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Are you teaching “distillation” correctly in your chemistry classes? An educational reconstruction

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Abstract: Distillation is often taught at secondary level in chemistry classes. There are, however, several pitfalls in teaching and learning the topic. First, there is not enough accessible research on students' conceptions regarding distillation, which makes it difficult for teachers and teacher educators to teach accordingly in school or university. Second, the scientific explanation of distillation, especially the separation of liquid-liquid mixtures, is much more complex than represented in school books or other learning material. Third, teachers understandably rely on the representation in school books and other materials when teaching distillation, so that inappropriate concepts may be transferred to students. In this article, we follow the model of educational reconstruction and illustrate with reference to chemistry textbooks, school books, our own research results, and other studies on students' conceptions the three pitfalls named above. Thus, this article aims to provide support for teachers and teacher educators to structure lessons on distillation based on scientifically appropriate information and with regard to students' conceptions.

Keywords: chemistry education; distillation; misconceptions; scientific explanation; students' conceptions

1 Introduction

The topic ‘distillation’ is taught in chemistry classes at different levels. Objectives and competencies differ between the lower secondary level (ages 10–15) and the upper secondary level (ages 16–19). Usually, distillation is introduced in the context of substance properties and separation methods as an example of chemical separation processes in the beginning lessons of chemistry education (e.g., Department for Education, 2013; Lower Saxony Ministry of Education, 2007; Stratilová Urválková et al., 2019). Students at grades 5–6 (ages 10–11) should be able to use and explain the distillation process (e.g., Lower Saxony Ministry of Education, 2015). In doing so, they should acquire competencies for the basic concept “substance versus particles”. Looking at school books for grades 5–10 (lower secondary level) in the German context (e.g., Becker & Obendrauf, 2006; Haider et al., 2018), we can see that this is implemented by performing simple procedures for separating liquid-liquid (e.g., ethanol-water) or liquid-solid (e.g., water-salt) substance mixtures. Ethanol-water- and water-salt-mixtures are typical examples used at lower secondary level. The conceptual explanation refers to a specific substance property: the different boiling temperatures of the substances (e.g., Haider et al., 2018; Nichols, n.d.).

Our research findings and experiences (Koliander et al., 2023; Plotz et al., 2022) show that the topic of ‘distilling’ and the subject-specific explanations of it are at risk of being taught incorrectly, because of the

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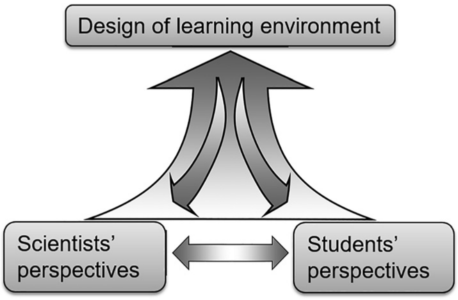

Figure 1: Model of educational reconstruction (adapted from Duit et al., 2012, p. 21; translated from Hüfner, 2020, p. 38).

complexity of the topic, the inadequate representation in school books and the insufficient research on students' conceptions in this field. We will have a deeper look at these aspects in this article.

According to the model of educational reconstruction (Figure 1), the scientists' perspectives and the students' conceptions are necessary for an appropriate structuring of the learning environment (Duit et al., 2012). Vice versa, teachers can only appropriately use learning environments, as presented in school books and other (digital) learning materials, if they have fully understood the subject complexity and can respond to the students' conceptions accordingly or are prepared for them. In the model of educational reconstruction, this is represented by the arrows pointing in downward directions (Figure 1) Thus, we analyzed existing learning environments and how they make use of the scientists' and students' perspectives. A next step would be to design and evaluate an intervention, i.e., a learning environment that allows for the appropriate use of these perspectives (arrows pointing in upward direction, Figure 1).

Using the model of educational reconstruction, in this article, we will first elaborate the scientists' perspectives as it can be found in chemistry textbooks. Secondly, we will present perspectives students have about distilling, i.e., their conceptions. In doing so, we will also draw on the results of our own case study (Koliander et al., 2023; Plotz et al., 2022). Thirdly, we will look at stumbling blocks in the educational reconstruction of distillation and present an analysis of German speaking school books comparing the results with the scientists' perspectives. Finally, implications for teaching the topic ‘distillation’ will be derived to support chemistry teachers at universities and at schools in teaching the topic. Throughout the article, we will use the example of an ethanol-water mixture.

