PROMOTING CRITICAL AND CREATIVE THINKING IN CHEMISTRY THROUGH TEACHER QUESTIONING

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One objective of chemistry teaching is to develop higher level thinking in students and help them become critical thinkers and independent, creative problem solvers. To achieve this, we need to stimulate students' thinking by requiring them to go beyond the factual recall or procedural levels, and to engage in more complex thinking skills which involve the application of knowledge. One way of doing this is through the art of skilful teacher questioning as the kinds of questions that teachers ask influence the type and level of thinking operations that students engage in. Furthermore, questioning is very much a part of the scientific inquiry process. Teachers can sharpen their questioning skills by becoming familiar with different categories of questions, and then applying this knowledge during lesson planning and in post-lesson analysis. This paper describes different categories of teacher questions, suggests tips for effective questioning, and provides examples to illustrate these ideas.

CATEGORIES OF TEACHERS' QUESTIONS

Much of the literature on teacher questioning has been in general, non content-specific domains or the teaching of science in general. In this paper, however, I will attempt to show how this may be adapted to the teaching of chemistry at the secondary level by giving examples that are relevant to this subject. There are several systems for classifying questions. One commonly used category is Bloom's (1956) taxonomy ranging through knowledge, comprehension, application, analysis, synthesis, and evaluation. As this should be familiar to all teachers, it will not be elaborated here.

Blosser (1995) referred to a category system for questions used in science lessons. This includes managerial, rhetorical, closed and open questions. *Managerial* questions are used to keep classroom operations moving (e.g., "Does everyone have the necessary apparatus for today's experiment?"). *Rhetorical* questions emphasize a point or reinforce an idea (e.g., "Copper sulphate is blue in colour, right?"). *Closed* questions have a limited number of acceptable responses or "right answers", and can be further divided into cognitive memory or convergent types. An example of the *cognitive memory* type which is of a lower order and focuses on factual recall would be "What is the chemical formula for ethanol?" *Convergent* questions help to focus thinking on a common set of ideas. Although they lead to a limited number of acceptable answers, such questions need not always be pitched at lower levels of thinking. Examples include those which require students to compare and contrast or give similarities and differences (e.g., "Based on your observations in today's laboratory activity, what are the differences between an acid and an alkali?"), apply previously learned information to a new problem (e.g., "Why do people throw salt on ice in winter in the temperate countries?"), or to make a judgment (e.g., "Which metal, zinc or copper, would you use to coat iron to prevent it from rusting?").

Open questions, on the other hand, anticipate a wide range of reasonable responses rather than one or two "right answers", and often have the potential to stimulate higher level thinking. They serve to promote discussion and allow freedom to hypothesize, speculate, invent possibilities, interpret, and share ideas. They require students to give and justify their opinions, infer or identify implications, and to make judgments based on their own values and standards. They may be further subdivided into divergent or evaluative thinking questions. An example of a *divergent thinking* question is "What do you think life on Earth might be like if the proportion of gases in the atmosphere were different?", while an *evaluative thinking* question might be "What is the best way to depict the results of this experiment -- by using just words, a drawing, table, line graph, bar chart, or ....?".

Elstgeest's (1985) guide to questioning, although originally devised for primary science, is also applicable to chemistry teaching. His criteria for good questions are those that are "productive" because they stimulate *productive* physical or mental activity and reasoning in students, and take them forward in their thinking. They provide scaffolding for students to construct their own understanding. On the other hand, "wrong" questions are those which are unproductive in encouraging learning; these are verbal questions which require wordy answers, often neatly dressed in bookish phrases. Productive questions include attention-focusing, measuring and counting, comparison, action, problem posing, and reasoning questions. This sequence of productive questions may be seen as proceeding systematically from concrete to abstract (Anderson, 1999).

