

Chapter 5

CONCEPTUAL DEPTH AND CONCEPTUAL USEFULNESS IN CHEMISTRY: ISSUES AND CHALLENGES FOR CHEMISTRY EDUCATORS

Kevin C. de Berg

Avondale College, PO Box 19, Cooranbong NSW 2265, Australia

Abstract

In the 1990's two movements began to challenge the practice of science education from an historical and philosophical perspective. The International History and Philosophy of Science and Science Teaching Group (IHPST) maintains that not enough attention is being given to the intellectual heritage of many of our concepts in science with the result that, while students might be able to solve some quantitative problems in an algorithmic fashion, they have little understanding of the meaning or significance of the concepts they are using. The International Society for the Philosophy of Chemistry (ISPC) focuses its attention on the discipline of chemistry and has challenged practising chemists and chemistry educators to address, amongst other things, such fundamental questions as the meaning of the terms *atom*, *element*, *law*, and *theory* as they are used in chemistry. Is it possible to seek and accomplish conceptual depth, a desire of both international groups, without compromising conceptual usefulness, or must one be compromised in the pursuit of the other? In this paper this question is addressed in relation to the thermodynamic concepts of *energy*, *heat*, and *work*; the foundational concepts of *element* and the *mole*; and *quantum mechanical* concepts in chemistry. A textbook analysis of the definitions and use of these concepts in a tertiary level general chemistry course is given as is the implications of the study for chemistry education.

Introduction

At the time when the International History and Philosophy of Science and Science Teaching Group (IHPST) was being formed, journals like "Interchange", "Synthese", "Educational Philosophy and Theory", and "Studies in Philosophy and Education" dedicated a whole volume to the question of the place of history in science teaching. The topic was not a new one of course and, although past attempts at incorporating history into science teaching had

met with only limited success, a new wave of optimism descended on the science education community in the late 1980's with the result that IHPST was formed, conferences were convened in North America or Europe every two years, and a dedicated journal, "Science & Education", was organised with Kluwer Academic Press and now Springer Press. Part of the reason for this new wave of optimism was the need to address falling enrolments in science classes with new approaches to science curricula which were more human-oriented. Ian Winchester's editorial for the dedicated "Interchange" volume in 1989 signified the urgency of the matter in these words: "When it (science) is introduced.....two distinct tendencies are present. The first is to treat science (and mathematics) as something with results but without a history. And the second is to treat science as something which can be nearly completely captured by working examples from a textbook. Both of these activities, namely, dwelling on agreed upon scientific results and standard examples, are important and part of the initiation into the complex of activities involved in a scientific discipline. But they fail to convey to the student.....anything of the excitement of scientific discovery, of the conceptual problems involved in forging a new realm of scientific inquiry or of advancing in an old one, of the myriad difficulties of interpretation, theory construction and abandonment or the moral and aesthetic problems faced in the process" (Winchester 1989, p.(i)). It is argued by members of the history in science teaching movement that providing students with the historical background of a scientific concept gives a dynamic character to it and illustrates the progressive rather than static nature of science. Those more skeptical of the movement argue that conceptual clarity is compromised when students are introduced to the conceptual errors of the past.

As far as chemistry is concerned it is true that history of chemistry has traditionally received more attention from educators than has philosophy of chemistry (Scerri 1997). This lack of philosophical influence in chemistry teaching and learning has led to the establishment of the International Society for the Philosophy of Chemistry (ISPC). It is argued that chemistry education will benefit from discussions that detail the nature of chemical knowledge. As examples of this approach Erduran and Scerri (2002) address the problem of 'reduction' and how this might clarify the relationship between chemical composition, bonding, and molecular structure; they address the nature of 'explanation' in chemistry and claim that "there is a distinction to be made about the explanatory status of electronic orbitals in chemistry and their ontological status in quantum mechanics. Reflective classroom discussions based on such distinctions are likely to promote deeper understanding of chemical explanations among university students"(Erduran & Scerri 2002, p.15); they address the question of the nature of 'law' in chemistry and in relation to the periodic law conclude that, "The crucial feature which distinguishes this form of 'law' from those found in physics is that chemical periodicity is approximate. For example, the elements sodium and potassium represent a repetition of the element lithium, which lies at the head of the Group I of the periodic table, but these three elements are in no sense identical"(Erduran & Scerri 2002, p.16); and they briefly address the case of 'supervenience' in chemistry in terms of the maxim, "macroscopic identity need not imply microscopic identity"(Erduran & Scerri 2002, p.17).

