Educational research

# Using lecture demonstrations to promote the refinement of concepts: the case of teaching solvent miscibility

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**Abstract:** Novices often lack the descriptive knowledge of phenomena that is the basis for an expert's interpretation of scientific concepts. Such lack of knowledge may lead to poor conceptual understanding, and misinterpretation of these concepts. Lecture demonstrations can provide essential experiences that serve as a context for discussion of over-generalized or over-simplified concepts. The design of such demonstrations starts from surveying the limited knowledge base of the student, followed by exploration of the richness of relevant contexts of the expert, and identifying key instances that can serve as meaningful discussion topics. An example of the design of a demonstration set for teaching solvent miscibility and its relation to intermolecular interactions is given, followed by results of its application in two different presentation modes: confrontation (aims at generating a conflict with existing conceptions) and refinement (aims at promoting differentiation and contextualization of scientific concepts). The students' involvement in peer discussion, associated with these demonstrations, is evaluated by considering the distribution of students' predictions. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 186-196]

**Keywords**: lecture demonstrations, classroom discussion, confrontation demonstrations, refinement demonstrations, solvent miscibility, intermolecular interactions

> *"To approach demonstrations simply as chances to show off dramatic chemical changes or only to impress students with the 'magic' of chemistry is to fail to appreciate the opportunity they provide to teach scientific concepts and descriptive properties of chemical systems... In planning a lecture demonstration, I always begin by analyzing the reasons for presenting it."*
>
> Shakhashiri (1984)

## Introduction

The above citation, from demonstration master Bassam Z. Shakhashiri, highlights the importance of lecture demonstrations as pedagogical, rather than just motivational, opportunities. What kind of pedagogical reasoning can help transform a demonstration from being simply a form of entertainment into a learning tool? In this paper, we will discuss two factors that affect the pedagogical effectiveness of lecture demonstrations – their design focus and mode of presentation.

By tradition, the aim of lecture demonstrations was to show students a concrete example of an abstract description they encountered in class, and to help them make connections between the theory they were taught and reality (Tanis, 1984). These *verification* demonstrations focused on the scientific concepts that were taught in class. They were



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designed to illustrate these concepts visually, and to assure the students that the theory actually works in practice.

A more contemporary, research-based strategy is to focus the design of the demonstration on students' misconceptions – what they actually believe rather than what they have been taught. When targeting misconceptions, there are two different theoretical approaches that can be followed. The first one considers misconceptions as inappropriate pieces of knowledge, which contradict the current scientific concepts, and therefore should ultimately be replaced with proper concepts (Posner et al., 1982). According to this approach, these misconceptions should be actively confronted – the students should be exposed to discrepant events and anomalous data, which contradict their expectations. Only after the students are dissatisfied with their existing conception can the instructor present the proper scientific concept that explains the data. One way to introduce discrepant events in the classroom is by demonstrating an unexpected behavior of a chemical system (Bodner, 2001; Zimrot and Ashkenazi, 2007). Such *confrontation demonstrations* focus on the differences between students' misconceptions and the scientifically accepted concepts. They are designed to emphasize the shortcomings of these misconceptions, while providing a fruitful context for the application of the accepted concepts.

The second approach considers misconceptions as "*faulty extensions of productive prior knowledge*" (Smith et al., 1993). These so-called 'misconceptions' are regarded as fruitful elements of knowledge that serve both novices and experts. The difference is that novices apply these knowledge elements indiscriminately, even where they are inappropriate, while experts know in which contexts, and under which conditions, the application of a knowledge element will still prove fruitful. For example, the idea that motion implies a force is scientifically 'incorrect' and considered a 'misconception', but is fruitful in everyday situations which involve high friction, and is also a good model for the linear dependence of electrical current on voltage. Instruction should help students reflect on their present commitments, find new productive contexts for existing knowledge, and refine parts of their knowledge for specific scientific purposes.