Attention-focusing questions guide the initial exploration of new materials and direct students' attention to significant details that they might overlook. An example is "What do you notice about the physical properties of this substance?". *Measuring* and counting questions nudge students to move from purely qualitative to quantitative ideas, and to strive for greater precision in their observations and measures. For instance, in the design of an experiment in a lesson on chemical kinetics, the teacher could ask "How would you measure the amount of gas evolved in this reaction?". *Comparison* questions bring about sharper observation and help students "bring order into chaos and unity in variety" (p. 38) as in the classification of substances (e.g., "What patterns do you notice in the atomic structure and properties of the elements of the periodic table?"). *Action* questions ask "what happens if?" and encourage simple hands-on experimentation and the investigation of relationships. A motivational aspect of such questions is the challenge to predict the outcome. An example would be "If this paper chromatography experiment were repeated at a higher temperature, would the spots separate more quickly?". Finally, *problem-posing* questions of the "can you find a way to ....?" type set up a real problem solving situation that invites students to predict, hypothesize, identify and control variables, plan and conduct experiments. They require students to integrate and apply their knowledge in new and creative ways. A question such as "Given these three unknown white solids, how would you identify what they are?" would be of this type.

Elstgeest (1985) advised teachers to approach *reasoning* questions such as those beginning with "why", with caution. These questions are meant to make students think and reason, search for cause-effect relationships among variables, draw conclusions, or make generalisations. However, because these questions often ask for some sort of explanation, anxious students may mistake them for test questions and be afraid of being "wrong", especially if they feel that there is only one right model answer. And if the content is pitched beyond a student's ability and experience, these questions often cannot be answered by anything other than the recall level. If asked prematurely, asking why something occurs may be too abstract for students and beyond their ability, as the answer often involves some mechanism that is explained by theorising at the molecular rather than the macroscopic level. An example is "Why is there an increase in temperature when sodium carbonate dissolves in water but a decrease in temperature when ammonium chloride dissolves?". The reasons given by students themselves based on their reasoning, own evidence, and experiences are more important than those impressive sounding answers, faultlessly recited without understanding. Care is needed in how these questions are phrased and in when they are presented. A question phrased as "Why, *do you think* ....?" sounds less intimidating than "Why ....?" as the student's ideas and thinking, and not an authoritative answer is sought. Also, ask these questions only when students have had the necessary experience and knowledge to reason from evidence and construct sensible arguments.

Alfke's (1974) questioning model is an elegant, but simple means of helping students identify, control, and manipulate variables in science experiments. It systematically directs the teacher and student to investigate science phenomena through the use of *operational* questions which manipulate variables through: (a) elimination, (b) substitution, and (c) increasing or decreasing the presence of the variable. The questions lead to a task by which the student can arrive at answers by doing something with science materials and obtaining first-hand evidence. For example, when teaching the rate of reaction between zinc and dilute sulphuric acid, such questions might include: "What would happen if a few drops of copper sulphate are not added?", "What if we use calcium/magnesium instead of zinc?", and "How would the rate of reaction be affected if we use larger/smaller pieces of zinc?". *Non-operational* questions are those that cannot be easily answered by first-hand experimentation and are more abstract, requiring theoretical answers. They include: "Why does salt dissolve in water?"

However, a question such as "How does a change in temperature/concentration affect the amount of salt that dissolves in water?" would be operational. Allison and Shrigley (1986) found that when teachers modelled the asking of operational questions, their students also asked more of such questions during their science demonstrations. Since variable identification and manipulation are central to much of cause-effect relationships in scientific inquiry, operational questions are a means of encouraging students to think about such relationships.

Gilbert (1992) described a taxonomy for questions in the domain of creativity. He referred to the categories of association, imagination, brainstorming, organisation, analogy and metaphor, and reconceptualisation. Possible questions falling into these categories in teaching chemistry include "What do you think of when I say the word 'bonding'?" (*association*), "What do you think you would see in this solution if you saw it through magic magnifying glasses?" (*imagination*), "What are all the variables that might affect this experiment?" (*brainstorming*), "How many different ways might you group these substances?" (*organisation*), "How is the kinetic theory of matter like people's behaviour?" (*analogy and metaphor*), and "If matter is energy, what does that make us?" (*reconceptualisation*).

