (Anderson & Shattuck, 2012; The Design-Based Research Collective, 2003; Wang & Hannafin, 2005). DBR provides a means of developing, evaluating, and revising designs such as learning environments (LEs) and teaching-learning sequences (TLSs) in close cooperation with the intended target group. Based on the suggestions by previous studies utilizing DBR (Haagen-Schützenhöfer, 2016; Haagen-Schützenhöfer & Hopf, 2020; Zloklikovits & Hopf, 2021) and the Model of Educational Reconstruction (Duit et al., 2012), a clarification of the scientific content (i.e. knowledge about historic and current acid-base models) and research on teaching and learning the topic (i.e. research about alternative conceptions, challenges, and beliefs) led to the formulation of design principles. According to Haagen-Schützenhöfer (2016, p. 27), design principles are similar to hypotheses in scientific inquiries as they predict what *helps* students but can and oftentimes are revised in design-based research cycles. They depend on the science content and the learners' perspectives of and challenges with the topic, and constitute the basis for designing explanatory frameworks, learning environments and teaching-learning sequences. In this case, the design principles, and knowledge of challenges acid-base reactions pose, led to a design in the form of six *key ideas* (KIs) about the topic (Tab. 2 in section 4.1; for a delineation on how the key ideas were developed see Krebs & Lembens, 2021). The key ideas are then assessed in interviews utilizing the method of probing acceptance (Fig. 2, cf. Jung, 1992) with individual learners of the target group, upper secondary students in grades 10 to 12. This method is used to assess whether an explanatory framework based on the key ideas is deemed intelligible, plausible, and applicable to tasks and problems by the participating learners, thus following Posner et al.'s (1982) prerequisites of conceptual change (cf. Zloklikovits & Hopf, 2021). Interviews employing the method of probing acceptance comprise "a very intensive[, one-on-one] and in[-]depth interaction between student and interviewer [so as to] find out typical resistances to elements of the explanation" (Jung, 1992, p. 278).

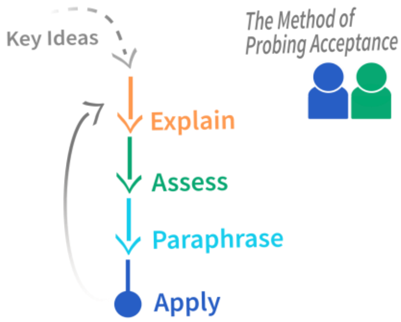


**Fig. 2.** Structure of an interview using the method of probing acceptance (Jung, 1992), © Sarah Zloklikovits, CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0, via Wikimedia Commons.

To do so, the interviewer presents an explanation based on a key idea to the learner (1), subsequently asking the learner to assess the explanation's plausibility and comprehensibility (2). The learners then paraphrase the key idea in their own words (3), followed by using the explanation to solve either one or two tasks with increasing difficulty (4). Altogether, six key ideas (K1-K6) have been assessed in the course of three separate online interview rounds ($N_1$=7, $N_2$=4, $N_3$=7). As this study follows the DBR approach, every evaluation round of the key ideas leads to a reflection and a possible revision (The Design-Based Research Collective, 2003). The analysis of the interview transcripts has been conducted by one person via evaluative text analysis (Kuckartz, 2014) to ascertain the level of correctness and appropriateness the learners exhibit during the assessment, paraphrase and task solving phase; in other words, we evaluate whether the results were successful, satisfactory or inadequate (Tab. 1). Subsequently, the first author and a second rater – a trained research assistant – coded twenty per cent of the transcripts, i.e. four interviews of the third round of interviews (Amsterdam, Pat, Sun, and Ignaz). Coding segments were pre-defined in a step of communicative validation (Rädiker & Kuckartz, 2019) and the percentage agreement between the two raters calculated. Even though this approach to calculating interrater agreement is rejected in most cases (O'Connor & Joffe, 2020), it is sufficient in this case to assess the level of 'acceptance' the learners exhibit towards the explanatory framework.