What is the relationship, then, between conceptual depth, conceptual usefulness, and history and philosophy of chemistry? In this paper, conceptual depth refers to the multilayered structure of a concept and hence its meaning. Conceptual usefulness refers to the capacity of a concept to assist in calculation and problem-solving, that is, to arrive at answers

to important questions that do not necessarily enrich the meaning of the concept. One could say that conceptual depth focuses on a concept as a signature of meaning while conceptual usefulness focuses on a concept as a problem-solving tool. However, depth and usefulness may not be necessarily mutually exclusive. The possibility of a concept contributing as both a tool and a signature of meaning will be explored in this paper. History and philosophy by nature contribute to meaning in slightly different ways. History provides the story behind the concept and philosophy clarifies the nature of the concept.

The use of concepts as problem-solving tools has been the focus of the research comparing the prevalence of qualitative problems with quantitative problems in chemistry (Reif 1983; Gabel et al. 1984; de Berg 1989; Bodner & Herron 2002). Algorithmic problem-solving exercises using quantitative data have been the main orientation of chemistry curricula. That is, the emphasis has been on the use of concepts in their quantitative dress as problem-solving tools. By comparison, only a small number of problem-solving qualitative exercises are typically used in textbooks (de Berg 1989). Reif (1983, p.952) compares these two problem-solving approaches as follows. "Students tend to place a great emphasis on remembering and using facts and mathematical formulas without trying to embed these in a rich framework of qualitative knowledge. Accordingly, students may be able to answer some quantitative questions by merely manipulating some mathematical formulas, but they may be quite unable to answer simple qualitative questions of a similar kind. Furthermore, students seldom use qualitative knowledge to plan solutions or to check whether results obtained by them make any sense". Stenhouse (1985, p.21) is critical of the algorithmic mathematical problem-solving approach and argues that, "What is inculcated in a great deal of science education is, all too often, not understanding, but rather a sort of recipe book acquaintance with a number of mathematical techniques which tend often to be used on an ad-hoc basis without any proper understanding either of the mathematical theory and assumptions on which the techniques are based, or of the subject matter to which they are applied". In this paper, problem-solving exercises, whether quantitative or qualitative, are classified in the category of 'conceptual usefulness' because of the use of the concept as a tool. It is exercises that enrich the meaning of a concept that are classified in the category of 'conceptual depth'.

Deepening one's understanding of a concept occurs during the process of *abstraction*. Peter Atkins (2003, p.110) gives an illustration of this process in relation to the steam engine as follows. "When we strip away the iron to leave the *abstraction* of a steam engine, we obtain a representation of the spring of all change. That is, provided we look at the *essence* of a steam engine, its abstract heart, and ignore the details of its realization – the steam, the leaky pipes, the drips of oil and grease, the rattles, bangs, and rivets – we find a concept that applies across the range of all events. Science is like that: science distils from reality its essence, its great ideas, then finds the same phantom spirit elsewhere in nature". Abstraction and conceptual depth depend so much on the provision of adequate time for students to experience such orientations in science teaching and learning. Students and teachers tend to find that an orientation towards the use of concepts as tools is more readily accessible given the practical problem of time constraints. Winchester (1989, p.(vi)) proposes the following solution. "As regards the question of whether or not one has time to teach everything one would like to teach in science, the answer seems to be that since we want scientists who are not only capable of solving the puzzles in normal times but also of advancing in revolutionary ones, we must try for a more liberally educated student. It would seem to be better not to teach too much in science (to echo Whitehead) but to teach what one does teach thoroughly,

in context and in depth. And here the depth would include the history of what is taught in both its scientific and social context as well as the initiation into the technical mastery of the subject". But it is now twenty years since this suggestion was made and there appears to have been little progress in addressing the imbalance between teaching for understanding and a teaching orientation towards the solving of a set of standard problems. This is an issue and a challenge to chemistry educators which demands some attention. This paper now looks at some of the dilemmas chemistry students and teachers face when it comes to the teaching and learning of topics in thermodynamics, particularly *energy*, *heat*, and *work*; in the foundational concepts of *element* and the *mole*; and in some *quantum mechanical* concepts in chemistry. An exploration of these ideas may help to shed some light on the difficulties we face in teaching for understanding.