*Refinement* involves the differentiation of contexts in which knowledge elements are applicable, and helping students use the appropriate scientific terminology to distinguish these contexts. For example, students often think that in a car-truck collision, the truck exerts more force on the car. Instead of confronting this misconception by stating that it contradicts Newton's 3$^{rd}$ law, the students' conception that the car 'reacts' more than the truck can be refined by making a distinction between 'reaction' as force (inappropriate context) and 'reaction' as acceleration (appropriate context). Since the mass of the car is smaller, it may 'react' (accelerate) more even if it experiences the same force. This results in a refined understanding of the situation, which is consistent both with the students' prior conception and Newton's 2$^{nd}$ and 3$^{rd}$ laws (Hammer, 2000).

In physics, many misconceptions may be traced back to students' previous experience with nature (Driver, 1983), and the refinement process utilizes these experiences as the building blocks for a more robust interpretation of physical situations. In high-school or tertiary level chemistry, however, students' direct experience with relevant chemical phenomena and concepts is quite limited (Taber, 2001). In many cases, this lack of personal experience, coupled with the small number of illustrative examples they encounter, leads to two possible outcomes:

1. Over-generalization: The coincidental association of two properties in a limited context is taken to be the general rule for all other cases. For example, when students are taught about titration curves, the primary illustration is the neutralization of HCl with NaOH, which has a neutral pH at the equivalence point. This may lead to the misconception that the equivalence point is always neutral (Schmidt, 1997). This is a good generalization for



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all strong acid-strong base titrations, but is an over-generalization when weak acids or bases are considered. The result is under-differentiation of concepts; students do not differentiate between seemingly similar but fundamentally different concepts like equivalence ($n_{acid} = n_{base}$) and neutrality ($[H^+] = [OH^-]$).

2. Over-simplification: A continuum of properties or interactions is replaced by two mutually exclusive categories, which correspond to the two extremes of the continuum. For example, when students are taught about precipitation reactions, the illustrations are of either freely soluble salts, or practically insoluble salts. This may lead to the misconception that solubility equilibrium only occurs with 'insoluble salts', and when 'soluble salts' reach their solubility limit it is because "*all the $H_2O$ molecules are holding onto the salt, and no more are freed up in order to dissolve the extra salt on the bottom*" (Brown, 2005). The result here is over-differentiation – students distinguish between two seemingly different but fundamentally similar concepts like soluble and insoluble salts.

We suggest that it is the students' lack of experience with chemical phenomena that hinders them from making meaningful distinctions between related concepts. Lecture demonstrations can be used to expand the relevant experience base of students, providing a context in which such distinctions may become meaningful.

*Refinement demonstrations* should focus on similarities between students' knowledge elements and the ways experts use the scientifically accepted concepts. They should be designed to test the validity of these knowledge elements in different contexts. This would support a process of refining limited 'misconceptions' into robust scientific concepts, by letting students experience the need for making relevant distinctions.

Regarding the mode of presentation, we argue that in order to be effective, lecture demonstrations need to provide an opportunity for classroom discussion. By tradition, lecture demonstrations (as their name implies) were demonstrated to an audience of passive observers. Even if the teacher supplemented the demonstration with relevant questions (Shakashiri, 1984), this would only engage a small number of participants, while most of the students would remain passive in the process. Research in physics education has shown that students learn difficult scientific concepts most effectively when actively engaged with the material they are studying, and that cooperative activities, such as classroom discussion, are an excellent way to engage students effectively (Hake 1998, 2002). Crouch and Mazur (2001) describe one such interactive teaching method – Peer Instruction – in which students are required to apply core concepts in the context of a conceptual question, and then to discuss those concepts with their fellow students. Students are given one or two minutes to formulate individual answers and report their answers to the instructor, using an electronic class response system. Students then discuss their answers with others sitting around them; the instructor urges students to try to convince each other of the correctness of their own answer by explaining the underlying reasoning. Following the discussion, students' answers are collected again. The researchers report that after discussion, the number of students who give the correct answer increases substantially, as long as the initial percentage of correct answers is between 35% and 70%, and that the improvement is largest when the initial percentage of correct answers is around 50%. When most of the students start out choosing the same answer (whether correct or incorrect), the discussion doesn't seem to be fruitful, and there is little benefit from it.