2 Scientists' perspectives on distillation

Evaporation of a liquid occurs at any temperature, not only at the boiling temperature. Thus, a gaseous phase forms above the liquid even below the boiling temperature, e.g., water already evaporates at 1 °C. The vapour pressure of the liquid increases with increasing temperature. At the boiling temperature, the vapour pressure of the liquid equals the external pressure (e.g., Binnewies et al., 2016), and gas bubbles can now form within the liquid. We refer to the formation and rise of these bubbles as “boiling”. If a liquid mixture consists of several liquids that dissolve in one another, they all contribute to evaporation and to the total vapour pressure.

There are differences between conditions for boiling of a pure liquid and of a mixture of two liquids (Nichols, n.d.). Boiling of a pure liquid continues at the constant boiling temperature, which depends on external pressure and substance. Boiling of a mixture consisting of two liquids occurs when the sum of the two partial pressures is equal to the external pressure – the boiling temperature thus depends on the mixing ratio (see e.g., Binnewies et al., 2016, p. 207; Nichols, n.d.). Data can be determined experimentally and is recorded in boiling temperature diagrams. Figure 2 shows the boiling temperature diagram for the mixture ethanol-water at standard conditions. The composition of the mixture is entered on the *x*-axis (in mass percentage of ethanol = mass fraction), and the boiling temperature on the *y*-axis. For example, an ethanol-water mixture with 20 mass percentage ethanol boils at 86 °C, a mixture with 10 mass percentage ethanol at 90 °C (Hodgeman et al., 1963), whereas the standard boiling temperatures of the pure liquids are different (Figure 2)

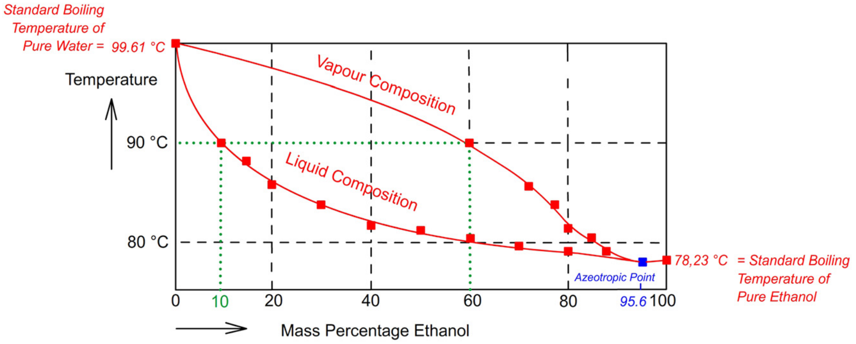

Figure 2: Boiling temperature diagram for the mixture ethanol-water at standard conditions (100 kPa) (data from Hodgeman et al., 1963, pp. 2582–2584).

The vapour formed can be condensed again by cooling. In the case of mixtures consisting of two liquids, it should be noted that the vapour formed during boiling contains both liquids and not exclusively the liquid with the lower-boiling temperature. The vapour usually contains the two liquids in a different ratio than the boiling liquid. The composition of the vapour for the respective mixture of the boiling liquid can also be found in Figure 2 (horizontal green dotted line). For example, a vapour with 60 mass percentage ethanol forms above an initial liquid mixture with 10 mass percentage ethanol. The more heat is supplied, the faster the liquids evaporate, but the temperature will not rise anymore when the mixture’s boiling temperature is reached. Furthermore, and to bring another difficulty in reconstructing and presenting the distillation of an ethanol-water-mixture, water and ethanol form an azeotrope at 95.6 % by mass ethanol. At the azeotropic point, the composition of the gas formed corresponds to the composition of the liquid, so that neither ethanol nor water can be further enriched by distillation. There will be no pure ethanol as a result of the distillation process, no matter how often we repeat the distillation process (Nichols, n.d.).