**Tab. 1**. Categories for the evaluative qualitative text analysis (in accordance with Burde, 2018; Haagen-Schützenhöfer, 2016; Zloklikovits & Hopf, 2021).

| | successful (0.0) | satisfactory (0.5) | inadequate (1.0) |
|---|---|---|---|
| Assessment | The key idea is assessed as plausible and intelligible. | The key idea is accepted partially, whilst some parts are deemed intelligible/not plausible. | The key idea is deemed not intelligible/plausible. |
| Rephrasing | The paraphrase is complete and correct. | The paraphrase of the key idea is partially complete or partially correct. | The key idea cannot be paraphrased correctly or independently. |
| Task solving | The task is solved successfully with the use of the key idea. | The task is solved mostly independently and correctly. | The task is not solved in a satisfactory manner. |

Guided interviews using the method of probing acceptance were conducted with overall 18 students (ten female, eight male) attending grade ten, eleven and twelve of Austrian upper secondary schools. In the first round, seven interviews were conducted, followed by a second round of four interviews, and a third and final round of seven interviews ($N_1$=7, $N_2$=4, $N_3$=7). Eligibility requirements were that students attended an upper secondary school and had completed at least half a year of advanced chemistry classes at school. The interviews themselves were conducted in form of video-conferences (due to Covid-19 restrictions); in the first round, interviews focusing on key ideas one to three took about an hour, whereas the second-round interviews were 90 minutes long. This discrepancy is due to the fact that the interviews in the first round comprised only K1, K2 and K3, whereas we added K4 and K5 in the second round. The interviews in the final round were shortened to an hour again, even though key idea six was introduced in this round. This was done by changing the format from presenting the explanations orally to the students to letting them read a text and then discussing it. As can be seen in the results section (cf. Fig. 2), the codenames used to refer to the participants are rather uncommon; this is due to the fact that the students chose their own codenames.

## 4 Results

Overall, the aim of the study was to evaluate the learner 'acceptance' of the proposed explanatory framework about acid-base chemistry. In order to do so, we will briefly explain the delineation of the key ideas and explanatory framework (for a more detailed description see Krebs & Lembens, 2021) and subsequently enumerate whether the learners of rounds one, two and three found the key ideas plausible, could paraphrase them adequately, and use them to solve the given tasks.

### 4.1 Delineating key ideas to assess learners' acceptance of a prospective learning environment

As described above, the Model of Educational Reconstruction (Duit et al., 2012) prescribes the design of learning environments and the like as a process influenced by both a clarification and analysis of science content and research on teaching and learning. In this case, topic-specific challenges were identified from a teaching-learning perspective (research on alternative conceptions and common teaching approaches), and the scientific Brønsted-Lowry concept of acid-base reactions (Brønsted, 1923; Lowry, 1923) was analysed.

**Tab. 2**. The design principles and key ideas, as well as examples and tasks derived from the challenges when teaching about acid-base reactions.

| | | | |
|---|---|---|---|
| Challenge | Belief that all acid-base reactions are neutralisation reactions, or irreversible reactions (Jiménez-Liso et al., 2020; Schmidt, 1991). | Belief that being an acid/base is an inherent feature of a particle (Krebs, Hofer & Lembens, 2022). | Belief that acidity is connected to the pH value, or dependent on the number of hydrogen atoms of an acid (Özmen et al., 2009). |
| Design Principle | The use of the Electron Pushing Formalism highlights electron transfers in the course of acid-base reactions and their reversibility (Sieve & Bittorf, | Acids and bases are introduced as particles in acid-base reactions independent of the associated substances to highlight that acidity and basicity are not intrinsic characteristics of a particle but depend on the | Acidity and basicity are represented in the form of a particle models (beaker models, cf. Barke, 2015, and simulations, cf. Lancaster et al., 2021; Watson et al., 2020). |