Peer Instruction can be easily coupled with lecture demonstrations, by using the demonstration as the context for discussion. The students are asked to predict the outcome of the demonstration before it is carried out, discuss their reasoning with their neighbors, and report their predictions. Crouch et al. (2004) tested students' ability to recollect the outcomes of lecture demonstrations and explain them a few weeks after witnessing them. They have shown that students that predicted and discussed the demonstrations in class scored



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significantly better than students that just observed the demonstrations; the students that were passive observers scored only marginally better than students that didn't witness the demonstration at all. Similar results were found for lecture demonstrations in chemistry (Zimrot and Ashkenazi, 2007).

The combination of research-based design focus with research-based presentation mode results in increased effectiveness of lecture demonstrations. Sokoloff and Thornton (1997) have developed a set of Interactive Lecture Demonstrations (ILD) for physics, where the term 'Interactive' refers to the prediction-discussion presentation mode. These demonstrations are designed to target specific concepts that students have difficulty understanding and applying, based on research of students' misconceptions. Fagen (2003) found that in a prediction-discussion presentation mode, misconception-focused ILDs were more effective in enhancing students' learning than traditional demonstrations adapted to the same mode of presentation.

This paper demonstrates a combination of research-based design focus with research-based presentation mode, applied to lecture demonstrations in chemistry. We first present the elaborate process of designing a refinement demonstration, which focuses on the similarities between the multifaceted nature of expert knowledge and the limited experience base of students, rather than on the differences between correct scientific concepts and 'misconceptions'. We then show how the same demonstration set can be interactively presented with different emphases, to produce different effects that match the aforementioned design approaches – verification, confrontation, or refinement. We conclude by examining the relative effectiveness of these presentation modes in promoting classroom discussion.

## Design

To illustrate the design process of a refinement demonstration, we chose a topic in which students' experience is limited – solvent miscibility and its relation to intermolecular interactions. This topic is typically associated with the rule of "*like dissolves like*", which is used by novices and experts alike, but not in a similar way. Novices use the rule literally, and apply it excessively, even when its use leads them to incorrect conclusions. Experts, on the other hand, have a wider set of experiences, which compels them to change the meaning they confer on the rule in different contexts. The simple textbook definition – "*substances with similar intermolecular attractive forces tend to be soluble in one another*" (Brown et al., 2005, p. 538) – cannot be used as a literal problem solving algorithm, because it contains much room for interpretation (what forces are considered 'similar'? How general is this 'tendency'?). We will show that this rule serves to guide the expert's meaning making process, but can not be used to replace it.

We start by examining students' prior experience in the field. Most general chemistry textbooks give two examples for liquid-liquid solubility: water and oil don't mix, and water and alcohol are miscible. These are also two common everyday phenomena – the separation of phases in Italian salad dressing, and the homogeneity of alcoholic beverages. The first demonstration repeats this common experience, by introducing a hydrocarbon layer (pentane) and an alcoholic layer (methanol) over water (Figure 1a, left cylinder); after a short vigorous shake, the methanol mixes completely with the water, and the pentane stays as a separate phase (Figure 1b).



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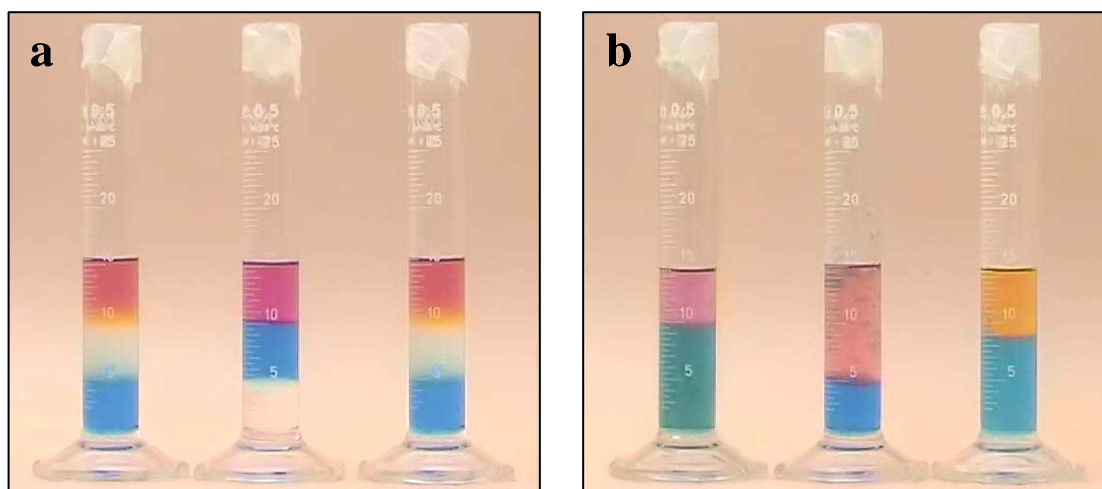
**Figure 1**. Relative miscibility demonstration