3 Learners’ conceptions about distillation

The realization that learners do not enter formal and informal learning opportunities without prior knowledge or conceptions is empirically supported (Krumphals et al., 2022). Vosniadou (2019, p. 1) describes this consensus as follows: “[r]esearchers agree on the presence of these intuitive understandings, but disagree when they try to describe their nature.” Regardless of the discussion about the inner structure of these understandings (Chi, 2008; di Sessa, 2013; Potvin & Cyr, 2017; Vosniadou, 2013), we can assume that teaching ideally changes these understandings and brings them closer to scientifically grounded concepts (Treagust & Duit, 2009).

Despite the presence of distillation in curricula and core syllabuses, only few studies address students’ conceptions about it (e.g., Güven & Uyulgan, 2021; Valanides, 2000). However, there are studies on related concepts that are a prerequisite for understanding the distillation process. Many learners struggle with the idea of air and other gases as part of matter (Savasci-Acikalin, 2021). A lot of studies deal with learners’ conceptions about phase transitions (liquid-gas, gas-liquid; Coştu et al., 2007; Savasci-Acikalin, 2021; Schmidt et al., 2009) or ideas related to the heating of a liquid, the boiling temperature and the heat of evaporation (Valanides, 2000). Barke et al. (2015) summarize some of these learners’ conceptions about the evaporation of water: on the level of phenomena, students may think that water divides into hydrogen and oxygen or water becomes air. At the particle level, students may think that the water particles evaporate into water vapour particles or the water particles divide into oxygen atoms and hydrogen atoms. Students performing a distillation can observe formation and condensation of vapour (as did students in our study, Koliander et al., 2023) and so they get a chance to realize vapour as part of matter.

Our own studies revealed some other fundamental inappropriate conceptions regarding the boiling temperature and the composition of the vapour during the distillation of ethanol-water mixtures (Koliander et al., 2023; Plotz et al., 2022), not only held by the students but also by the teacher. A first conception became apparent when the teacher told the students what to do as a task (Plotz et al., 2022). The teacher’s elaboration indicated that distillation is about complete separation: “we want a bowl with water here and one with alcohol there”. This expectation of a complete separation cannot be met with simple equipment and a batch distillation. If you start to distill a mixture with 10 mass percentage ethanol, even the first drop in the distillate will only reach 60 mass percentage ethanol (Figure 2).

We identified a second inappropriate conception in our studies (Plotz et al., 2022). The students heated the ethanol-water mixture and started to control the temperature with the thermometer in the liquid mixture (Figure 3). They used this experimental setup to fulfill the teacher’s task of separating water and ethanol.

The students were trying to separate the mixture of ethanol and water and struggled with the fact that the mixture did not start to boil at “about 78 °C”, the boiling temperature of pure ethanol (Koliander et al., 2023). The interactions of the students with each other and with the apparatus indicated that the students wanted to control the boiling temperature via the heat supply. The students’ conception is illustrated in Figure 4: in order to “keep the boiling temperature at 78 °C”, the heat supply must be stopped when the liquid has the “right” boiling temperature (cf. Valanides, 2000). This conception might be initiated by the teacher asking them “to control the temperature”.

From the scientific perspective, we know that it is not possible to control the boiling temperature via heat supply. At a given external pressure, a liquid will start boiling when it reaches its boiling temperature at this external pressure. Stopping the heat supply and lowering the temperature will stop boiling. This may contrast everyday experience with cooking, because we lower the heat supply when water or soup start to boil. However, the supply of heat does not regulate the boiling temperature, but only the speed of evaporation. Boiling and evaporation are two concepts often confused (Güven & Uyulgan, 2021).

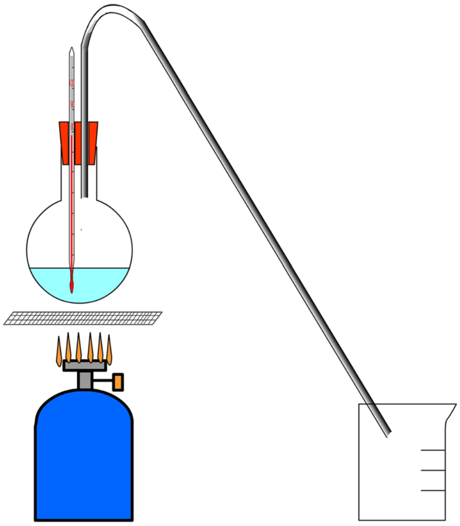

Figure 3: Students’ experimental setup (camping stove, round-bottomed flask, thermometer in the liquid, glass tube, beaker) (own design according to video data from Plotz et al., 2022).