| | | | |
|---|---|---|---|
| | 2016). The donor-acceptor concept (Barke & Harsch, 2016) is foregrounded in the reaction mechanism. | reaction partner. The decision whether a particle reacts as an acid or base is based on the reaction partner and solvent. | |
| Key Idea(s) | **KI 1:** Acid-base reactions are protolysis reactions (Brønsted, 1923; Lembens et al., 2019).<br>**KI 2:** The Electron Pushing Formalism (EPF) can be used to better comprehend the movement of electron pairs and bond formation in acid-base reactions (Sieve & Bittorf, 2016).<br>**KI 4:** Acid-base reactions can be reversible, especially if they take place in an aqueous solution and the equilibrium constant K and modified constants for aqueous solutions can be calculated (Brønsted, 1923; Jiménez-Liso et al., 2020). | **KI 3:** Particles which have a positively polarised hydrogen atom can react as Brønsted acids. Particles that have at least one free electron pair to bind the positively polarised hydrogen atom can react as Brønsted bases, if they attract the hydrogen more strongly than its bonding partner(s) (Brønsted, 1923; Authors, 2019). | **KI 5:** Strong and weak acids and bases exist, and their relative strength can be quantified in aqueous solutions (Brønsted, 1923; Lembens et al., 2019).<br>**KI 6:** Simulations and experiments such as the one by PhET Interactive Simulations (Lancaster et al., 2021; Watson et al., 2020) can highlight the connection between the particles (acids, bases) and substances (acidic and basic solutions). |
| Example / Visualisation | **KI 1 & KI 2:** The participant is presented with the reaction equation of the acid-base reaction between hydrogen chloride (HCl) and fluoride (F-); the reaction mechanism is highlighted using EPF.<br>**KI 4:** The visualisation of the reaction equation is expanded by adding EPF arrows to highlight its reversibility. | **KI 3:** The participant is again presented with the reaction equation of the acid-base reaction between hydrogen chloride (HCl) and fluoride (F-); the mechanism and the participating particles are explained in more detail. | **KI 5:** The participant is presented with animated beaker models / short simulations of the reactions of strong and weak acids and bases with water molecules. The dissociation constants for acids and bases in reaction with water ($pK_a$, $pK_b$) are introduced in connection with the $pK_a$ / $pK_b$ table and visualisations.<br>**KI 6:** The PhET simulation detailing acidic and basic solutions (Lancaster et al., 2021) is used to explain ionisation. With the help of an LED, the conductivity of acidic/basic solutions is explored. |
| Task(s) | **KI 1 & KI 2:** The learner is asked to solve a similar reaction equation using EPF and then highlighting similarities between the two, thus explaining why this reaction is also an acid-base reaction.<br>**KI 4:** The learner is asked to similarly solve a reaction equation and highlight the reaction's reversibility with EPF arrows. | **KI 3:** The learner is asked to first discuss which of the particles reacted as and acid and which as a base in the previous task. Then, they solve a more difficult reaction equation, again explaining which of the particles reacted as an acid and which as a base. | **KI 5:** The learner should decide which of three beaker models depicts a reaction between a weak base and water at equilibrium best and give reasons for their choice. Concerning $pK_a$ and $pK_b$, the learner decides whether a given acid or base reacts as a strong or weak acid or base with the use of the $pK_a$ or $pK_b$ value.<br>**KI 6:** The electrical conductivity of three solutions is compared so as to assume their degree of ionisation. |

Combining these two aspects against the backdrop of the target group, i.e. Austrian upper secondary chemistry students, led to the delineation of key ideas (cf. Tab. 2). These key ideas were expanded into an explanatory framework by making the formulations more learner-appropriate and adding adequate visualisations and learning tasks (cf. Tab. 2 and Appendix).

## 4.2 Interview Round 1: Acid-base reactions and the Electron Pushing Formalism

The first interview round intended to evaluate learners' reactions towards the use of the Electron Pushing Formalims (EPF) to explicate the reaction mechanism in the course of acid-base reactions (Krebs, Hofer & Lembens, 2022). This approach proved to be somewhat successful, as the participants in round one, with the exception of Lia, rated this explanation as plausible to most plausible. As shown in Figure 2, Lia's assessment of our explanation based on key idea 2 was rated as inadequate. Additionally, the learners could solve the tasks connected with key ideas 1, 2 and 3 in a satisfactory to successful manner, which is why we deemed our approach worthwhile and adequate, and moved on to the second round of evaluation. Additionally, differences regarding the learners' acceptance of the explanations were not noticeable with regard to their grade or prior schooling in the first round; e.g. Apple's results were similar to Jo's and Butterfly's, even though the former attended grade ten and the latter both were in grade twelve.