Energy

The term, "energy", is very much a part of the language of society in general in addition to its special significance in science. This has become particularly so in an era of the attempted political control of a country's greenhouse gas emissions and the consequent search for alternative energy sources. Society in general identifies the term 'energy' with its sources rather than as an abstract definable term. So people will think of the sun, of electricity, of motor vehicles, of power stations and such like. Scientists, on the other hand, attempt to be more precise with the term and try to distinguish it from its sources. Richard Feynman (1963, p.4-2), however, claims that, as far as the scientific concept of energy is concerned, "It is important to realise that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, and when we add it all together it gives....always the same number. It is an abstract thing in that it does not tell us the mechanism or the reason for the various formulas". This immediately presents a problem for chemistry educators. If 'we have no knowledge of what energy is', but are confined to using a mathematical principle that shows that, whatever energy is, it is always conserved, then we are forced to admit that 'energy' is a tool rather than a signature of meaning. But do we need to be as bland as this?

Joan Solomon (1992, p.107) takes issue with those purists who maintain that energy can only be thought of as a type of mathematical accountancy. In her opinion, "Adult physicists may possibly end up with the bare mathematical formulation, although it seems somewhat doubtful, but pupils' learning of such an important and difficult concept as energy must begin somewhere. Getting to understand energy is a long and gradual task during which the pupils' minds play with the idea in progressively more sophisticated ways". Even Feynman used the analogy of a child's twenty-eight playing blocks to illustrate conservation of energy while drawing our attention to the fact that as far as energy is concerned there are no playing blocks. Thus thinking of energy initially as some sort of 'stuff' that can be transferred from one object to another, and a little later as 'the capacity to do work' or 'the capacity to transform', and finally as a 'kind of accountancy', are important stages in a person's cognitive growth in relation to energy. Domenech et al.(2007, p.50) agree with this view and claim that initial qualitative considerations about energy such as those described above "should not be judged in the light of the body of knowledge accepted today (after much development) but in light of

their capacity to facilitate the construction process, during which the initial ideas will evolve to more elaborated and fruitful conceptions". This multilayered structure for a concept, while containing some inadequate initial conceptions, helps to display the dynamic character of concept development and ways of understanding the concept even though we cannot actually say what energy is intrinsically. Thus while one may primarily regard 'energy' as a tool to account for changes in a chemical system for example, there is a sense in which its meaning is enriched as it is used as a tool.

First-year General Chemistry textbooks do not usually begin a discussion of energy as a purely mathematical accounting principle but instead focus on the different forms of energy such as solar energy, electrical energy, chemical energy, mechanical energy, and nuclear energy. While analysis into these different forms of energy is important, can a process of abstraction also yield fundamental energies common to all forms of energy listed here? And can these fundamental energies inform us about what is really meant by the term 'chemical energy'? Peter Atkins (2003, p.96) answers these questions in the affirmative as follows. "At this stage, we see that there are just two forms of energy (as far as energy stored in matter is concerned) – kinetic energy (the capacity to do work by virtue of motion) and potential energy (the capacity to do work by virtue of position). Although you will often encounter terms like 'electrical energy', 'chemical energy', and 'nuclear energy' there is really no such thing: these terms are just handy shorthand terms for special and particular combinations of kinetic and potential energy". For example, a battery stores electrical energy in the form of potential energy and when allowed to push electrons (voltage) around a circuit results in the conversion of potential energy into kinetic energy (current).

Table 1. Explanations of energy changes during molecular collisions across five General Chemistry textbooks

PE = potential energy; KE = kinetic energy

Textbook	Is rise in PE explained?	Is thermal energy released related to temperature difference?	Is temperature related to KE on product side?	On what basis is a reaction exothermic?
Kotz et al. 1999, pp. 710-715	Yes – twisting molecules	No	No	Energy of products less than energy of reactants
Moore et al. 2002, pp. 587-593	Yes – bonds stretched, twisted	No	No	Energy of products less than energy of reactants
Silberberg 2006, pp.697-700	Yes – electron clouds repel	No	No	Exothermic so reactants higher in energy than products
Spencer et al. 2006, pp.640-642.	No	No	No	E_a (forward) is less than E_a (reverse)
Whitten et al. 2000, pp.676-680	No	No	No	E_a (forward) is less than E_a (reverse)

The interrelationship between potential and kinetic energies has been shown to be very useful in detailing the energy changes which occur during a chemical reaction. Using the analogy of the pendulum as a potential energy (PE) – kinetic energy (KE) converter, de Berg (2006) explains why exothermic reactions result in a temperature rise and endothermic reactions result in a temperature fall. In this study it was found that very few textbooks detail this process with the result that the term ‘energy’ remains rather elusive. The responses of five textbooks are shown in Table 1.

Consider the energy changes shown in Figure 1 during the course of a reaction.