SOME RESEARCH FINDINGS ON TEACHER QUESTIONING

Carr (1998), a departmental head of science in a British secondary school organised a paired observation exercise where the science teachers paired up to observe each other's lessons on class questioning and compare notes. Some types of questions asked included (a) *open* questions, (b) *probing* questions which are asked to obtain more detailed and specific information, (c) *reflective* questions which are used to crystallise a particular point (e.g., "But what if this happened?"), (d) *closed* questions, and (e) *hypothetical* questions which pose a situation for the student and are very useful in teaching investigative skills.

The above study found that open questions were not asked as frequently as closed questions. Closed questions were used during review to consolidate information and to keep straying students on track. It was also observed that questions coupled with *ad hoc* diagrams and illustrations were a richer learning experience and were likely to be more effective at prompting student involvement, questions and answers. The teachers were concerned that when students were asked multiple questions coming in pairs or threes before they had a chance to respond, it was confusing and unhelpful to their thinking and learning. The teachers also felt that they had to focus on asking more open questions as their students needed to be given the opportunity and scope to develop extended answers and to learn, by doing so, to structure their thinking.

Koufetta-Menicou and Scaife (2000) classified science teachers' questions into nine categories, according to the mental operation required for each of them to be answered. The two categories of lower level thinking questions asked for (a) *recall* of facts, events, and definitions, and (b) *descriptions* of a situation and the identification of variables. Higher level questions included (c) those that basically begin with *how* and ask for a description and justification of procedures (e.g., "How did you test whether ...."), (d) those that seek *proof* or evidence (e.g., "What evidence have you got for that?"), (e) those that recognise a *pattern* or describe the trend in a graph, (f) those that begin with *why* and ask for a *reason* behind the procedure followed (e.g., "Why is this fair?"), (g) *what-if* questions that ask students to hypothesize (e.g., "What would be the problem if ....?"), (h) *prediction* questions, and (i) *conclusion* questions that require students to reframe information (e.g., "What did we learn about the ....?").

The above authors found that questions which require lower level mental operations (categories a and b) were not positively connected to any kind of desired learning outcome. The implication is that this type of question "makes very little contribution to the quality of teaching" and that "unless a teacher offers students appropriate experiences in categories beyond the recalling/memory one, teaching cannot be assumed to be effective in developing higher level thinking" (pp. 82-83). Also, "how" questions (category c) appeared to be associated with students' use of metacognitive skills. It seems that requiring students to think not only about the "how" (procedure) of a particular setting, but also the underlying reasons, was an important step towards metacognition. Furthermore, questions seeking evidence (category d) were strongly associated with teachers' guidance towards appropriate resolution of cognitive conflicts. This may be because the resolution of cognitive conflicts depends on giving explanations and constructing scientific arguments, which is in turn, linked to the identification of evidence. Additionally, the findings suggested that "asking more questions ... does not guarantee higher level learning" and that "it is the types of questions that matter and not simply their quantity" (p. 83).

ASKING HIGHER ORDER THINKING QUESTIONS

Asking questions is a common teaching activity. However, many teachers ask questions to determine only whether a student does or does not know a particular piece of information. Hence, most questions tend to be of the closed type. But our questions need to do more than just assess whether students know some information.

A closed recall question such as "What is Avogadro's number?" only encourages accurate memorisation of the most basic information, while a convergent one such as "How many grams of H_2O can form from 2 g of H_2 and 4 g of O_2?" requires students to integrate and apply their ideas of equation balancing, atomic and molecular masses, the mole, limiting and excess reagents, and to decide what happens in the non-stoichiometric mixture. However, the latter question basically requires students only to crank through a rote mathematical approach. Thus, emphasizing only closed questions encourages students to become skilful in the accumulation, memorisation, and retrieval of information. To promote higher order thinking in students, our questioning should not stay entirely within the closed question areas but include open ones as well.