a) Setup of the demonstration: the violet phase is pentane (d = 0.63, μ = 0.00) colored with iodine; the blue phase is water (d = 1.00, μ = 1.85) with food coloring; and the colorless phase is (from left to right) methanol (d = 0.79, μ = 1.70); 1,1-dichloroethane (d = 1.17, μ = 2.06); and acetone (d = 0.78, μ = 2.88). Density values (d) are in g/mL, dipole moment values (μ) are in Debye (CRC, 2001a). b) The results after a short vigorous shake: the methanol transfers completely into the water phase; the 1,1-dichloroethane transfers completely into the organic phase; and the acetone partitions between the two phases, with a water:organic ratio of about 4:1. A video of the demonstration is available at http://www.fh.huji.ac.il/~guy/links/CERP2007b.html .

Next, we examine the experts' explanation for the phenomena, noting what knowledge elements influence their interpretation of concepts such as "similar" and "tend to". Being familiar with solvent miscibility charts (for example, http://www.phenomenex.com/phen/Doc/z366.pdf), an expert knows that all the organic solvents that are miscible with water are made of molecules that can form hydrogen bonds with water (contain an O or N atom) and have less than 4 carbon atoms. An expert also knows that hydrogen bonds have a partly covalent character (Gilli et al., 1994), which accounts for the fact they are specific and directional, for example in ice (Isaacs et al., 1999). ΔH and ΔS values for the solvation of hydrocarbons in water show that the hydrophobic effect is entropy driven (Silverstein, 1998). Taking all this data into account, the expert easily accepts the explanation that the immiscibility of a hydrophobic solvent with water is due to the inability of its molecules to form hydrogen bonds with water; the water is forced to form ice-like structures around the solvated molecules, and the formation of these rigid structures lowers the water's entropy. The expert summarizes all this knowledge in the rule "*like dissolves like*", with the implicit distinction that hydrogen bonds are "unlike" any other intermolecular interaction.

Novices, oblivious to all of the above data, are left to consider the only two examples they know, in which, coincidentally, the hydrogen-bonding methanol is also a polar molecule. This knowledge is coincidental, because even though all molecules that can form hydrogen bonds are polar, not all polar molecules can form hydrogen bonds. Based on this limited information, and their knowledge of bond polarities and molecular structure, it is reasonable to over-generalize the 'like dissolves like' rule and say that polar molecules dissolve in polar solvents, while non-polar molecules don't. The novice fails to differentiate between the concepts *hydrogen bond* and *dipole-dipole interaction*, because the distinction between them serves no useful purpose – they coincide in all known cases. This under-differentiation can also be found in many general chemistry textbooks, which consider the former concept merely as an extreme case of the latter.



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To help students differentiate between the two concepts, we chose a demonstration in which this coincidence is broken, i.e. in which a distinction between hydrogen bonds and dipole-dipole interactions becomes fruitful. We replaced the methanol with a highly polar molecule that cannot form hydrogen bonds: 1,1-dicholoroethane (Figure 1a, middle cylinder). Even though the molecular dipole moment of this molecule is larger than the dipole moments of water and methanol, experience shows that it does not dissolve in water, and is miscible with pentane (Figure 1b).