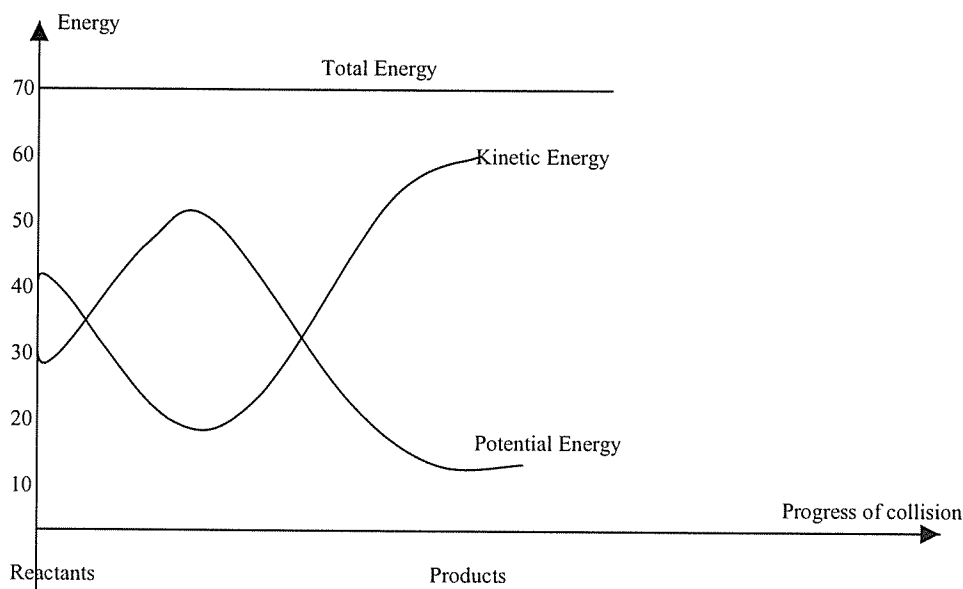


Figure 1. Energy exchange during a chemical reaction (exothermic case).

Some textbooks never specify that the vertical axis represents PE (in the case where only PE is plotted) and that PE rises as the molecules approach for collision. The PE – KE relationship can be described this way. As molecules begin the process of collision their electron clouds start to merge resulting in repulsion due to like charges and this raises the PE and therefore lowers the KE. One must remember that attraction of opposite charges lowers PE but repulsion raises PE. The KE of the molecules before collision is used to break chemical bonds by increasing the PE of the system. This is analogous to a spring or pendulum system where the bob is raised an increasing distance above the centre point of motion (pendulum) or stretched further from the point of support (spring). As new bonds form the PE starts to decrease and therefore the KE starts to increase again. If the products' PE lies above the reactants' PE, then the KE of the products is less than that of the reactants and since KE is proportional to absolute temperature, the temperature must fall. Conversely, if the PE of the products lies below that of the reactants, the temperature must rise since the KE of the products is greater than that of the reactants. None of the textbooks shown in Table 1 use KE differences to explain why a reaction is exothermic or endothermic. The textbooks talk about

an energy difference between reactants and products but they do not specify what kind of energy this is. Figure 1 shows that (PE + KE) is conserved which is what might be deduced from a smoothly operating pendulum.

The discussion in the previous paragraph showing how PE and KE interrelate during the breaking and making of chemical bonds in a chemical reaction did not help us gain any insight into the intrinsic nature of 'energy'. But it did provide us with the tools for understanding the changes that occur during a chemical reaction. Thus while the concept of energy may be an abstract mathematical one at its heart, visual representations of this mathematical principle through the use of analogies like the pendulum or vibrating spring certainly enhance the usefulness of the energy concept and, to some extent, enhance the abstract nature of the energy concept.

Heat and Work

The concepts of heat and work are intimately tied to the concept of energy although they had independent histories till about the middle of the 19th century (de Berg 1997). Both the caloric theory of heat and the connection between the concept of work and the development of efficient engines for industry gave rise to the 'quantity' nature of heat and work. So, for example, in the field of calorimetry, one speaks about 'the amount of heat gained by the water' or 'the amount of heat lost by the metal'; and in the field of thermodynamics one speaks about 'how much work was done by the engine'. The difficulty for chemistry educators arises because heat and work are no longer regarded as 'quantities' but as 'processes'. Some textbooks use the 'quantity' understanding in problem-solving while stipulating in the definition of heat and work that they are not quantities but processes by which energy is transferred. Examples of this are given in Table 2. The textbook by Kotz and Treichel (1999) defines q as the quantity of energy

transferred as heat but in the end-of-chapter exercises questions such as, 'How much heat is required to heat a 168 g piece of metal from -15.2°C to $+23.6^{\circ}\text{C}$?' is indicative of the style of questions across the textbooks with the possible exception of the textbook by Moore et al. (2002). Their standard questions are worded like this: 'How much thermal energy is required to heat 500 g of Al from 25°C to 250°C ?' This is the only textbook out of the five listed that takes this linguistic care in the wording of exercises to reflect the subtle differences exhibited in the definitions.