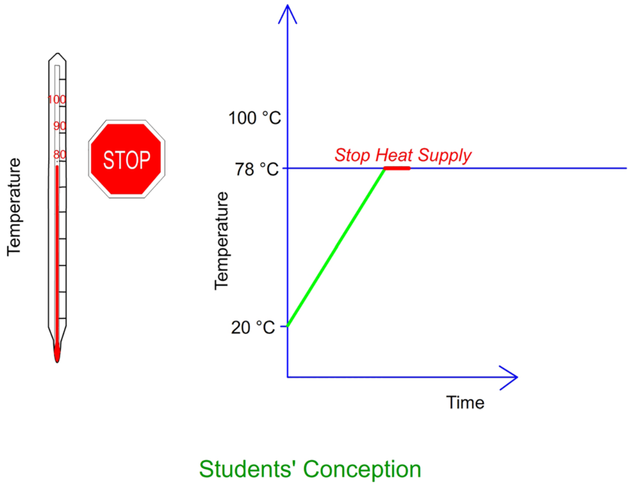

Figure 4: Inappropriate students’ conception: students expect to be able to control the boiling temperature of the ethanol-water-mixture by stopping heat supply (own design).

With this conception (Figure 4), it is not possible to fulfill the task: the liquid should boil to separate the mixture, and it will not boil at 78 °C. Therefore, the students discarded this conception. An analysis of a dialogue between teacher and students shows that they then apply a third conception (Plotz et al., 2022): ethanol boils first (starting at around 78 °C) and then, only at 100 °C, the water boils. The conclusion of the students was: They are allowed to heat up to 99 °C, until this temperature ethanol is boiling and evaporating, and only at 100 °C water will boil (and evaporate) (Figure 5). Valanides (2000) also showed that primary student teachers participating in his study hold this conception.

However, if you look at the chapter 2 “Scientists’ perspectives on distillation” again, a different view on boiling temperature becomes apparent. The ethanol-water mixture begins to boil at a boiling temperature depending on the mixing ratio. So a mixture with 10 mass percentage ethanol would boil at 90 °C (Figure 2). In the course of the distillation, the ethanol mass fraction of the mixture decreases and the boiling temperature slowly shifts towards higher temperatures (Figure 6, the straight lines are a simplification).

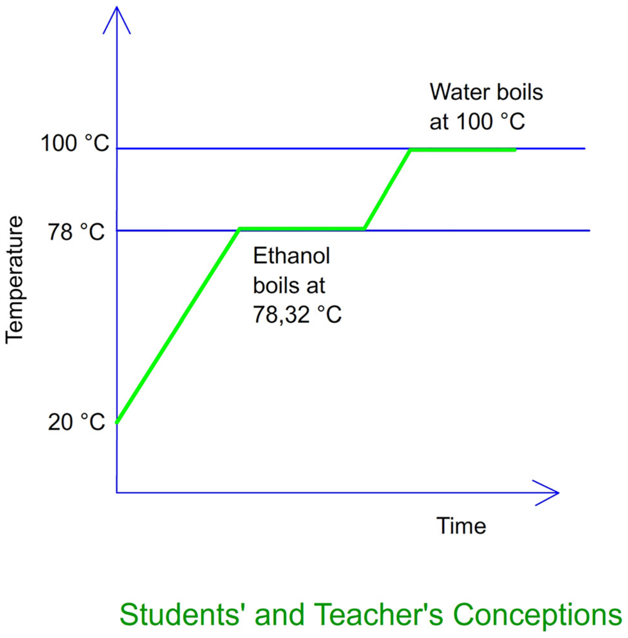

Figure 5: Inappropriate students’ and teacher’s conception concerning the development of the boiling temperature of ethanol-water-mixtures (own design).