Open questions can be used before introducing a new topic and can provide useful information about students' prior ideas and misconceptions in this area. They can challenge the more able students to consider alternative ways of interpreting data and formulate additional hypotheses to test. You can also use open questions to probe what students are thinking of by asking them to elaborate on what they have said (e.g. "Tell me a little more about that, please?"). In addition, you can ask students to analyse their ideas by asking for examples about alternatives, assumptions, inconsistencies in arguments; and for how data can be classified or compared. Questions that stimulate divergent thinking can also help teachers and their students to decide on things to investigate that stem from students' interests and curiosity. As both closed and open questions serve different purposes, asking a variety of questions at varying levels is important.

Some students may find it difficult to answer open questions and may need lots of practice before they can become skilful at thinking at this level. Also, if they have been accustomed to trying to come up with the "right" answer that meets the teacher's expectations, they may feel insecure and be unwilling to take cognitive risks. Many teachers may also have difficulties with open questions because such questions present opportunities for students to express divergent views, may get the lesson off the track, and cause teachers to lose focus. Furthermore, students can bring up many unexpected issues and topics about which teachers know little or nothing, and this can be uncomfortable for some teachers. However, with practice and experience, teachers can come to better anticipate the nature of students' questions, and deal with them more effectively.

HOW TO ASK HIGHER ORDER THINKING QUESTIONS?

Here are some suggestions to help you ask higher order thinking questions:

1. **Familiarise yourself with the levels of thinking elicited by different types of questions.**

To ask higher order thinking questions, you must first be familiar with the level of thinking expected of the various types of questions, as discussed earlier. However, the context in which a question is asked affects its level of categorisation. A question may be of a higher order if it helps the students to relate their prior knowledge with some other knowledge. However, if the teacher had previously told the students the relationship between these two pieces of knowledge, then the question might be lower order if the students have to just simply remember this relationship.

2. **Identify the mental behaviours that you would like your students to engage in.**

Identify the mental behaviours that you require of your students, i.e., the process skill(s) that they will have to engage in, and then consider how they can be made to think at these levels. Ask yourself if your questions require students to (a) recall facts and procedures that they have come across before, (b) explain an event or phenomenon, (c) infer from patterns, trends, or underlying relationships in data, (d) predict outcomes, (e) evaluate and use criteria to make a judgment about some given information, (f) generate alternative hypotheses for the same observations, (g) plan and design an experiment to test something that they would like to investigate, or (h) propose and generate solutions to a problem, especially one where the problem is embedded in a real world context and the solution is non-stereotypical, yet feasible.

Questions that require students to engage in thinking at the recall level as in (a) above (e.g., "What is Le Chatelier's Principle?") would be of a lower order. Those that expect students to give explanations as in (b) encourage them to apply their understanding of concepts to a new situation, provided that the explanations have not been rote learnt or rehearsed before (e.g., "Why does copper(II) carbonate decompose easily when heated, but sodium carbonate does not?"). When students are asked to infer (e.g., "Why do you think the phenolphthalein changed colour?"), predict (e.g., "What would happen if I drop this ping-pong ball into a tank of liquid nitrogen?"), and evaluate (e.g., "What are some of the pros and cons of obtaining water by desalination of sea water?") as in (c) through (e) above, such questions are pitched at the critical thinking level and are of a higher order. And if the questions demand students to suggest alternative hypotheses (e.g., "What might be some possible reasons why ....?") as in (f), design an investigation or generate solutions to a problem in a new situation (e.g., "How would you determine whether red dye no. 5 to which you are allergic is found in *Smarties* chocolates?") as in (g) and (h), they invoke creative thinking on the part of the students.