### 4.3 Interview Round 2: Adding explanations about reversibility and acid/base strength

The results of interview round one led to the inclusion of key ideas three to five in the second round of interviews. Due to the inclusion of new key ideas, the decision was made to combine key ideas 1 and 2 into one key idea, thus focussing on introducing acid-base reactions with EPF only. During the second round of interviews, our explanation of acid-base reactions using Electron Pushing Formalism was accepted well to moderately well by the participating students. Except for Monkey and Severus, all of them were able to solve the two tasks on the representation of acid-base reactions using Electron Pushing Formalism moderately successfully or even successfully (Fig. 2). The definition of acids and bases as particles was also well accepted by two learners and moderately well accepted by the remaining two. However, the paraphrase involving partial charges was problematic for two learners (Serena, Severus). Several learners also found it difficult to distinguish between positive polarization and positive charge whilst paraphrasing (e.g. Paul). The reversibility explanation of acid-base reactions was well accepted (Monkey, Severus) to moderately well accepted (Serena, Paul) in the second round of interviews and was applied moderately successfully to a task by all four learners. As these were the key ideas presented nearing the end of the interviews, the results might not only be due to issues with the wording and tasks but also due to cognitive load and interview length (around 90 minutes per interview). Consequently, there is a need for revision here in the wording of the explanatory offer and the more advanced tasks. Regarding key idea 5, Monkey's explanation of acid strength/base strength using a beaker model (K5a) was deemed incomprehensible and both Paul's paraphrase and his processing of the two tasks were categorized as poor. In comparison, the explanation for the $pK_a$ table (K5b) was accepted well to moderately well by the four participants in round two.

| | | Round 1 | | | | | | | Round 2 | | | | Round 3 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LIA ■ | MARIE ■ | BUTTERFLY ✸ | JO ✸ | APPLE ■ | JONAS ✸ | MAX ✸ | SERENA ■ | MONKEY ■ | SEVERUS ■ | PAUL ■ | AMSTERDAM ✸ | BERNHARD ✸ | PAT ✸ | LISA ✸ | SUN ✸ | IGNAZ ✸ | JAKE ✸ |
| KI 1 | Assessment | 0.5 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | | | | | | | | | | | |
| | Paraphrase | 1.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | | | | | | | | | | | |
| | Task 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | | | | | | | | | |
| | Task 2 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | | | | | | | | | | | |
| KI 2 | Assessment | 1.0 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Paraphrase | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 |
| | Task 1 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 |
| | Task 2 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 0.0 | 0.0 |
| KI 3 | Assessment | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Paraphrase | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.5 |
| | Task 1 | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Task 2 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.5 | 1.0 | 0.0 | 0.0 | 0.5 |
| | Mean | 0.4 | 0.1 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.4 | 0.4 | 0.6 | 0.3 | 0.2 | 0.1 | 0.1 | 0.6 | 0.1 | 0.0 | 0.2 |
| | successful | 0.0 | satisfactory | | 0.5 | inadequate | | 1.0 | | | | | | | | | | | |

**Fig. 2.** Excerpt of a visualisation of the evaluative qualitative text analysis. The answers are divided into the categories 'successful', 'satisfactory', and 'inadequate' in order to highlight their accordance with the explanatory framework. An added diamond symbol (◆) to the learners' names corresponds with their being in year one of upper secondary chemistry classes. The star (✸) refers to second-year chemistry learners.

Overall, the data from the first round of interviews suggest that it is worthwhile to continue with the approach taken, while the data from the second round of interviews indicate that a careful re-design of key ideas four and five is necessary so as to achieve a high level of learner acceptance (cf. Fig. 2 and Appendix).

### 4.4 Interview Round 3: Using written texts and adding a simulation and experiment

In response to the satisfactory to inadequate results from the second round, round three offered an explanatory framework that was not only re-designed with regard to wording but also with regard to setting. In order to reduce complexity and cognitive load, the explanatory framework as well as the paraphrase and tasks were offered to the students in a written format, i.e. as learning tasks (Prediger et al., 2014). Thus, the interviews consisted of the interviewer presenting each task to the student, the student reading the explanation and rating its plausibility followed by paraphrasing and task solving. Figure 2 illustrates the successful acceptance of the explanations and tasks in the course of round three.

Here, the overall acceptance of all the key ideas improved from round two to three. Especially the explanations focussing on acid/base strength and $pK_a$ and $pK_b$ values ameliorated. In addition, simulations and graphics such as the one in Figure 3 were added to offer better insight into acid-base reactions on the submicroscopic level.

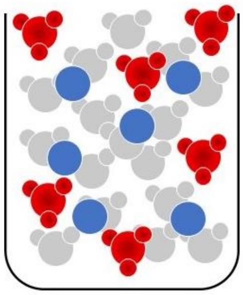

**Fig. 3.** Example of a visualisation, i.e. a 'beaker model' (Barke, 2015), used in the course of the third round of interviews to highlight the submicroscopic make-up of hydrochloric acid.