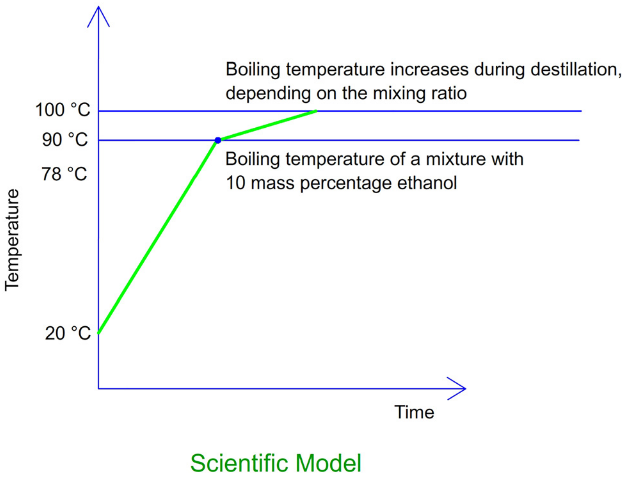

Figure 6: Scientifically appropriate model of the heat input and boiling temperature of ethanol-water mixtures (10 mass percentage ethanol) (own design).

Once students or teachers have understood the concept of the constant boiling temperature of a pure substance (an important insight in itself about the behavior of boiling liquids), they may apply it to liquid-liquid mixtures in a manner similar to Figure 5. However, they transfer a conception inappropriately and they will predict boiling temperatures of liquid mixtures in the wrong way. You need data sets or diagrams as shown in Figure 2 to predict boiling temperatures of liquid-liquid mixtures in a scientifically accepted way.

4 Stumbling blocks in the reconstruction of the topic ‘distillation’

In this section, four stumbling blocks from the educationally reconstructed learning environments for the topic ‘distillation’ in school books are presented and related to the scientific perspective. We chose those school books that are usually used in lower secondary in Austria.

Distillations in lower secondary school books are mostly shown as batch distillations. Students use a distilling flask in which the educt is heated, a glass tube or a condenser where the heated vapour is cooled and condenses to the liquid state, and a receiving flask where the concentrated liquid (the distillate) is collected. Important phenomena that students can observe and explore are that the liquid changes to vapour and the vapour changes back to a liquid. However, there are some pitfalls in presenting distillation of a liquid-liquid mixture when the aim is to separate these liquids.

(1) *A mixture of two liquids, which differ in their boiling temperatures, can be separated by distillation.* – Yes, but …

This and similar statements in school books of lower secondary may lead to the inappropriate conception that in an ethanol-water mixture at standard conditions, ethanol boils at its standard boiling temperature of 78,23 °C, allowing the vapour of ethanol to be collected purely, followed by a second boiling temperature of water (100 °C) (also cf. Valanides, 2000). This idea is not compatible with the scientific evidence. An ethanol-water mixture will not start boiling at 78,23 °C, but at some temperature between 78 °C and 100 °C, depending on the mixing ratio (Figure 2).

Here we cite some examples from school books that may lead to the misconception that ethanol boils at about 78 °C, followed by a second boiling temperature of water at 100 °C:

“When distilling, we use the different boiling temperatures of liquid substances” (Moritz, 2016, p. 44, translated).

“A mixture of alcohol and water is heated to about 80 °C. The escaping alcohol can be burned at the end of the glass tube. You see: due to the different boiling temperatures (water 100 °C, alcohol: 78 °C) both liquids can be separated” (Haider et al., 2018, p. 13, translated).

“When the red wine is heated, the alcohol boils first. Bubbles rise and the alcohol evaporates at 78 °C with some of the water” (Anders et al., 2005, p. 30, translated).

(2) *A liquid boils at a constant boiling temperature.* – Yes, but …

This statement is basically correct, but it only applies if the liquid is a pure substance. In a mixture, however, the composition and thus the boiling temperature changes in the course of the boiling process (Figure 2).

The boiling temperature depends on the composition of the ethanol-water mixture, as shown in Figure 2. This is not part of the school books of lower secondary schools, but the example itself is – from what we know – very commonly implemented at this level.

