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Advancing Conceptual Understanding of Science

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Abstract. Categorisation of the entities of the world are important to help one make sense of the world and this process forms an integral part in the development of concepts. Inadequate clarifications and understanding of concepts in science may result in difficulties in the learning of science. In this paper, the authors discuss what the term, 'conceptual understanding', entails in the learning of science, using examples from the topics of 'Acids and Bases' and the 'Particulate Nature of Matter'. The authors also provide suggestions on how teachers can teach for conceptual understanding in the classroom as well as in the laboratory.

Keywords: conceptual understanding, acids and bases, volume of gases, practical work, modelling

1. Introduction

When a mother wants to teach her young daughter what a fish is, usually she will show the girl a live fish if she has access to an aquarium or a pond, or a whole fish from her refrigerator, in the supermarket or at a fishmonger's stall. Most likely, the mother will point out the fins, gills and scales of a fish, and inform the girl that fishes live in water. During formal lessons, the girl also will be taught that fishes are vertebrates and cold-blooded. These attributes that the girl learns will enable the girl to differentiate fish from other creatures that live in water, for example, crab, turtle, prawn, squid and jellyfish (even though there is 'fish' in the term 'jellyfish'). However, she may be bewildered and have difficulties identifying the stingray and mudskipper as fish because their appearances are so unlike a typical fish. She may also wonder why dolphins and whales are not considered as fishes when they look so much like a fish.

A family of four was travelling in a car. The father was driving and after a while he felt thirsty. He asked his wife to hand a bottle of water to him. When he was about to take a sip of water, his son, sitting in the back seat of the car, suddenly jumped up and grabbed his hand which was holding the water bottle. Due to surprise and the action of the boy grabbing his hand, the father swerved the car and it almost went into a ditch at the side of the road. He turned to the boy angrily and asked the boy why he grabbed his hand. The boy tearfully replied that he saw a sign in a restaurant earlier which read, "Don't drink and drive", so he wanted to stop his father from doing so. Although the boy understood the literal meaning of the sign, he has little awareness of its contextual meaning, giving rise to his unfortunate action in the car.

2. Understanding concepts

Herron (1996) defines a concept as a set of objects, symbols or events grouped together based on shared characteristics and referenced by a particular label. Novak (2002) defines concepts in a similar manner – concepts are "perceived regularities in events or objects, or records of events or objects designated by a label" (p. 550). In order to explain or clarify a concept, one has to be able to identify its critical attributes (must be present) and variable attributes (need not be present), and give examples and non-examples of it. The critical attributes of a fish are that it is a vertebrate which has gills, scales and fins. Variable attributes of a fish include its shape, size, appearance and habitat. Thus goldfish, tuna, salmon and stingray are all considered as examples of fish as they have the critical attributes of a fish; a mudskipper is also considered a fish based on the critical attributes even though its bodily adaptations allow it to live out of the water. On the other hand, whales do not have gills or scales, so they are considered as non-examples of fish. J. K. Gilbert (personal communication, June 30, 2016) suggests that learning the critical attributes of a concept reduces the cognitive load presented by individual facts (e.g., characteristics of the different types of fish) and highlights the relationship between instances of the concept in apparently different contexts (e.g., mudskipper, stingray, goldfish).

3. Acids and bases

When a chemistry teacher asks her students what an acid is, she will most likely get these answers from the students:

- It turns blue litmus red
- It has a pH of less than 7
- It has a sour taste
- It reacts with a reactive metal to produce a salt and hydrogen
- It reacts with a base to produce salt and water
- It reacts with a carbonate to produce salt, water and carbon dioxide