Another piece of data that is not disclosed in textbooks is the fact that alcohols and hydrocarbons are generally miscible[1]. A look at the solvent miscibility chart reveals that most organic solvents are inter-miscible, whether polar or non-polar. Therefore, there is no prohibition that excludes polar liquids from dissolving in non-polar solvents. The fact that the methanol transfers completely into the water phase, and does not transfer into the organic phase, is due to its higher affinity towards water (lower ΔG of solvation), than towards pentane. This relative affinity between liquids can be quantified as a polarity index (Snyder, 1978), which is an average measure of the interaction of a solvent with three test solutes (ethanol – medium dipole, proton donor; dioxane – weak dipole, proton acceptor; nitromethane – strong dipole, proton acceptor). Solvents with high affinities towards these polar, hydrogen bonding, test solutes have higher polarity values. The polarity index is strongly influenced by the hydrogen bonding capability of the solvent, and therefore does not always correlate with the molecular dipole moment. For example, methanol has a higher polarity index (6.6) than acetone (5.4), even though acetone has a larger molecular dipole moment (Figure 1, legend). The polarity index correlates well with other experimental measures that depend on the relative affinity of a solute to a solvent, e.g. the elution strength on silica or alumina in chromatography (http://home.planet.nl/~skok/techniques/hplc/eluotropic_series_extended.html), or the partition coefficient in water-octanol extraction (CRC, 2001b). Experts regard the polarity of a substance as a continuous measure of interaction, and evaluate it based on a set of considerations that they know to be relevant to the case at hand. In this context, 'like dissolves like' means that the closer the polarity of two substances, the stronger the interaction is between them.

Novices are unaware of all these considerations. Based on their limited experience with the water-oil and water-alcohol systems, they may over-differentiate and think of polarity in terms of a dichotomy; for them, substances are either polar or non-polar, and substances from different groups simply do not interact (because they are not 'like' one another). Since textbooks do not mention the polarity index, novices are also likely to interpret *substance polarity* only in terms of *molecular dipole moments*. Again, this over-differentiation into two distinct groups is common in many general chemistry textbooks.

The second demonstration has already introduced students to the idea that polar molecules can interact favorably with non-polar molecules. The London dispersion forces which hold non-polar molecules together originate in induced dipole-induced dipole interactions; therefore, polar molecules can interact with non-polar molecules by dipole-induced dipole interactions. But they may still think of solubility as a dichotomous property, seeing that all of the dichloroethane had transferred into the pentane. To allow students to see intermolecular interactions as a continuous measure, we replaced the dichloroethane with acetone (Figure 1a, right cylinder). Being only a proton acceptor, the acetone is less attracted to the water than the methanol was (both a proton donor and acceptor), and partitions between the two phases (Figure 1b). If the substances are ordered twice, once according to their

[1] Except for methanol, which becomes miscible with most hydrocarbons (C < 7) at slightly elevated temperatures (Kiser et al., 1961). In our case, methanol and pentane are miscible at temperatures above 15°C.



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relative affinity to water, and a second time according to their dipole moments, the need for a more refined definition of substance polarity becomes evident.

## Presentation and results

The two authors have used this set of demonstrations on six different occasions (Table 1). In all cases, the topic of intermolecular interactions was taught during two lecture sessions to first year general chemistry students at two large research universities. The first session was a background lecture, in which all the relevant theoretical concepts were taught (such as hydrogen bonds, dipole-dipole interactions and London dispersion forces). The second session was devoted to the interactive presentation of the demonstrations. For each demonstration, the system before shaking was shown, together with structural formulas for all substances and their dipole moment values. The students were asked to predict the state of the system after a short vigorous shake, and discuss their predictions among themselves. Following a short discussion (2-3 minutes), the students used an electronic classroom response system to vote for one of the following options: (1) The colorless layer will stay separated; (2) It will mix with the water layer; (3) It will mix with the pentane layer; (4) It will mix with both. After the votes were collected and displayed to the students, the result of the shaking was shown. The instructor followed up each demonstration with a discussion of the result, soliciting explanations from the class, and addressing the students' predictions. The discussion following the first demonstration (methanol, water and pentane) concerned the polarity of the methanol and its ability to form hydrogen bonds, whereas the pentane is non-polar and does not form hydrogen bonds. The second discussion (following the dichloroethane, water and pentane demonstration) focused on the differences between hydrogen bonding and dipole-dipole interactions, including a summary of the necessary conditions for hydrogen bonding to occur. The third demonstration (acetone, water and pentane) was followed by a discussion of relative polarity, in terms of relative strengths of interactions between solvent and solute.