(3) *After distillation, the ethanol is in the distillate.* – Yes, but …

If the distillation starts with low concentration of ethanol (e.g., 10 mass percentage), even the first drops of distillate show only 60 mass percentage ethanol. In some school books, illustrations at the macroscopic and the particle level illustrate that only ethanol (macroscopic level) or a single type of particle (particle level) would pass from the mixture into the gaseous state and could be collected as a pure substance in the receiving flask (cf. Haider et al., 2018, p. 13, Figure 7; cf. Moritz, 2016, p. 44, Figure 8), ignoring differences between solid-liquid mixtures and liquid-liquid mixtures.

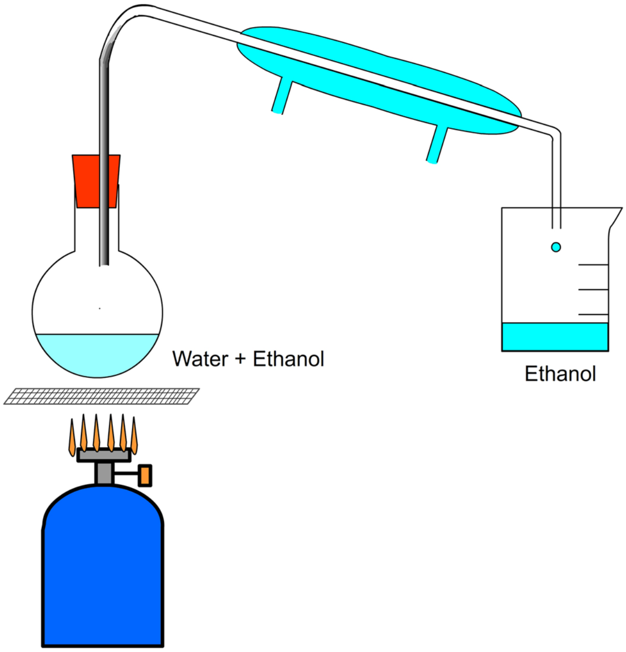

Figure 7: Misleading picture, illustrating pure ethanol would be gained (re-designed according to Haider et al., 2018, p. 13).

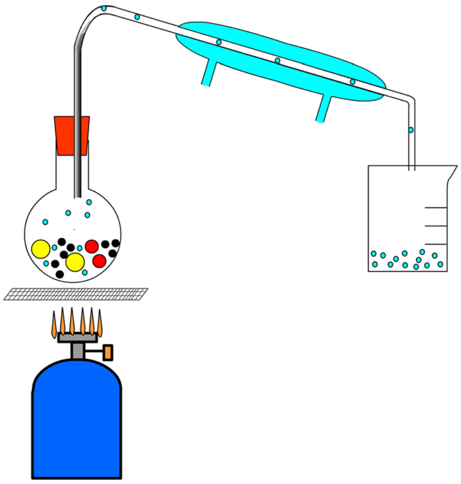

Figure 8: Misleading picture, illustrating only a single type of particles is found in the vapour and the distillate (re-designed according to Moritz, 2016, p. 44).

Another school book presents ethanol production and distillation. Ethanol is produced from a raisin-water-yeast mixture by fermentation; in a second step, the mixture is distilled. The text inappropriately reads, “[t]he boiling temperature of the first liquid distilled over is approximately 78 °C, so it is not H_2O” (Becker & Obendrauf, 2006, translated).

A fourth statement should be discussed, although we did not find it in the conversation of the students nor within the school books. However, the students in our case study (Plotz et al., 2022) believe that pure ethanol can be gained. They neither know about the idea of an azeotrope nor about water and ethanol evaporating from the beginning. From our experience, the explanation of the azeotrope is often used alone to explain the impossibility of pure ethanol in the vapour.