Turning now to the interrater reliability we computed for the coding of interview round three. Percentual overlap was 72.94 % for the two coders; however, the low percentual overlap calculated by MAXQDA is in contrast to the percentual overlap calculated when disregarding the exact coding segments. Altogether, a reasonable intercoder agreement was achieved when focussing on the codings of the segments only (86.25%), thus supporting the claim that the third round of interviews offered positive acceptance of the learning environment.

## 5 Discussion and Conclusions

This study has examined learner 'acceptance' of key ideas about acid-base reactions. Our initial objective was to evaluate whether the key ideas are understandable and plausible for learners and applicable to further tasks and problems so as to promote the learning of new concepts according to conceptual change theory (Posner et al., 1982). The key ideas were based on an adapted version of the Brønsted-Lowry model of acids and bases (Krebs, Hofer & Lembens, 2022; Krebs & Lembens, 2021), and prepared for Austrian upper secondary students. The method used for this evaluation, the method of probing acceptance (Jung, 1992), helps investigate whether the key ideas are understandable and plausible for learners and transferable to tasks and problems. The findings add to our understanding of how this group of learners understands acid-base reactions using the Electron Pushing Formalism (Ghosh & Berg, 2014; Shaffer, 2006; Sieve & Bittorf, 2016) as well as our explanations of acids and bases as particles. In order to do so, both real-world experiments and models (i.e. beaker models, simulations; e.g. Barke, 2015; Watson et al., 2020) were used to explain the reaction processes and submicroscopic 'composition' of acidic and basic solutions.

The findings of the first round suggest that the explanations for acid-base reactions and acids and bases, i.e. explanations focussing on modelling acid-base reactions with the Electron Pushing Formalism and introducing acids and bases as particles within the course of the reaction, are suitable to upper secondary chemistry students. As shown in Figure 1, however, Lia's assessment of our explanation based on key idea 2 was rated as inadequate. This might be due to the fact that hers was the first interview conducted in the study, and therefore constituted a practice round for the interviewer as well. Our definition of acids and bases in the course of the reaction was rated as mostly plausible by the learners, which led to a refinement of this explanation. In the second round of interviews, the four participants struggled with the key ideas one to three from round one as well as the added key ideas four and five. It appears, thus, that the explanations we provided for reversibility of acid-base reactions and acid-base strength cause confusion amongst the learners, but that key ideas one to three were also problematic for these students. In connection with the participants' backgrounds – all four attended a grammar school with emphasis on the natural sciences – the results from round two led to another re-design, especially with regard to K4 and K5.

The re-design and inclusion of learning tasks as opposed to teacher-centred explanations resulted in mostly successful acceptance of the explanatory framework in the third and final interview round. Here, the participants except for Lisa found the explanations overall plausible, could paraphrase them well and solved the tasks accurately. What stands out in interview round three is that Lisa's overall acceptance was poor at first, and then very successful. However, the successful results are in brackets because, during the interview, Lisa was overwhelmed and unfocussed because of personal reasons and decided to discontinue the interview at this point. In order to complete her data set, however, she decided to complete the tasks on her own and relayed her answers via email. This is also why parts of her answers are coded in brackets, highlighting that these answers were given in writing only. Altogether, the data collected in the course of this interview does not reflect the others' outcomes, but we deemed it unethical to exclude the data set. In other words, Lisa's poor results appeared to be mostly due to her state of mind during the course of the interview. Overall, the third re-design led to the design of a learning environment mostly accepted by the target group. Consequently, we argue that our teaching approach to acid-base chemistry shows merit and should be investigated more in the future.