Atkins (2003, pp.102-104) clarifies the current understanding of heat and work by defining heat as the "transfer of energy that stimulates random motion of atoms in the surroundings", and, "heat is the transfer of energy as a result of a temperature difference"; while work is defined as "the transfer of energy that stimulates uniform motion of atoms in the surroundings". Heat is not the "energy possessed by anything". Heat and work, then, are ways of transferring energy, not the energy itself. Atkins (2003, p.102) gives a historical perspective here when he says, "The full understanding of heat and work, and how they were manifestations of energy, had to await the development of a molecular understanding of the distinction. As so often in science, with the understanding came the realization that they did not exist; there is no such *thing* as heat, and there is no such *thing* as work!". The problem, of course, is that it is very helpful, indeed useful, to think of heat and work as things or quantities when doing thermodynamic problems. In fact, the dilemma here is between

emphasizing conceptual depth or conceptual usefulness. The clarity of the definition is lost when one focuses on the ‘quantity’ aspect in problem-solving while the usefulness of the concept tends to be lost if one focuses on the ‘depth and clarity’ aspect in the definition.

Table 2. The concepts of heat and work across five textbooks

Text-book	Definition of q	Definition of w	Heat exercise	Work exercise	Radiant energy
Kotz et al. 1999	Quantity of energy transferred as heat	Quantity of energy transferred by work	How much heat is required to heat a 168 g piece of metal from -15.2°C to 23.6°C?	-	Is mentioned as an exception to the rule that all energy transferred must be accounted for as heat and work
Whitten et al. 2000	Amount of heat absorbed by the system	Amount of work done on the system	How much heat is liberated when 0.0662 mole of sodium reacts with excess water?	Calculate the amount of work done in the oxidation of 1 mole of HCl (g) at 200°C.	Radiant energy not mentioned as a means of transferring energy
Moore et al. 2002	Quantity of energy transferred by heating the system	Quantity of energy transferred by doing work on the system	How much thermal energy is required to heat 500 g of Al from 25°C to 250°C?	If a system does 75.4 J of work on its surroundings and simultaneously there is 25.7 cal of heat transfer from the surroundings to the system, what is ΔE for the system?	Is mentioned as an exception to the rule that all energy transferred must be accounted for as heat and work
Spencer et al. 2006	Heat is energy in transit	Raising a weight requires work	The same quantity of heat is added to equal moles of CCl_4 and H_2O . The temperature increases more in CCl_4 than in H_2O . Which has the highest heat capacity?	What happens to the energy of a system when it does work on its surroundings?	Radiant energy not mentioned as a means of transferring energy
Silberberg 2006	Heat (or thermal energy) is the energy transferred between a system and its surroundings as a result of a difference in their temperatures only	Work is energy transferred when an object is moved by a force	A system receives 425 J of heat and delivers 425 J of work to its surroundings. What is ΔE ?	What is ΔE of a system that releases 675 J of thermal energy to its surroundings and has 525 cal of work done on it?	Radiant energy not mentioned as a means of transferring energy

One must sympathize with textbook authors and the observations in Table 2 because it is difficult to be consistent in the use of the language because the ‘quantity’ aspect of heat and work have deep historical and cultural roots which are difficult to leave behind. The very framework of the laws of thermodynamics use heat and work as quantities. For example, when Holton and Brush (2001, p.245) discuss the first law in the form, $\Delta E = H - W$, H is

defined as the “heat added to the body”, and W is defined as the “work done by (the body) on its surroundings”. Strictly speaking, according to current understanding, one should define H as the thermal energy transferred by heat to the body, and W as the mechanical energy transferred by work to the surroundings. But the historical relics of heat and work as quantities are so embedded in our culture that even though one might present the current definitions, when it comes to problem-solving and stating the laws one easily reverts to the old framework.