Simple enhancements in crafting a question can turn it from an algorithmic exercise to a real problem. Consider the question "How much heat is produced by burning 2 moles of propane given that the heat of combustion of propane is 2200 kJ/mole?". To solve this exercise requires very little understanding; one only needs to use a simple strategy. Often, problems given by teachers can be solved by substituting numbers into a memorised formula, with all the knowns and unknowns clearly identified. We can stimulate significant thought in students by omitting information, requiring assumptions, or including superfluous but seemingly relevant information. Context-rich problems that present real-world situations where the key variables, concepts, and essential information must be identified by students can also be used (Hanson & Wolfskill, 2000). Consider the question "If you are camping out on a cold, deserted island and have only one kg of propane remaining in your gas tank, will you be able to take a hot bath tonight?". For such a question, students need to consider the amount of water needed, the temperature of the water before and after heating, the energy needed to heat the water, and the heat of combustion of propane. They also need to identify and make necessary assumptions and the question does not have a unique solution. Such a question promotes discussion of what assumptions must be made, what must be done and how to do it, and will help students develop critical thinking and problem solving skills.

3. **Use Wait Time**

After asking a question, teachers are often anxious for an immediate response. And if none is forthcoming, they may answer their very own questions themselves. You need to pause or build in wait time of about three to five seconds for students to formulate reasoned responses, particularly for higher order questions. Rowe (1987) reported that when science teachers extended their wait time to three seconds or more, the length of student responses, the incidence of speculative thinking, and the number of unsolicited but appropriate responses, inferences, students' questions, and contributions by slow learners all increased. Tobin (1987) also reported similar findings and higher levels of student achievement with extended wait time. In addition, he also found that teachers who increased their wait time asked fewer lower order questions but more probing and application questions.

4. **Provide a warm classroom atmosphere**

To venture a response to an open question publicly among peers requires courage. Sometimes, highly competitive or achievement-oriented students who perceive themselves as having to meet high standards are not comfortable with risk-taking and thus would refrain from responding to the teacher's questions. They may be afraid of losing face or be laughed at by their classmates. A warm classroom climate with a low risk of censure, criticism, or ridicule is essential for promoting thinking via teacher questioning. Where teachers are intolerant of "wrong" or "stupid" answers, students will be less forthcoming in venturing their ideas, fearing that they may be dismissed as silly or "rubbish". Teachers who believe in the virtue of divergent thinking will not be afraid to let their students make mistakes and turn those mistakes to good use as building blocks in their search for understanding and workable solutions.

There are also students who are mere attention-seekers and who would blurt out the very first idea that comes to mind, without much thought. Often, teachers are wary of such student behaviour and would prefer to discourage such students from speaking up and taking up much precious and limited curriculum time. However, while they need to maintain classroom discipline, they should also be mindful that discouraging students' verbal responses can curtail higher level thinking, and should thus try to work at striking a balance between these tensions. Another word of caution. Don't fall into the trap of thinking that the more questions, the better the teaching. Also, remember that your questions should be asked more in the spirit of an inquiry rather than an inquisition.

5. **Check the wording of your questions and responses**

A question such as "Would you get an acid or a base if you dissolve sulphur trioxide in water?" limits your students to respond with "acid" or "base" or "I don't know." However, asking "What do you think might happen if you dissolve sulphur trioxide in water?" requires students to think harder and apply what they have learnt. If you ask "*Do you know why* there is a precipitate formed when dilute hydrochloric acid and barium chloride is added to copper sulphate solution?", students may answer "Yes, I know why" or "No, I don't know why" and such a response would be technically correct. Instead, if you omit the "do you know" and ask something like "Why does a *white* precipitate form?", your students would have to figure out how the reaction between a blue solution and a colourless solution produced a white precipitate. In doing so, they would have to articulate their thinking in more depth as they try to explain what was going on. Try to phrase your questions to avoid "yes" or "no" answers, unless that is what you really want. Compare "Do you think hydrogen gas will be produced if you add dilute hydrochloric acid to iron?" with "What do you think will happen if you add dilute hydrochloric acid to iron?". The former encourages a simple "yes/no" response, while the latter requires the students to think through much more about the properties of acid and the activity series of metals.

Design questions that are process-oriented, seek explanations, ask for evaluations, or stimulate imagination. Place emphasis on "how", "why", and "what if", and on relationships to previous information. For example, *why* magnesium is more reactive than iron in acids is more important than *which* metal is more reactive.