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# Appendices

## Appendix 1: Complete overview of the interview results

| | | LIA ■ | MARIE ■ | BUTTERFLY ● | JO ● | APPLE ■ | JONAS ● | MAX ● | SERENA ■ | MONKEY ■ | SEVERUS ■ | PAUL ■ | AMSTERDAM ● | BERNHARD ● | PAT ● | LISA ● | SUN ● | IGNAZ ● | JAKE ● |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Round 1 | | | | | | | Round 2 | | | | Round 3 | | | | | | |
| **KI 1:** Acid-base reactions are protolysis reactions. | Assessment | ~ | ✓ | ✓ | ~ | ~ | ~ | ✓ | | | | | | | | | | | |
| | Paraphrase | × | ✓ | ✓ | ~ | ~ | ✓ | ~ | | | | | | | | | | | |
| | Task 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | |
| | Task 2 | ~ | ~ | ✓ | ~ | ✓ | ✓ | ✓ | | | | | | | | | | | |
| **KI 2:** The Electron Pushing Formalism (EPF) can be used to better comprehend the movement of electron pairs and bond formation in acid-base reactions, or protolysis reactions. | Assessment | × | ✓ | ~ | ~ | ✓ | ~ | ✓ | ~ | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ✓ |
| | Paraphrase | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ~ | ✓ | ~ | ~ | ✓ | ✓ | ✓ | ✓ | ~ | ✓ | ✓ | ~ |
| | Task 1 | ✓ | ✓ | ~ | ✓ | ✓ | ✓ | ✓ | ~ | ✓ | × | ~ | ✓ | ✓ | ✓ | ✓ | ~ | ✓ | ✓ |
| | Task 2 | ~ | ✓ | ~ | ✓ | ~ | ✓ | ✓ | ~ | × | ~ | ~ | ✓ | ~ | ✓ | × | ~ | ✓ | ✓ |
| **KI 3:** Particles with a positively polarised hydrogen atom can react as Bronsted acids. Particles with at least one free electron pair can react as Bronsted bases, if they attract the hydrogen more strongly than its bonding partner(s). | Assessment | ✓ | ~ | ~ | ~ | ✓ | ~ | ~ | ~ | ✓ | ~ | ✓ | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ✓ |
| | Paraphrase | ~ | ✓ | ✓ | ✓ | ✓ | ~ | ✓ | × | ~ | × | ~ | ~ | ✓ | ✓ | × | ✓ | ✓ | ~ |
| | Task 1 | ~ | ✓ | ✓ | ✓ | ~ | ✓ | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Task 2 | ✓ | ~ | ✓ | ~ | ~ | ✓ | ~ | ✓ | ~ | ~ | ~ | ✓ | ~ | ~ | × | ✓ | ✓ | ~ |
| **KI 4:** Acid-base reactions can be reversible, especially if they take place in an aqueous solution and the equilibrium constant K and modified constants for aqueous solutions can be calculated. | Assessment | | | | | | | | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ✓ | ~ | ~ | ✓ | ✓ |
| | Paraphrase | | | | | | | | ~ | × | ✓ | ✓ | ✓ | ~ | ✓ | ~ | ✓ | ✓ | ✓ |
| | Task | | | | | | | | ~ | ~ | ~ | ~ | ✓ | ✓ | ✓ | ✓ | ~ | ~ | ~ |
| **KI 5a:** Strong and weak acids and bases exist. | Assessment | | | | | | | | ✓ | × | ~ | ~ | ~ | ✓ | ✓ | (✓) | ~ | ~ | ✓ |
| | Paraphrase | | | | | | | | × | ~ | ✓ | × | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ | ~ |
| | Task 1 | | | | | | | | ✓ | ~ | ✓ | ✓ | ✓ | ✓ | ~ | (✓) | ✓ | ✓ | ✓ |
| | Task 2 | | | | | | | | ~ | ~ | ✓ | × | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ | ✓ |
| **KI 5b:** Their relative strength can be quantified in aqueous solutions. | Assessment | | | | | | | | ~ | ✓ | ✓ | ~ | ✓ | ✓ | ✓ | (~) | ✓ | ✓ | ✓ |
| | Paraphrase | | | | | | | | ✓ | ✓ | ✓ | × | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ | ✓ |
| | Task 1 | | | | | | | | ✓ | ~ | ✓ | × | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ | ✓ |
| | Task 2 | | | | | | | | ✓ | ✓ | ✓ | × | – | – | – | – | – | – | – |
| **KI 6:** Simulations and experiments can highlight the connection between the particles and substances. | Assessment | | | | | | | | | | | | ✓ | | ✓ | | ✓ | | ✓ |
| | Paraphrase | | | | | | | | | | | | ✓ | | ✓ | (✓) | ✓ | ✓ | ✓ |