**Table 1**. Distribution of students' predictions of the three demonstrations.*

| *Tested solvent* | *Prediction* | *Confrontation mode* | *Refinement mode* | |
|---|---|---|---|---|
| | | University A<br>Spring 2005<br>n = 277+241 | University A<br>Fall 2006<br>n = 387+322 | University B<br>Fall 2004/5<br>n = 140+127 |
| *methanol* | Stay | 1% | N/A | N/A |
| | **Mix with water** | **90%** | | |
| | Mix with pentane | 8% | | |
| | Mix with both | 1% | | |
| *1,1-dichloroethane* | Stay | 9% | 21% | 21% |
| | Mix with water | 77% | 39% | 47% |
| | **Mix with pentane** | **7%** | **25%** | **16%** |
| | Mix with both | 7% | 15% | 16% |
| *acetone* | Stay | 10% | 13% | 4% |
| | Mix with water | 36% | 23% | 16% |
| | Mix with pentane | 26% | 5% | 9% |
| | **Mix with both** | **28%** | **59%** | **71%** |

* Correct prediction is in bold. Each column combines data from two different sections of the same course. In university B, the two sections were taught in two different academic years.



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The procedure for staging each demonstration was always the same. However, we found out that the way the students interacted with them was dependent on the emphasis given to certain concepts in the background lesson. This resulted in two different presentation modes, the *confrontation* mode and the *refinement* mode, which correspond to the two theoretical approaches described in the introduction.

***Confrontation mode***

In the spring of 2005, one of us had taught the topic of intermolecular interactions in a traditional manner without emphasizing the differentiation between dipole-dipole interactions and hydrogen bonds, and without emphasizing interactions between different types of molecules. The instructor did emphasize the rule of 'like dissolves like', and showed a demonstration of how iodine transfers from a polar water phase into a non-polar dichloromethane phase. The fact that dichloromethane is considered non-polar, even though its molecules have a dipole moment comparable to water ($\mu$ = 1.60D), was never mentioned. Following this lesson, the instructor was introduced to the demonstrations, and decided to implement them on the next lesson. The results of the students' votes on each demo, in the following lecture, are given in Table 1.

The first demonstration can be classified as a *verification demonstration*. The students have been taught a rule, and were asked to apply it in a specific case. 90% of the students were able to apply the rule correctly.

The second demonstration can be classified as a *confrontation demonstration*. Almost none of the students expected the result of the demonstration – they applied the rule, according to the best of their understanding, and obtained an incorrect result. It is evident that there is one prime misconception that guides their thinking – 77% of the students chose the same incorrect answer

In the first and second demonstrations, the students' vote was almost unanimous. There was little room for discussion, as the students just technically followed a rigid rule. Only after the second demonstration caused them to be dissatisfied with the algorithmic application of the rule, could they start to explore the meaning of the concepts behind the rule.

The third demonstration can be classified as a *refinement demonstration*, because the students need to refine their use of concepts such as 'like' and 'polar', to fit what they saw in the second demonstration and predict the outcome of the third. The results show that students are indeed exploring different avenues, as no one prediction gets a majority of the votes.

***Refinement mode***

On four other occasions, the topic was taught by both authors at their respective universities, with a different emphasis. In light of the demonstrations, the emphasis in the background session was on the differentiation between dipole-dipole interactions and hydrogen bonds, and on possible interactions between different kinds of molecules. The rule of 'like dissolves like' was presented as a guideline, rather than a strict rule. Also, the notion that different intermolecular interactions can be at work simultaneously for a single substance was emphasized and described for various examples, such as detergent molecules and phospholipids membrane molecules.

In this presentation mode, the first demonstration was just explained and demonstrated, without student interaction. The rationale was that if the students don't know what to expect, they have to resort to use memorized rules, as they did in the previous mode. By showing an *expository* demonstration, the students know what to expect, and can start applying their reasoning to identify relevant distinctions that will help them transfer the results of the first demonstration to the other systems. In this case, we expected them to note that methanol is



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like water in two ways – it is both polar and can form hydrogen bonds. This point was raised in the discussion.

The effect of the demonstration mode can be seen in the shift of distribution of student responses for the second demonstration. The results show that students are exploring these different options rather than following a rule, as no prediction gets a majority of the votes. Therefore, in this mode of presentation the second demonstration serves as a *refinement* demonstration, where students try to see which aspects of 'like' are more relevant in the current context.