Textbook authors interpret the current understanding in two ways according to the analysis shown in Table 2. Moore et al. (2002) define q and w as Atkins (2003) has defined them, that is, as the energy transferred by heating and doing work respectively, and follow this up with a fairly consistent usage of the term ‘thermal energy’ instead of ‘amount of heat’ in the set exercises. Others, like Spencer et al. (2006), associate the term ‘heat’ with transfer of energy but use the term ‘heat’ to focus on the amount of energy transferred rather than on the process of transferring the energy. This is evident in the questions shown in Table 2. Spencer et al. (2006) consequently have no use for the term ‘thermal energy’ but simply use terms like ‘amount of heat added’. Some textbook authors like Silberberg (2006) are inconsistent in that the term ‘thermal energy’ is used sometimes and ‘amount of heat’ is used at other times. This is a symptom of what happens as concepts receive a more refined definition. The challenge to chemistry educators is the question of how refined one should be in the use of definitions and the issue of whether qualitative and quantitative problem-solving should take precedence over conceptual clarity and depth. When Atkins (2003, p.104) was introducing readers to the modern interpretation of ‘heat’ and ‘work’, he added this footnote: “I am being pedantic, of course. I should really admit that all nouns – cats, dogs, heat, thermal energy, chemical energy – are but convenient ways of referring to things. But I want to purge and purify your thoughts”.

The current definitions of *heat* and *work* have deep historical and philosophical roots which add great depth to one’s understanding of the concepts. This leads to another dilemma for chemistry educators. While professional groups like IHPST and ISPC rightly advocate more emphasis on conceptual depth than currently happens in our science classrooms by exposing students to more historical and philosophical background, there is a danger that students will get lost in the quagmire of history and philosophy and lose the point of the strength of the concept as a problem-solving tool. Like many education reforms it is again a question of balance. But how to achieve this is a challenge.

Finally, it has been noted that the first law of thermodynamics in the form,

$$\Delta E = q + w,$$

is not always applicable. Domenech et al. (2007, p.56) comment that, “Energy variations may take place, not only through work and heat, but also by means of other processes, such as radiation exchange.....It cannot be forgotten that most of the energy resources available on earth (including fossil fuels) have their origin in solar radiation; neither can it be ignored that gaining a grasp of the greenhouse effect is not possible without reference to exchanges of energy by radiation”. Atkins (2003, p.96) also notes that, “The exception to the universality of the terms kinetic and potential energy is the energy of electromagnetic radiation (for instance, the energy of light, such as that carried from the Sun to the Earth and used to warm us or drive photosynthesis and the production of food). As far as energy stored in matter is

concerned, it is entirely composed of kinetic and potential energy". Two of the five textbooks in Table 2 recognize this fact by noting this exception to the $(q + w)$ contribution to ΔE .

Element

It is the philosophers of chemistry who have been recently drawing our attention to a renewed consideration of what a chemical element is. In a recently published book on the Periodic Table, Eric Scerri (2007) discusses two important ways of thinking about an element; the element as a *basic substance* and the element as a *simple substance*. The chances are that in our own chemistry education we have only been exposed to that view of an element as a simple substance. This view is commonly traced back to the late 18th century to the time of Lavoisier who established the idea that an element cannot be broken down into simpler substances by ordinary chemical means. This view and the one that emerged in 19th century atomic theory that saw an element as consisting of only one type of atom are those expressed in all our General Chemistry textbooks and summarized in Table 3. This is the view of an element as a simple substance.

Table 3. Definition of *element* and comments on elements of Group VII across five General Chemistry textbooks

Textbook	Definition of <i>element</i>	Comments on Group VII elements
Kotz et al. 1999	Substances like hydrogen and oxygen that are composed of only one type of atom are classified as elements.	Elements are quite similar but completely different from elements in other groups. All exist as diatomic molecules and combine violently with alkali metals to form salts.
Whitten et al. 2000	An element is a substance that cannot be decomposed into simpler substances by chemical changes.	Chemical properties of the halogens resemble one another closely but their physical properties differ significantly.
Moore et al. 2002	Substances that cannot be changed by chemical reactions into two or more new substances are called chemical elements (or just elements).	Diatomic molecules and highly reactive and form salts by vigorous reaction with alkali metals and with other metals as well. A picture of the different physical states of Cl_2 , Br_2 , and I_2 is shown but no comment made.
Spencer et al. 2006	Elements are substances that contain only one kind of atom.	All diatomic molecules and react with alkali metals to form ionic compounds or salts.
Silberberg 2006	An element is the simplest type of matter with unique physical and chemical properties. It consists of only one kind of atom and cannot be broken down into a simpler type of matter by any physical or chemical methods.	Regular trends in physical properties such as melting point increasing as one goes down the group. Exist as diatomic molecules that react with most metals and nonmetals to give many ionic and covalent compounds. A picture of the different states of Cl_2 , Br_2 , and I_2 given.