The answers given by the students describe the properties of an acid but do not explain what an acid is. In addition, what an acid is depends on what model one is using to explain what it is. Using the Arrhenius model, which is the model commonly used in Grades 7 to 10 chemistry in Singapore, an acid is a substance which produces hydrogen ions in aqueous solution. This is a critical attribute of an acid as the hydrogen ions produced are responsible for the properties and reactions of acids. For example, calculation of pH involves the hydrogen ion concentration of the acid, and it is the hydrogen ions that will react with the bases and metals, as well as the dyes in indicators to cause colour changes. There are many examples of acids, and these include hydrochloric acid, sulfuric acid, ethanoic acid and phosphoric acid. These acids have different variable attributes such as containing different elements and number of atoms, as well as having different strengths and proticities. On the other hand, using the Arrhenius model, methane, potassium chloride and sodium hydroxide are considered to be non-examples of acids because they do not have the critical attribute of producing hydrogen ions in solution. There is a need to compare and contrast examples and non-examples to bring out, more explicitly, the critical and variable attributes, and this should facilitate better understanding of a concept; when a student understands a concept, he/she will have little difficulty in differentiating between examples and non-examples of the concept (Herron, 1996). This is also supported by variation theory which proposes that teachers help students to focus on critical features of concepts and to contrast between examples and non-examples to make sense of the concepts that the students are learning (Bussey, Orgill, & Crippen, 2013).

A base in the Arrhenius model is one which produces hydroxide ions in solution. Thus, sodium carbonate is not considered as a base when the Arrhenius model (unless another concept, hydrolysis, is introduced) but the carbonate ion can be considered as a base if the Lowry-Bronsted model is applied; bases are proton acceptors and the carbonate ion can accept a proton to produce the hydrogencarbonate ion. Thus, the critical attribute of a concept depends on the model used, so using different models can result in different critical attributes, and hence, different examples and non-examples of the concept. A more 'powerful' model will usually subsume the examples and non-examples of a less 'powerful' model but, as shown in the example of sodium carbonate, it may not be true the other way round. Therefore, it is not surprising students find the topic of acids and bases difficult due to the confusion over the models that are used in teaching the topic (Carr, 1984; Schmidt, 1991) especially if the use of the different models is not "carefully sign-posted" (Carr, 1984, p. 99) by teachers or textbooks.

If the chemistry teacher asks her students what they need to do if they accidentally splashed some hydrochloric acid into their eyes, a possible response will be to wash the eyes with sodium hydroxide to 'neutralize' the acid (Schmidt, 1991); this response is logical given what the students learn about neutralization reaction in which an alkali reacts with an acid to give a salt and water. However, the students may not realise that sodium hydroxide is also corrosive and harmful (Nakhleh & Krajcik, 1994). In addition, the heat liberated in the neutralization reaction may cause further damage to the eye. Thus, the best solution is to wash the eye with copious amounts of water to dilute the acid and flush it from the eye. However, if acid was spilled on a road by an overturned tanker, what would be the best way to removing the acid? In this case, using water to remove the acid from the road may not be an effective solution as the acidic waste water may pollute the immediate surroundings. The acid should be neutralized but a soluble base cannot be used because it is almost impossible to determine how much of the base should be used; if too much soluble base is used, the excess base will now be the environmental problem, while if too little of it is used, the acid will not be removed. A relatively insoluble base such as oxides, hydroxides or carbonates of calcium can be used; after neutralizing the spilled acid, the excess insoluble base can be swept up and removed with relatively minimal impact on the environment. Thus, application of one's knowledge requires more than the understanding of a particular concept, it requires understanding of concepts in relation to other concepts which are linked to them and the context of the situation (Novak, 2002). This applies to the boy in the car who understands the literal meaning of "Don't drink and drive" but may not realise that the 'drink' refers to the imbibing of alcohol before or during driving which may impair one's driving ability rather the drinking of water when driving. It has to be mentioned, though, that the act of drinking water while driving may actually pose a hazard as the driver may not be concentrating fully on the road while drinking. Thus, there can be more than one level of conceptual understanding involved in a situation.