| successful | satisfactory | inadequate |
|---|---|---|
| ✓ | ~ | × |

| | | Round 1 | | | | | | | Round 2 | | | | Round 3 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LIA ■ | MARIE ■ | BUTTERFLY ✸ | JO ✸ | APPLE ■ | JONAS ✸ | MAX ✸ | SERENA ■ | MONKEY ■ | SEVERUS ■ | PAUL ■ | AMSTERDAM ✸ | BERNHARD ✸ | PAT ✸ | LISA ✸ | SUN ✸ | IGNAZ ✸ | JAKE ✸ |
| **KI 1:** Acid-base reactions are protolysis reactions. | Assessment | 0.5 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | | | | | | | | | | | |
| | Paraphrase | 1.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | | | | | | | | | | | |
| | Task 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | | | | | | | | | |
| | Task 2 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | | | | | | | | | | | |
| **KI 2:** The Electron Pushing Formalism (EPF) can be used to better comprehend the movement of electron pairs and bond formation in acid-base reactions, or protolysis reactions. | Assessment | 1.0 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Paraphrase | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 |
| | Task 1 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 |
| | Task 2 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 0.0 | 0.0 |
| **KI 3:** Particles with a positively polarised hydrogen atom can react as Brønsted acids. Particles with at least one free electron pair can react as Brønsted bases, if they attract the hydrogen more strongly than its bonding partner(s). | Assessment | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Paraphrase | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 1.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.5 |
| | Task 1 | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Task 2 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.5 | 0.5 | 1.0 | 0.0 | 0.0 | 0.5 |
| **KI 4:** Acid-base reactions can be reversible, especially if they take place in an aqueous solution and the equilibrium constant K and modified constants for aqueous solutions can be calculated. | Assessment | | | | | | | | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.0 | 0.0 |
| | Paraphrase | | | | | | | | 0.5 | 1.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Task | | | | | | | | 0.5 | 0.5 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 |
| **KI 5a:** Strong and weak acids and bases exist. | Assessment | | | | | | | | 0.0 | 1.0 | 0.5 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.0 |
| | Paraphrase | | | | | | | | 1.0 | 0.5 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| | Task 1 | | | | | | | | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Task 2 | | | | | | | | 0.5 | 0.5 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **KI 5b:** Their relative strength can be quantified in aqueous solutions. | Assessment | | | | | | | | 0.5 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| | Paraphrase | | | | | | | | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Task 1 | | | | | | | | 0.0 | 0.5 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Task 2 | | | | | | | | 0.0 | 0.0 | 0.0 | 1.0 | -- | -- | -- | -- | -- | -- | -- |
| **KI 6:** Simulations and experiments can highlight the connection between the particles and substances. | Assessment | | | | | | | | | | | | 0.0 | | 0.0 | | 0.0 | | 0.0 |
| | Paraphrase | | | | | | | | | | | | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Mean | 0.4 | 0.1 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.3 | 0.4 | 0.3 | 0.5 | 0.1 | 0.1 | 0.1 | 0.3 | 0.1 | 0.1 | 0.1 |

successful 0.0 satisfactory 0.5 inadequate 1.0

**Appendix 2: Excerpt from the interview guide for interview round 3 (translation)**

**What is an acid-base reaction?**

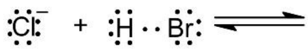
- *Read the text and watch the animation*[1]*.*
- *Please mark terms and passages in the text that you find unclear or incomprehensible.*

A hydrogen chloride molecule HCl and a fluoride ion $F^-$ react with each other. The hydrogen chloride molecule consists of two atoms, a chlorine atom and a hydrogen atom. They are connected to each other by a pair of electrons. The fluoride ion is a fluorine atom that has taken up an additional electron and is thus negatively charged.

With its negative charge, the fluoride ion $F^-$ attracts the positively polarised hydrogen atom H of the hydrogen chloride molecule stronger than the chlorine atom in the hydrogen chloride molecule does. The bond between the hydrogen atom H and the chlorine atom Cl is dissolved in such a way that both electrons from the bond remain with the chlorine atom. Thus it becomes the negatively charged chloride ion $Cl^-$. The fluoride ion $F^-$ binds the hydrogen particle H of the hydrogen chloride molecule HCl to itself and an uncharged hydrogen fluoride molecule HF is formed.

**Fig. 1.** Reaction equation showing the electron shift in the reaction between a hydrogen chloride molecule HCl and a fluoride ion $F^-$ by means of arrows.

- *Explain the reaction equation (Fig. 1) in your own words.*
- *Write the reaction equation for the reaction between a hydrogen bromide molecule HBr and a chloride ion Cl- and draw the electron shift using curved arrows.*



- *Explain with the help of the example why this reaction is called an acid-base reaction.*

[1] A link to an animation was provided to the participants at this point.