The following example (adapted from Kovacs-Boerger, 1994) illustrates the different types of teacher questions and responses that inhibit or promote thinking in students. Consider the following possible teacher responses to a student's incorrect prediction about the relative boiling points of ethane and ammonia: "Ethane has more hydrogen bonds than ammonia so its boiling point is larger". Teacher A who responds with "That's not quite right. Would someone else like to try?" terminates the interaction with the student and thereby unintentionally suppresses the student's further cognitive processing. Teacher B who replies "A hydrogen bond is an intermolecular force created under special circumstances and boiling points are affected by intermolecular interactions. Would you like to try again?" allows the student to think again. But this response is limiting because the teacher leads the student toward the right answer. Now consider Teacher C who responds with "What you are saying is that ethane, with six carbon-hydrogen bonds, has a higher boiling point than ammonia, with three nitrogen-hydrogen bonds; or that the greater number of bonds to hydrogen in a molecule is correlated with the larger boiling point. What happens during boiling? ...[Pause]... What kinds of interactions affect the boiling point?". This teacher paraphrases the student's ideas and highlights the implicit assumptions in the student's response. It encourages the student to re-think and decide if that is indeed what he or she meant, helps the student to reflect on the earlier response, and find and correct his or her own mistake.

6. **Look for questioning opportunities in each and every lesson and use open questions to stimulate critical and creative thinking**

Periodically interrupt the passivity of expository delivery teaching with active situations where students are required to answer questions at a variety of levels. Plan the questions so that they fit in with the natural flow of the lesson, coordinating questioning towards particular directions. Questions requiring thinking beyond the recall level make excellent introductions, bridges, and trigger activities. Some useful sources for developing open questions include newspaper and magazine articles, short problem situations, and discrepant events. The latter refers to situations which have a surprising and paradoxical outcome that is not what the observer would normally expect (e.g., see Chin [1992] for more details on the use of discrepant events).

HOW CAN TEACHERS IDENTIFY AND IMPROVE THEIR QUESTIONING SKILLS?

Most teachers rely on intuition and chance in asking their students questions, and these questions are often not pre-planned but generated on the spot, depending on the prevailing situation. While it is important to tailor our questions according to the context and progress of a discussion, it is also useful to make conscious attempts to ask questions that target at higher levels of thinking.

Some teachers may not be aware of their customary questioning patterns. To find out your questioning behaviour, you can tape-record your lesson or a "typical segment" of it, listen to yourself and your students' responses, and then analyse the questions that you asked. Analyse the number of possible and acceptable responses, and check the level of thinking that the questions stimulate. Also, ask yourself whether the questions require your students to go beyond recalling information in formulating a response. You can also analyse the way you phrase your questions. Words such as *who, what, when, where, name*, and sometimes *how* and *why* are often indicative of closed questions (Blosser, 1973). Words such as *discuss, interpret, explain, evaluate, compare, if*, and *what if* may elicit more than the retrieval of memorised information. However, they may also require only memory operations if the questions focus only on information from a previous lesson.

If you find that there is a lot of information-giving and a paucity of questions in your "teacher talk", you could intersperse your exposition with questions. If you find that your questions are often pitched at the factual recall level and do not sufficiently stretch your students' minds, you may try asking a wider variety of questions to tap on students' higher level thinking processes. On the other hand, if you find that you are asking questions that are well above the heads of most students and are not getting any satisfactory responses, you may wish to ask more basic questions first and then follow up with more difficult ones progressively. Too many higher order questions can be frustrating for students and detrimental to the inquiry process. Lower order questions are helpful in reviewing basic concepts and can lay the foundation for meaningful discussions. You can consider locating one or more of the above-mentioned question categories that you can use comfortably and then apply them in your teaching, remembering to establish a balance between questions of different degrees of complexity. This will also ensure that you ask a diversity of question types and that promoting critical and creative thinking is part of your daily lesson plan.

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