According to Scerri (2007, p.113), the view of an element as a *basic substance* can be traced back to the philosophy of Aristotle where "the elements themselves were to be regarded as abstract even though they gave rise to all the physical variety that is observed. The four elements (fire, earth, water, air) were considered as property bearers, responsible for the tangible features of substances although they were themselves unobservable. The elements were immaterial qualities impressed on an otherwise undifferentiated primordial matter and were present in all substances".

With the development of atomic theory at the beginning of the 19th century and with the expansion of the number of substances that appeared to be elements from the simple substance point of view, chemists were left with the question of what happens to the elements when they react to form a compound. Common salt, for example, neither contains the shiny metal element, sodium, nor the noxious yellow-green gas, chlorine, but mass was conserved when sodium reacted with chlorine to produce common salt. There was a sense (on the basis of mass) in which the elements remained and a sense (on the basis of physical properties) in which the elements disappeared. From the early 19th century this dual view of an element was established in order to explain this phenomenon. The dual view was that of an element as a *simple substance* and, drawing upon Aristotelian views, that of an element as a *basic substance*.

Simple substances did not survive in a compound but abstract elements did survive. The 19th century view of an abstract element differed from that of Aristotle in that an abstract element has a material ingredient as opposed to an immaterial ingredient due to the fact of the law of conservation of mass in chemical change discovered by Lavoisier. Scerri (2007, p.114) concludes that, "There are thus three important concepts regarding elements carried over into the 19th century: abstract element as property bearer owing its heritage to Aristotle; indestructible material ingredient of substances behaving according to Lavoisier's law of the conservation of matter; abstract element as unobservable whereas simple substances can be observed. In contemporary chemistry only the notion of simple substance has been retained in the concept of element". This latter conclusion is confirmed by the data in Table 3.

Mendeleev (1891, p.23) had this dual view of an element as evidenced by the following statement. "It is useful in this sense to make a clear distinction between the conception of an element as a separate homogeneous substance, and as a material but invisible part of a compound. Mercury oxide does not contain two simple bodies, a gas and a metal, but two elements, mercury and oxygen, which, when free, are a gas and a metal. Neither mercury as a metal nor oxygen as a gas is contained in mercury oxide; it only contains the substance of the elements, just as steam only contains the substance of ice, but not ice itself, or as corn contains the substance of the seed but not the seed itself". Scerri (2007, p.115) observes that this is probably the reason for Mendeleev's preoccupation with atomic weight in relation to the Periodic Table. "Mendeleev's genius now lay in recognizing that just as it was the 'basic element' that survived intact in the course of compound formation, so atomic weight was the only quantity that survived in terms of measureable attributes".

Can we expect chemistry educators to hone the definition of *element* to this level of precision particularly since it is not a topic of study in current textbooks? Scerri (2007, p.16) answers this question in the affirmative by giving the following example. "If a novice chemist were asked to group the halogen elements according to their appearances, it is inconceivable that he or she would consider classifying together fluorine, chlorine, bromine, and iodine. This is one instance where the subtle distinction between the observable and the abstract sense of the concept of element can be helpful. The similarity between them lies primarily in the nature of the abstract elements and not the elements as substances that can be isolated and observed". In Table 3, textbook authors draw attention to the similar chemical properties over and above the physical properties of the halogens and, in some cases, while showing the different physical states of the elements, do not present the difficulty either with respect to classification or with respect to the question of the sense in which elements are retained in compound formation.

The Mole Concept

The mole concept is central to understanding stoichiometric relationships in chemistry and is primarily a useful tool in determining amounts of reactants and products involved in chemical reactions. It is the means by which the number of entities involved in a chemical process can be obtained by weighing the appropriate amount of matter. All definitions shown in Table 4 focus on the *number* of entities involved and it is this emphasis on *number* which makes it such a useful concept in chemical calculations. However, that part of the definition that refers to *amount of substance* is not that commonly referred to because it is not explored to any depth in normal quantitative calculations. The amount of matter in 1 mol of Mg is not the same as the amount of matter in 1 mol of Zn, although they contain the same number of atoms, and this fact is usually not the focus of a calculation. *Number of moles* rather than *amount of substance* is the focus of the exercises shown in Table 4.