(4) *The reason why a distillation does not produce pure ethanol is the formation of an azeotrope.* – Yes, but …

From the beginning of the distillation process, water and ethanol evaporate. The ethanol is not evaporating as a pure substance and not even at the end of the distillation process you will gain pure ethanol. However, the formation of an azeotrope with 95.6 mass percentage of ethanol is the absolute limit you may reach by distilling ethanol-water-mixtures. This does not happen during a “normal” distillation. To reach this limit, you either need to repeat batch distillations several times, which results in ever-increasing concentrations of ethanol. Or you have to use rectification with a column that allows steam to condense and drops to evaporate in many steps: there is a flow from the condenser back within the fractionating column – this generates multiple steps of condensing and evaporating – which allows a higher enrichment, but never more than 95.6 mass percentage of ethanol, i.e., the azeotrope. Distilling the water-ethanol mixture, you will never have pure ethanol in the receiving flask.

5 Discussion and conclusions

In our own research (Koliander et al., 2023; Plotz et al., 2022), we found inappropriate students’ and teacher’s conceptions regarding the separation of mixtures by means of distillation. Other studies found that also student teachers have difficulties in understanding the topic (Güven & Uyulgan, 2021; Valanides, 2000). Teachers often rely on school books in planning their teaching, but we could demonstrate that the structuring in the German speaking school books of lower secondary is not helpful to avoid the formation and reinforcement of inappropriate conceptions on the subject of distillation. Teachers and teacher educators are at great risk in teaching distillation of liquid-liquid mixtures incorrectly, when relying on school books. The difficult scientific concepts are not made explicit enough to enable understanding. Also in research studies, the scientific perspective is hardly explained. They rather focus on explaining the inappropriate conceptions found, but not on why they are inappropriate in comparison to scientific models. We invite teachers and teacher educators to reflect on teaching distillation correctly. Developing a full educational reconstruction (Figure 1) is the goal of subsequent projects, although not trivial, that will support teachers here. Understanding the content of Figure 2 is a prerequisite to make the mental step represented in Figures 5 to 6. A consequence may be to move the subject of distillation of liquid-liquid mixtures to upper secondary school and to focus on solid-liquid separation methods during lower secondary to not mislead students in transferring conceptions from one procedure to the other. However, many teachers especially use the ethanol-water separation for students’ motivation at lower secondary level. If implemented, and we leave that open for discussion, teachers need to be fully aware of how to teach distillation correctly.

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References

Anders, A., Cieplik, D., & Tegen, H. (2005). *Projekt Chemie 4 [Project Chemistry 4]*. Dorner.

Barke, H., Harsch, G., Marohn, A., & Krees, S. (2015). *Chemiedidaktik kompakt: Lernprozesse in Theorie und Praxis [Chemistry education compact: learning processes in theory and practice]* (2nd ed.). Springer.

Becker, R., & Obendrauf, V. (2006). *Chemie heute [Chemistry today]*. Veritas.

Binnewies, M., Finze, M., Jäckel, M., Schmidt, P., Willner, H., & Rayner-Canham, G. (2016). *Allgemeine und anorganische Chemie [General and inorganic chemistry]*. Springer.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 61–82). Routledge.

Coştu, B., Ayas, A., Niaz, M., Ünal, S., & Çalik, M. (2007). Facilitating conceptual change in students’ understanding of boiling concept. *Journal of Science Education and Technology*, *16*(6), 524–536.

Department for Education. (2013). *Science programmes of study: Key stage 3*. National Curriculum in England. https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study (2023/05/16) di Sessa, A. A. (2013). A bird’s-eye view of the “pieces” vs. “coherence” controversy (from the “pieces” side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 31–48). Routledge/Taylor & Francis Group.

Duit, R., Gropengießer, H., Kattmann, U., Komorek, M., & Parchmann, I. (2012). The model of educational reconstruction – a framework for improving teaching and learning science. In D. Jorde, & J. Dillon (Eds.), *Science Education Research and Practice in Europe. Cultural Perspectives in Science Education* (Vol. 5, pp. 13–37). SensePublishers.

Güven, N. A., & Uyulgan, M. A. (2021). Linking the representation levels to a physical separation and purification method in chemistry: Understanding of distillation experiment. *Journal of Pedagogical Research*, *5*(3), 80–104.

Haider, R., Nest, W., & Petek, K. (2018). *Du und die Chemie [You and the chemistry]*. Ivo Haas.