In the third demonstration, there is a majority of students that chooses the correct prediction, a considerable increase from the prior case in which the third demonstration followed a *confrontation mode* presentation. Nevertheless, it is unlike the almost unanimous vote of 90%, encountered in the verification demonstrations. The students don't have a rule they can go by; they need to weigh the different possibilities and be open to the novel concept of partitioning of a solute between two solvents, which emerges from the outcome of this demonstration. Therefore, we regard this as a second *refinement* demonstration.

## Conclusions

### *Design*

We have shown an effective method for designing refinement demonstrations, which focus on the similarities between the multifaceted nature of expert knowledge and the limited experience base of students. It starts with an exploration of the way experts apply the target concepts in specific contexts, trying to identify implicit distinctions and interactions between concepts that they use to guide their meaning making process. Then the knowledge base of the students is compared against these distinctions and interactions, and the following questions are asked: Are the students likely to under-differentiate and treat two different concepts as synonyms, because they are unaware of any cases in which the two concepts don't coincide? Are they likely to over-differentiate and treat a single continuum as mutually exclusive categories, because they haven't encountered any intermediate states? If the answer is positive, a demonstration is constructed to provide an experience that will help the students refine their understanding by differentiating seemingly similar but fundamentally different concepts, or integrating seemingly different but fundamentally similar concepts.

This design method is not unique for the topic of intermolecular interactions, and can be applied to any topic in which students tend to over-generalize or over-simplify because of their limited experience with chemical phenomena.

### *Presentation*

This study was not designed to compare the effect of different modes of presentation on students' understanding and retention of the relevant concepts. However, we trust the research literature documenting the benefits of peer interaction, and believe that fruitful classroom discussion will ultimately lead to these desired goals. The data we presented suggests that if the objective of lecture demonstrations is to encourage discussion among students, then verification and confrontation demonstrations provide little opportunity for that. A good discussion will only occur if students are divided in their opinions, with a substantial fraction supporting at least two different opinions (Crouch and Mazur, 2001). Table 1 shows that in both the verification and the confrontation demonstrations, most students agreed on the prediction (whether right or wrong). Refinement demonstrations are more likely to produce a fruitful discussion, because each one of the relevant concepts has merit in a specific context (rather than being just 'right' or 'wrong'), and therefore each one can be argued for or against. This is supported by the data, which shows a larger spread in predictions for the refinement



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demonstrations. While the confrontation mode of presentation can serve to stimulate surprise and interest on the part of students because of the unexpected result, it does not appear to be an effective way for them to learn about the scientific basis of the apparent anomaly. The refinement mode of presenting a demonstration is more effective at helping students extend their reasoning to new and ambiguous situations. Based on our personal experience in conducting these lessons, we feel that the class discussion which followed each demonstration was more productive in the refinement mode. The outcome of such discussions is a better understanding of the relation between different concepts, and the ability to apply the relevant concept in the appropriate context.

We also found the demonstrations had great impact on our approach to teaching the subject in the introductory lesson. Being ourselves explicitly aware of the different meanings the rule 'like dissolves like' acquires in different contexts, we changed the emphasis of the lesson. More attention was given to differentiate hydrogen bonds from dipole-dipole interactions, and to show similarities between permanent dipoles and induced dipoles. This emphasis during the introductory lesson wasn't enough to bring the desired learning outcome, as can be seen from the results of the students' predictions to the second demonstration in the refinement mode. However, it sets the theoretical background to which the results of the demonstrations can be tied back, and gives the students the required vocabulary to conduct meaningful and fruitful discussions.

Our presentation concentrated on a specific topic. Still, this approach is applicable in most other topics in chemistry in which students have limited experience. Following a similar design process, refinement demonstrations can be constructed for many other hard-to-teach concepts. We believe that it is only through discussions of actual phenomena that the students can construct a mature scientific understanding of such concepts. The validity or utility of scientific concepts cannot be decided by theoretical arguments alone. Their validity and utility are always associated with specific contexts, and their meaning is derived from their application in these contexts. It is imperative for a novice to be introduced to these contexts, and be provided with an opportunity to discuss the relevant concepts in context. The effective design of lecture demonstrations provides such a context. Their effective presentation provides the opportunity.

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