Title	Can advanced level chemistry students (11th and 12th graders) reason scientifically?
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CAN ADVANCED LEVEL CHEMISTRY STUDENTS (11TH AND 12TH GRADERS) REASON SCIENTIFICALLY?

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Abstract

This paper reports on in-depth interview studies conducted with Advanced level students (11th and 12th graders) in the UK and Singapore to examine their ability to reason scientifically when confronted with a range of chemical phenomena.

The results show that the majority of the students studied were unable to reason scientifically. The paper presents some such cases. It also discusses some of the possible reasons behind these students' difficulties as well as suggestions on their alleviation.

Introduction

Background

Whilst there has been considerable research into younger children's' understandings and alternative conceptions in chemistry, for example, Andersson (1990), BouJaoude (1991), Prieto, Watson and Dillon (1993), there have been few studies of older, pre-University students who, having decided to specialise in Chemistry and been subject to a number of years of formal chemistry teaching, should be expected to have a reasonable 'scientific' view of the subject together with the command of language to fully articulate their understandings.

The research programme has been based upon students' understandings of five common chemical reactions that are studied in the school curriculum:

Event 1	hot copper in air
Event 2	the burning candle
Event 3	the bunsen flame
Event 4	magnesium and dilute hydrochloric acid
Event 5	sodium chloride and lead chloride solutions.

In the programme, 48 British and 65 students were interviewed in depth and the interview sessions audio-recorded. For more detail of the research method, refer to Boo (1995).

Throughout the interview students were asked to articulate, in detail, their understandings of each chemical reaction in terms of four key aspects:

Aspect A	Prediction of the type of change
Aspect B	Prediction of the overall energy change
Aspect C	How the reaction takes place
Aspect D	The driving force, i.e. why the reaction takes place at all.

The major objectives of the programme had been to investigate the nature of conceptions and reasoning processes displayed/employed by students . It was observed that most students held a range of conceptions, including both scientifically acceptable conceptions and alternative conceptions, and that the students would reason differently between the five events depending upon their perception of the categorisation of the base event (see Boo, 1995).

What is 'Scientific Reasoning' ?

In order to understand what we mean by the term 'scientific reasoning', it is necessary to consider what the nature and aims of science are.

In 1954, Einstein offered the following definitions of science, and the aim of science:

> *Science is the attempt to make the chaotic diversity of our sense-experience correspond to a logical uniform system of thought.*
>
> *The aim of science is, on the one hand, a comprehension, as complete as possible, of the connection between the sense experiences in their totality, and on the other hand, the accomplishment of this aim by the use of a minimum number of primary concepts and relations.*

Implicit in Einstein's definition is that scientific knowledge is never absolutely true but is a theoretical construct to be constantly refined.

Chalmers (1990) suggested that:

> *the aim of science is the establishment of generalisations governing the behaviour of the (physical) world.*

Reif and Larkin offered the following definition in 1991:

> *The central goal of science is to achieve optimal prediction and explanation by devising special theoretical knowledge which parsimoniously (i.e. on the basis of a minimum number of premises) permits inferences about the largest possible number of observable phenomena.*

The important point from all these definitions is the predictive nature of science; i.e., the ability of science to not only adequately explain observable phenomena but also to provide a basis for the prediction of unfamiliar or unobserved events.

From these definitions, it could be inferred that, among other things, scientific reasoning involves both inductive and deductive thinking. It involves inducting concepts, principles, generalisations, theories, models from perceptual experiences with natural phenomena, and then through a process of deductive thinking uses these (few) basic concepts, generalisations, principles, theories or models, to explain and make predictions about a wide range of natural phenomena.

Examples of A-level Chemistry Students' Reasoning in Chemistry

It is against this definition of science as the process of construction of a logically consistent model to both explain and predict a range of events that my major research has been carried out.