Hodgman, C. D., Weast, R. C., Shankland, R. S., & Selby, S. M. (1963). *CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data* (44th ed.). The Chemical Rubber Publishing.

Hüfner, S. (2020). *Was heißt hier erneuerbar? Eine didaktische Rekonstruktion der Energiewende* [What does renewable mean here? An educational reconstruction of the energy transition] [Dissertation]. http://fox.leuphana.de/portal/files/16424063/Huefner_Was_heisst_hier_erneuerbar_Dissertation_2020.pdf

Koliander, B., Plotz, T., & Abels, S. (2023). Fachbezogene Interaktionen von Schüler*innen im Chemieunterricht während des Destillierens [Subject-Related interactions of students in chemistry classes during distillation]. *Zeitschrift für Didaktik der Naturwissenschaften 29*(1). https://doi.org/10.1007/s40573-022-00150-9.

Krumphals, I., Plotz, T., & Haagen-Schützenhöfer, C. (2022). Delphi-Studie zum Begriff Schülervorstellungen in der deutschsprachigen Physikdidaktik-Community [Delphi study on the term ‘student conceptions’ in the German-speaking physics education community]. *Zeitschrift für Didaktik der Naturwissenschaften*, *28*(1), 9.

Lower Saxony Ministry of Education. (2007). *Kerncurriculum für das Gymnasium, Schuljahrgänge 5–10, Naturwissenschaften [Core curriculum for the Gymnasium, grades 5–10, natural sciences]*. Unidruck.

Lower Saxony Ministry of Education. (2015). *Kerncurriculum für die Realschule, Schuljahrgänge 5–10, Naturwissenschaften [Core curriculum for the Realschule, grades 5–10, natural sciences]*. Unidruck.

Moritz, P. (2016). *Chemie auf Schritt und Tritt [Chemistry at every turn]*. E. Weber.

Nichols, L. (n.d.). *Organic chemistry lab techniques*. LibreTexts. https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Organic_Chemistry_Lab_Techniques_(Nichols)

Plotz, T., Koliander, B., & Abels, S. (2022). Adaption der Dokumentarischen Methode zur Bearbeitung von naturwissenschaftsdidaktischen Fragestellungen [Adaptation of the documentary method for the treatment of science education questions]. Martens, M., Asbrand, B., Menthe, J. *Dokumentarische Unterrichtsforschung in den Fachdidaktiken*. Theoretische Grundlagen und Forschungspraxis (pp. 155–175) Springer VS. https://doi.org/10.1007/978-3-658-32566-4_9.

Potvin, P., & Cyr, G. (2017). Toward a durable prevalence of scientific conceptions: Tracking the effects of two interfering misconceptions about buoyancy from preschoolers to science teachers. *Journal of Research in Science Teaching*, *54*(9), 1121–1142.

Savasci-Acikalin, F. (2021). How middle school students represent phase change and interpret textbook representations: A comparison of student and textbook representations. *Research in Science Education*, *51*(6), 1651–1685.

Schmidt, H.-J., Kaufmann, B., & Treagust, D. F. (2009). Students’ understanding of boiling points and intermolecular forces. *Chemistry Education: Research and Practice*, *10*(4), 265–272.

Stratilová Urválková, E., Teplá, M., & Janoušková, S. (2019). A comparative analysis of chemistry curriculum for lower secondary education in the Czech Republic, Poland, Slovenia and Estonia. *Scientia in educatione*, *10*(3), 50–71.

Treagust, D. F., & Duit, R. (2009). Multiple perspectives of conceptual change in science and the challenges ahead. *Journal of Science Math Education in Southeast Asia*, *32*(2), 89–104.

Valanides, N. (2000). Primary student teachers’ understanding of the process and effects of distillation. *Chemistry Education: Research and Practice in Europe*, *1*(3), 355–364.

Vosniadou, S. (2013). The framework theory approach. In S. Vosniadou. (Hrsg.), *International handbook of research on conceptual change* (pp. 11–30). Routledge/Taylor & Francis Group.

Vosniadou, S. (2019). The development of students’ understanding of science. *Frontiers in Education*, *4*, 32.