The student is responsible for his/her learning (Novak, 1988) as he/she has to decide that he/she wants to learn and make sense of the learning task (Ausubel, 1968). Teachers are often questioned, "so what" or "for what", by students when they are required to learn concepts that seem to be meaningless and/or have no apparent relevance to their everyday lives. Gee (2007) puts it succinctly:

One good way to make people look stupid is to ask them to learn and think in terms of words and abstractions that they cannot connect in any useful way to images or situations in their embodied experiences in the world. Unfortunately, we regularly do this in schools. (p. 72)

Students need to know the reasons for learning what they are taught and how it is useful to them, as well as to be given opportunities to practice or use the knowledge that they are learning in meaningful ways. If the students find what is taught by the teacher meaningless, "useless" or "stupid", they may not want to learn it at all or find it difficult to learn; they need "meaningful, goal-driven contexts" (Gee, 2007, p. 65).

Learning what acids are and the properties and reactions of acids in isolation may seem to be pointless to students. However, learning these in the context of a competition in which they have to build a gas-propelled rocket which can fly the furthest distance may make the learning of the reactions of acid (and kinematics) more interesting. Students will need to learn which reactions will produce gases and how reactions can be speeded up. Stoichiometry can be involved as well as the students might want to calculate the masses of reagents required and the volume of gas liberated, and they have a reason for doing; this is a contrast to the contextless problems that they are given to solve in class. It may also be interesting to get students to brush their teeth and then give them orange, lemon or lime juice to drink; this is something which the students may have encountered when they drink orange juice at breakfast. Most of them will find that the juice tastes terrible and they can be tasked to find out why. They can also be instructed to remove certain stains using material commonly found at home, for example, lemon juice, vinegar and baking soda, and find out why these work well as household cleaners. In these ways, students can experience science learning in a way which is meaningful and situated, and they can use the knowledge to solve problems (Gee, 2007) instead of merely studying to pass examinations.

4. Volume of gases

Students in Singapore learn the properties of solids, liquids and gas at the primary level (Ministry of Education, Singapore, 2013), for example, they learn that gases have no fixed volume and no fixed shape. In lower secondary (age 13-14), they learn that the behaviour of the particles in a gas is responsible for the properties of the gas (Ministry of Education, Singapore, 2020) and in upper secondary (age 15-17), they are taught that molar quantities of gases have a volume of 24 dm3 at room temperature and pressure in their chemistry lessons (Ministry of Education, Singapore, & University of Cambridge Local Examination Syndicate, 2021). In the authors' years of teaching in school and in a teacher education institution, nobody has ever pointed out the apparent contradiction between the fact that 'a (mole of) gas has no fixed volume' and that 'a mole of gas has a volume of 24 dm3 at room temperature and pressure', leading the authors to believe that the students and pre-service teachers merely accepted them as facts that they have to learn, with no further need to probe what they mean or the contexts in which they apply. According to the particulate nature of matter, an ideal gas will tend to spread outwards if not confined by a container, or occupy the volume of its container if confined in the container, as it consists of "particles that do not exert long-range forces and that move in straight lines until they collide with the container walls or other particles" (Robertson & Shaffer, 2013, p. 303). However, if a gas is liberated in a reaction involving known amounts of reactants and made to flow into a syringe with the plunger depressed under the conditions of room temperature and pressure, the gas will push against the plunger and move it outwards until the pressure of the gas in the syringe is equal to the atmospheric pressure acting on the plunger. When the plunger stops moving, the gas liberated will occupy a volume indicated on the marking of the syringe. This volume will be less than the calculated volume of the gas liberated as the gas has to work against the friction between the plunger and the walls of the syringe. Most of the trainee teachers that the authors taught only realized the significance of the different contexts involved when they were asked to design an experiment to determine the volume of a gas at room temperature and pressure; otherwise, the conditions of room temperature and pressure had little meaning to them.

Interestingly, Robertson & Shaffer (2013) reported that the undergraduates and K-12 teachers in their study also had difficulties with volume of a gas and the behaviour of the particles in the gas, this time in the context of being confined in rigid containers under the conditions of different temperatures. They found that many participants thought that the volume of a gas decreases with decreasing temperature such that it had a volume different from that of its container because the particles in the gas had more limited movement as they slowed down and hence occupied a smaller volume by gathering in the centre of the container. Thus, it seems that teachers and students need to clarify the behaviour of the particles in gas, and hence the volume of the gas, at varying temperatures in different contexts, for example, in an open environment, constrained in a syringe or in a rigid container.