All of the five reactions used as foci for discussion in the interview can be explained or their outcomes predicted by a single consistent reference model:

> Chemical change involves interaction between numerous particles which are in constant motion. Such interaction includes collision between particles of reactants; breaking of existing bonds and making of new bonds within/between particles. Bond breaking is a process which requires energy input while bond making is a process which is accompanied by the liberation of energy. The magnitude of the overall energy change is governed by the difference in strengths of the bonds formed vis-à-vis bonds broken. Where bonds formed are stronger than bonds broken, the reaction would be overall exothermic - as is the case in all 5 reactions discussed. Where bonds formed are weaker than bonds broken, the reaction would be overall endothermic. The driving force of the change is the decrease of heat energy in the chemical system resulting in an overall more stable state or the increase in the total entropy of the universe.

Only about 10% of the subjects interviewed were able to reason consistently according to this (or, indeed, any other) reference model.

In general it was found that students tended to use everyday/layman language rather than scientific concepts and principles in their reasoning overall energy change and driving force of chemical change.

At A-level, having studied at least 10 years of science and 3-4 years of chemistry, one would expect these students to be able to make predictions of the type of change expected based on concepts, principles or models that they have learnt. Instead, when asked for the bases of their predictions (of the type of change expected or of the overall energy change), the vast majority were: "based on what I can recall" or "based on what my teacher (or textbook) said" or "based on what I learnt in school" (or words to those effect). These responses showed that there were little understanding of the role of concepts, principles and models in prediction.

The following response given by Student A2.1 was fairly typical of the Singapore sample. Here the student predicted the following energy changes for the five reactions:

Event 1	**Energy change**	**Reasons**
1	Endothermic	Because without heat there is no reaction
2	Exothermic	Because you can feel the heat with your palm
3	Exothermic	Because number of bonds broken are greater than number of bonds formed
4	Exothermic	Because of strong ionic bonds formed between magnesium and chlorine
5	Endothermic	Because all precipitation reactions are endothermic

Several inconsistencies in this student's responses demonstrate a lack of ability to use scientific reasoning.

a) the range of different type of reason given in each answer event; for events 1 and 5 this student gave the wrong answer. In the case of event 1 the student was misled by the perceptual clue of the applied heat and for event 5 by an incorrect naive 'rule'. The answer for event 2 is no explanation at all and for events 3 and 4 the concept of bond energies is used.

b) whilst the concept of bond energies is employed, the student used the number of bonds in event 3 and bond strength in event 4

c) In event 3, the student perceived bond breaking as the exothermic process whilst in event 4 he perceived bond formation as being exothermic.

On the question why the reaction takes place at all or the driving force behind chemical change, student A2.1's responses are again quite typical of the group of students interviewed:

Event	Driving force
1	Heat supplied is the driving force
2	Oxygen is the driving force..because without oxygen, things cannot burn
3	The fuel..the gas is the driving force ..because of its flammable nature
4	The acid is the driving force..because it's very strong..corrosive.. it attacks the Mg
5	Water is the driving force..without water. there is no reaction

From these responses it can be inferred that this student probably held the naive view of chemical change which is discussed in Brosnan (1992). In this view, chemical change is thought to be brought about by an active agent (ie one of the reactants) acting upon passive substance(s) (ie the other reactant(s)), instead of the interaction of equal partners. The active agent varies from reaction to reaction - heat, oxygen, fuel gas, acid and water!

The corresponding responses of a typical British student - given by student C12.2 are set out in the following paragraphs:

Event	Energy change	Reasons
1.	Exothermic	Because joining copper and oxygen together give out energy to form a compound and breaking up molecules or bonds needs energy from outside.
2.	Exothermic	Because there are more bonds to break than make. Bond breaking is exothermic, bond making is endothermic because it is more difficult to make than break bonds
3.	Exothermic	Because oxygen and methane ..... you light methane .... they burn and heat is produced .... heat is produced from molecules breaking up .... sort of takes over the endothermic reaction .... there are more bonds to break on reactant side than bonds to be formed on product side.

4. Exothermic — Because magnesium is some kind of energy source which causes the reaction .... HCl is probably also some kind of energy source but not as much as magnesium .... heat from bunsen flame in event 1 (hot copper in air) reaction is the energy source for the reaction, not the copper, though copper is probably an energy source but not as strong as Mg because oxidise more readily than copper, it reacts with air on its own..forms a film of white powder.

5. Exothermic — There are more bonds to break than make.

Whilst this student recognised (or guessed) that all 5 reactions were exothermic, she was inconsistent in her reasoning, using different ideas in each event. In event 1 she saw bond making as exothermic whilst in events 2,3 and 5 she saw bond breaking as exothermic. In event 4 appeared to be using layman or everyday thinking that the heat released in the reaction came from the magnesium which is considered as very reactive hence capable of releasing energy - perhaps in the same way that an active child is considered to be "full of energy" , hence running around and being excited.

C12.2 's responses on driving force:

Event	**Driving force**
1	Heat from the flame is driving force..it makes the molecules more lively, given them more energy to react (classified as AC1 in Table I)
2	Heat again is the driving force (classified as AC1 in Table I)
3	Heat again is the driving force (classified as AC1 in Table I)
4	Mg is the driving force..it is some kind of energy source which causes the reaction (classified as AC2 in Table I)
5	Sodium is the driving force..it is reactive..more reactive than lead (classified as AC3 in Table I)

This response on driving force is not much different from that given by student A2.1 - in that essentially it reflects a naive view of chemical change - the view that chemical reaction is the result of some active agent (which can be heat - Andersson, 1986; or one of the reactants) acting upon passive substances instead of the result of interaction between equal partners.

The following table gives the overall pattern of responses on the question on driving force based on the sample of British students. This shows up more clearly students inability to use concepts, principles and models deductively across a wide range of phenomena to explain and make predictions. (The data based on the Singapore sample are not much different.)

TABLE I
STUDENTS' FRAMEWORKS ON ASPECT D (PERCEIVED DRIVING FORCE) BY EVENT

Framework	Event 1	Event 2	Event 3	Event 4	Event 5
AC 1: Heat as causal agent	39	39	39	10	8
AC 2: Internal energy of chemicals	2	2	2	17	11
AC 3: Difference in reactivity	0	0	0	14	13
AC 4: Water as causal agent	0	0	0	0	5
scientific framework	5	5	5	5	5
no response, other responses	2	2	2	2	6

Table I shows that only 5 out of the 48 students (10%) were able to use consistently the concept about energy change or entropy change to explain why the chemical reactions took place at all. The rest used frameworks which are at variance with the acccepted scientist view:

For events 1 to 3 where flames were involved, 39 (87%) of the students thought that heat was the driving force. This response was classified in as AC1 or alternative conception no.1 where heat input is viewed as the driving force behind the chemical reaction.

For events 4 and 5 where no heat is involved, it was perhaps not surprising that the most popular view about heat as driving force has shifted. Here, it was supplanted by two almost equally popular views viz. AC2, internal energy of chemicals as driving force; and AC3, the difference in reactivity between chemicals.

For event 4 the most popular view held by 17 (35%) of the students was that one of the susbtances (magnesium metal or the acid HCl) was the driving force because of their perceived 'reactivity'. This response was classified as AC2 or alternative conception no.2 where internal energy of some reactive chemcals is viewed as the driving force. Besides this view, another view which was almost as popular with the group (ie used by 14 students) was that "Magnesium is more reactive than hydrogen, hence it drives the reaction." This view was classified as different from the previous one and is labelled as AC3 or alternative conception no.3 where the driving force is perceived to be the difference in reactivity between chemicals.

For event 5, the most prevalent view AC3 was displayed by 13 students (27%) "The reason why the reaction happens is because.. sodium is more reactive than lead, hence it displaces lead resulting in the products observed." Another view, AC2 which was almost as popular and expressed by 11 students was "Sodium is the driving force..it is very reactive..it drives the reaction."