5. Understanding practical work

Generally, students spend a significant portion of the science curriculum time doing practical work where they handle equipment and material to perform experiments ranging from those which are supposed to help them to understand the science concepts taught in the classroom to investigations which address real life problems (Hofstein, Kipnis, & Abrahams, 2013). In addition to helping students to learn science, practical work has the potential to facilitate the acquisition of process skills and scientific habits of mind, as well as the development of positive attitudes towards science (Hodson, 2005; Hofstein, 2004; Hofstein, Kipnis, & Abrahams, 2013; Nakhleh, Polles, & Malina, 2002). However much of the practical work done in school seems to be recipe-driven and undemanding, emphasising mainly on the manipulation of equipment and getting the 'right' answer (Crawford, 2000; Hoftstein et al., 2013; McNally, 2006). Students tend to have little conceptual understanding of what they do during practical work and may not be able to engage meaningfully in it (Hart, Mulhall, Berry, Loughran, & Gunstone, 2000; Sere, 2002); they simply follow the instructions given to them, assemble the required apparatus without knowing why the apparatus and procedures are necessary for the experiment, and make the required observations without understanding what the observations mean (Gunstone, 1991; Sere, 2002; Tasker & Freyberg, 1985). Doing experiments incorrectly may result in safety hazards and/or wastage of reagents, so students normally learn or carry out the 'correct' procedures without being required to think of alternative procedures or why a procedure is 'correct' or more suitable for a particular purpose than alternative procedures (Tan & Chee, 2014). For example, to separate an insoluble solid from a liquid, filtration is normally used but distillation can also be used; however distillation is more time consuming, the experimental setup requires more effort and apparatus than filtration, and there may be safety issues arising from the heating in the distillation process. Unfortunately, students are seldom asked to ponder on the procedures that they carry out in the laboratory.

In a study (Tan, 2020) by the first-named author to determine how intermediaries can facilitate teachers' use of research to address student difficulties (Ratcliffe et al., 2004), teachers from a high school (Grades 11 and 12) whom the first-named author worked with chose to address the issue of student difficulty in planning experiments. To determine if student difficulty in planning experiment was widespread, teachers from five schools and a curriculum development branch were surveyed. All 28 participating teachers agreed that students had difficulties planning experiments. One of the main reasons for the difficulties proposed by the teachers was that students did not have enough knowledge of experimental procedures, reagents and apparatus. About half of the teachers believed that this could be due to the lack of opportunities to do a wide variety of experiments apart from those required for the national assessment, a lack of understanding of procedures, or following procedures without thinking about them. The teachers' comments on the students' difficulty in planning experiments agree with the findings of studies on practical work (Hart et al., 2000; Gunstone, 1991; Sere, 2002; Tasker & Freyberg, 1985) discussed in the previous paragraph.

Woolnough and Allsop (1985) have suggested that practical work should focus separately on allowing students to experience and understanding the phenomena and reactions involved in the experiments that they do, developing the skills and techniques to carry out experimental procedures effectively, and conducting investigations to experience how a scientist works. The separate objectives are intended to avoid overloading the working memory of students during practical work (Johnstone & Wham, 1982) as little learning can occur if students are concentrating mainly on carrying out the procedures given, and collecting and recording data within the time constraints of the laboratory session. Tan, Goh, Chia and Treagust (2002) developed an instructional package on qualitative analysis based on the principles proposed by Woolnough and Allsop (1985). The first focus of the instructional package was on helping students to experience and understand the reactions underlying the tests for cations, anions and gases; they had to relate their observations to what they had already learned in the topic of ‘Acids, Bases and Salts’. Next the ‘exercises’ were introduced where the students would practice the required procedures step-by-step until they were proficient in these procedures; students needed to master these skills and perform them ‘automatically’ to lower the demands on their working memories so that they could attend to other aspects of the experiment (Woolnough & Allsop, 1985). Finally, students would apply their knowledge and skills to design and implement investigations to identify the unknown ions present in given samples. It was found that the students who were taught using the instructional package had a better understanding of qualitative analysis than the other students who were surveyed in the study.