Why do students find it difficult to reason scientifically?

There are at least three possible reasons why students find it difficult to reason scientifically. These are:

1. They lack understanding of the nature and goals of science

   If students view science as a body of facts rather than predominantly a process of constructing predictive conceptual models, then it is likely that they might not have attained and internalised the scientific concepts, which in turn would mean that they would not be able to use these concepts consistently in explaining and making predictions about a wide range of chemical phenomena.

2. They learn labels for concepts without learning the full conceptual meaning.

Many studies have shown that students have a tendency "to reduce theoretical knowledge and principles to a 'factual' level and 'apply' this in a rote fashion" (Garnett, Garnett and Hackling, 1995, p. 89). If students have learnt by rote and have not abstracted or constructed the scientific concepts, principles and models for themselves, then it would be difficult for them to apply these across a variety of superficially different phenomena.

3.. They have confused the goals and hence ways of thinking of science with goals and ways of thinking of the everyday life.

This third reason is discussed by Reif and Larkin (1991) and is probably related to the preceding two reasons. As a consequence of not understanding the nature and goals of science, and/or of not having learned the concepts meaningfully or deeply, and because the influence of everyday life is stronger than that of school science, students tend to confuse the goals and ways of thinking of science with those of the everyday life. In everyday life, knowledge and rules of conduct tend to be compartmentalised i.e. various kinds of knowledge can be used as appropriate in different contexts without requiring great generality. Not understanding the nature of science and scientific knowledge means that students tend to compartmentalise their knowledge of different type of chemical reactions rather than recognise the generic model underlying all chemical reactions.

In fact another compounding factor which is suggested by Reif and Larkin (1991) is that school science often does not adequately foster the scientific goal of understanding. Instead, many science courses taught in schools tend "to encourage and reward the memorisation of knowledge rather than the ability to make diverse inferences leading to scientific understanding."

In order to investigate post-A level students' perceptions of what science is, earlier this year I posed the following question to 92 first year students (69 of whom were enrolled in the B.A./B.Sc with DipEd course,and 23 at the Dip Ed course) at the National Institute of Education in Singapore:

What is this thing called "science" and how do you differentiate science from non-science ?

The 'model' answer that I had in mind was based upon my expansion of the Reif and Larkin definition presented earlier:

Science is the total body of knowledge concerning the universe and the process of construction of theoretical models involving the minimum number of primary concepts to achieve the maximum level of generalisation of explanation of observable events and provide the basis of prediction about unobserved events. Science is therefore never absolute but is constantly being refined as new knowledge becomes available.

Only 27 (about 30%) of the students utilised the concept of science being explanatory of whom no students appeared to appreciate that generality of explanation might be important. Only 3 students out of the 91 (3%) mentioned anything that might be called the predictive nature of science.

Typical of the student's actual responses were:

"The study of the natural environment"

"Study and understanding of our surroundings and how they function"

"Explanation of natural phenomena"

"Knowledge of the world around us"

"It's the answer to 'Why'"

"Man's search for the relationship between himself and his environment"

"Physics, Chemistry and Biology"

"The study of fundamental concepts"

"Facts which can be proven"

In summary, very few students had any concept of there being an objective or goal of science; rather it seems that the vast majority of students see science as just an academic curriculum subject - an accumulation of factual knowledge and information under curriculum labels - viz., chemistry, physics and biology.

The following responses (quoted verbatim) were typical:

First year diploma-in-education course student S1:

"Science is the study of life, of how things work. It is full of experiments and discoveries. Science is based on facts about everything in life. Non-science is something that we can study or analyse based on personal opinions and views."

First year undergraduate Student S2:

"Science is something that is all around us. It has to do with why things are the way they are and how these things actually works. It concerns both non-living and living things. It emphasise on theory, facts, etc often being proven by experiments. Science has more to do with our physical living environment. Non-science deal more of that with languages, maths..more theoretically than factual."

Another first year undergraduate Student S3:

"Science is the study of life, the environment. Science is events and theories which can be proven to be true experimentally. Non-science is just pure imagination and deductions without specific examples."

These 3 responses illustrate the prevailing view that scientific knowledge is derived from, and can be proven through, experiments. The implication is that scientific knowledge is absolute and final.
They also typify a common view amongst the sample that appears to bound science within a narrow educational or curriculum driven view that the role of science is to present facts and theories (curriculum: introduce a topic), explain them (teach it) and then demonstrate or prove their correctness through experimentation (supporting lab work).

From the views expressed by this sample of post-A-level students, one could perhaps infer (albeit tentatively) that conception of the nature of science held by group of Singaporean students who were involved in the interview research were not too different. This is to suggest that they probably too held the view of science as a curriculum subject, and science is percevied of as dealing mainly with facts i.e. isolated facts, instead of with concepts, principles and models about the behaviour of natural phenomena.

Thus it is not surprising if they have not really learned the scientific concepts, principles and models meaningfully enough to be able to use them in explaining and making predictions about a wide range of chemical phenomena.

Implications for teaching

Today, much science teaching in the classroom is carried out in the 'top-down' manner reflected in the student responses just mentioned. The teacher will introduce a topic, present and explain the concept and its meaning and then follow up with practical work to reinforce the material covered.

As suggested by Gilbert (1991) science education should proceed from a definition of science as "a process of constructing predictive conceptual models". Students therefore need to be explicitly informed of the nature and goals of science and how these differ from those of non-sciences as well as from the everyday life. If they are not explicitly made aware of the nature and scope of science perhaps it is not surprising that their conception of science has been a rather narrow one.

This process of constucting predictive conceptual models has a number of well ordered steps:

1. Observation of a range of natural phenomena.

2. Grouping and categorisation of data collected from observations.

3. Constuction of a conceptual model to explain the relationships between data within a category.

4. Design of controlled experiments to test the correctness of the model against the possible values of data within the category.

5. Acceptance of the model as the best explanation currently available of the relationships between data within the category.

6. Use of the model to predict as yet unobserved outcomes, ie to extend the boundaries of the category.

7. In the event that

    a) the model is shown to be an inadequate representation during controlled experiments

    or

    b) new observations are at variance with the prediction

    then the process is repeated from either stage 2 or stage 3.

8. In the search for maximum explanation with the minimum number of primary concepts, science will test the boundaries between categories with the aim of one category subsuming another.

If science teaching is carried out in a 'bottom-up' manner, i.e. through using a wide variety of concrete and perceptual experiences to guide students to abstract and construct concepts, principles and models for themselves, then it in fact, maps the course of development of many scientific concepts, theories and models. In other words, it is this researcher's belief that that science teaching carried out in a 'bottom-up' manner and which takes into account the historical development of science could result in more meaningful and effective learning of concepts and principles, and hence, scientific reasoning.

As observed by Lunetta and Cheng (1987), students can learn that they are developing conceptual models to better understand the world around them and that they can come to understand that as they get more information then their conceptual models must grow and evolve and change. Following concept formation, students should be given examples illustrating the wide application of these concepts, rules, principles and then they given situations where they could learn to apply the concepts, principles to make inferences about unfamiliar phenomena.

Another reason for students' use of everyday thinking and everyday language in the context of solving science tasks or questions could be that science (school science) is often taught (and hence perceived by students) as dull and uninteresting. This is in contrast to their everyday life which encompasses things which are interesting and full of strong emotions. Thus another approach to alleviating the problem of wrong use of everyday thinking in a scientific context is to inject interest and emotions in school science. Yet another prong of attack is to ensure that the everyday life is brought into school science by emphasising the applications of particular science concepts, princples in the everyday life. .

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