6. Beyond practical work: Advancing conceptual understanding through modelling

Practical work allows students to experience the phenomena associated with the concepts learned, hence convincing students of the scientific ideas and addressing any alternative conceptions they might hold. Thus, experiments are useful for producing evidences to demonstrate macroscopic relationships (e.g., gases occupying the same volume despite a lowering of temperature will exert a lower pressure in a fixed container), convincing students to reconsider any misconceptions they might possess. However, practical work might not directly address developing conceptualisation related to causal explanations. For example, practical work cannot demonstrate the causal mechanism underlying the relationship amongst temperature, volume and pressure of a gas. In high school chemistry, such causal explanations often draw upon concepts visualised at the microscopic or sub-microscopic levels (Johnstone, 1982) and involve the use of scientific theories and models to construct the explanations. To advance conceptual understanding developed to include causal explanations, we propose the use of a representation-construction pedagogy, Image-to-Writing (I2W) (Yeo, Lim, Tan, & Ong, 2021), to complement experimentation in the learning of chemistry and thus extend learning towards the construction of causal explanations.

The I2W approach comprises three main stages: (1) exploring a phenomenon, (2) creating and transformation of images and (3) translation of images to writing. Through these stages, students are engaged in constructing and working with visual representations in their conceptualisation of a scientific idea before writing them down in formal scientific language. The I2W approach is modelled after the visualisation practices of scientists as they go about theory buildings (Gooding, 2004; Nersesian, 1992). Yeo and Gilbert (2014; 2022) also found that high school students often make use images with other modes of representations as they go about producing causal explanations in physics, including those related to the particulate theory of gases. The design of I2W learning process is anchored by a key question about a physical phenomenon that provides purpose for the visualisation activity and can be used in conjunction with practical work. Students are often engaged in making observations of phenomena and hands-on experiments. They create a series of images to represent their observations and meanings made about the phenomena and to use these images to help them think and reason about the relationships between related concepts. Writing in formal scientific language, which is often the expected form of output in school science learning, comes at the end of the process when students have developed a narrative account of how or why a phenomenon comes about.

To illustrate how I2W can be applied to advancing conceptual understanding of chemistry, let us consider its use in addressing students' conception that gases would occupy a smaller volume when temperature is decreased. The activity could start with demonstration (using video or simulation) of the macroscopic phenomenon whereby volume, temperature and pressure of the gas in a thick-walled container can be measured as temperature of the gas is decreased. With the available data and the premises from the kinetic theory of gases, students could be engaged in constructing a series of images to illustrate the behavior of the particles of gas as temperature decreases. They can also produce animations of the constructed images to develop a narration (causal explanation) so as to account for the observed macroscopic properties of the gas (Berg, Orraryd, Pettersson, & Hulten, 2019). These visuals and narration produced by the students can allow the teacher and their peers to identify any misconceptions students might have with the kinetic theory of gases as well as its application. This is because, compared to words, visuals are more effective in making clear the meaning of processes, topography and temporality, which are the key ideas underlying the kinetic theory of gas.

7. Conclusion

Conceptual understanding entails knowing the critical and variable attributes of the concept, and the ability to apply the critical and variable attributes to decide examples and non-examples of the concept. If abstract concepts are involved, students need opportunities to develop visual representations of these concepts to make sense of them. The contexts in which concepts are applied are also important and students need to have opportunities to apply what they have learnt in various situations to realise the affordances and limitations of concepts, as well as the value of learning these concepts. In a similar vein, students also need to be exposed to situations where there is no one correct answer but several alternative solutions and the need to evaluate these alternatives to choose the best among them for the particular situation. Practical work is important in science for students to be exposed to and understand these phenomena, as well as develop the thinking, skills and techniques to conduct investigations. However, the activities that students do need to be carefully thought out to prevent cognitive overloading, leading to mere manipulation of equipment and minimal learning.

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