Table 4. Definitions of ‘mole’ and ‘mass’ across five General Chemistry textbooks

Textbook	Mole Definition	Mass Definition	Nature of Exercises
Kotz et al. 1999	The mole is the amount of substance that contains as many elementary entities (atoms, molecules, or other particles) as there are atoms in exactly 12 g of the carbon-12 isotope.	The mass of a body is the fundamental measure of the amount of matter in that body.	Calculate the number of moles represented by 0.876 g of arsenic.
Whitten et al. 2000	The mole is the amount of substance that contains as many entities (atoms, molecules, or other particles) as there are atoms in exactly 0.012 kg of the carbon-12 isotope.	Mass is the measure of the quantity of matter a body contains.	How many moles of substance are contained in 15.6 g of calcium carbonate?
Moore et al. 2002	The mole is the amount of substance that contains as many atoms, molecules, ions, or other nanoscale units as there are atoms in exactly 12 g of carbon-12.	The mass of an object is a fundamental measure of the quantity of matter in that object.	Calculate the number of moles represented by 0.0034 g of platinum.
Spencer et al. 2006	A mole of any substance contains the same number of particles as the number of atoms in exactly 12 g of the ^{12}C isotope of carbon.	-	Calculate the number of moles of NO_2 that could be prepared from 0.35 mol of NO and 0.25 mol of oxygen.
Silberberg 2006	The mole is the amount of substance that contains the same number of entities as there are atoms in exactly 12 g of the carbon-12.	The mass of an object refers to the quantity of matter it contains.	How many moles of CaO can be produced from 4.2 g Ca and 2.8 g O_2 ?

This might appear to be a rather pedantic point, but, is something of the concept of *amount of substance* lost if one focuses on the number of units of amount (number of moles) rather than on the concept of amount itself? An analogous situation arises when one asks for the number of grams of a substance rather than its mass. Consider one of the exercises given in Table 4: “Calculate the number of moles represented by 0.876 g of arsenic”. To focus on what moles is a measure of, one could rephrase this question as: “Determine the amount of arsenic in 0.876 g of arsenic”. One, of course, has to be clear here that *amount* is measured in units *mol*. While it is true that the majority of stoichiometric exercises in General Chemistry textbooks could be solved without insisting on this level of conceptual clarity, it is worthwhile pondering how one might answer the following question related to the concept, *amount of substance* in Figure 2.

Question: Are the following statements true or false? Give an explanation for your response.

1. The amount of matter in 1 mol Mg is less than in 1 mol Zn.
2. The number of atoms in 1 mol Mg is the same as in 1 mol Zn.
3. The number of atoms in 1 mol CO₂ is the same as in 1 mol C₃H₈.
4. The amount of matter in 1 mol CO₂ is the same as in 1 mol C₃H₈.
5. The amount of matter in 0.5 mol O₂ is less than in 1 mol CH₄.

Figure 2. A question relating to the concept, amount of substance.

All the textbooks in Table 4 that define *mass* use the idea of the fundamental measure of *amount* or *quantity of matter* and this idea is reflected in the formal definition of the mole when referring to the amount of carbon-12 as 12 g or 0.012 kg. So the *amount of a substance* that has the same number of separate entities as that in 0.012 kg of carbon-12 is referring in a fundamental sense to the mass of the substance. But this is a special mass that has the same number of separate entities as that contained in 12 g of carbon-12 and is given therefore the special name, *amount of substance*, with the unit, *mol*. It was in this context that Hudson (1981) questioned the definition of mole as ‘the chemists’ dozen’, commonly used by secondary school chemistry textbooks of the 1970’s and 1980’s (de Berg 1986). Such a definition identified the mole with Avogadro’s number of particles rather than with the amount of substance contained in Avogadro’s number of particles. While it is true, as Hudson (1981) observes, that the use of the concept can precede its understanding, it does not necessarily follow that exercises involving the various calculations with a complex concept such as the mole can provide an understanding of it. This is a dilemma we all face in chemistry education.

The Uncertainty Principle

Peter Atkins (2003, p.201) commences his chapter on “Quanta” by quoting from Richard Feynman as follows. “If anyone claims to know what the quantum theory is all about, they haven’t understood it”. Jim Baggot (1992, pp.(ix)-(x)) assesses quantum theory as “unnerving. Not only is the theory mathematically complex, it is also conceptually challenging.....Students are taught about a theory which they have to accept and which they have to learn how to apply, but for which they cannot expect to be told its meaning....Most undergraduate courses on quantum theory never touch on the theory’s profound conceptual problems. This is because the theory brings us right back to some of the central questions of *philosophy* and, as we know, there is no room for philosophy in a modern science degree. I find this an absurd situation”. Baggot touches here on the central issue of this paper: the challenge for chemistry educators to meet the demands for conceptual depth and meaning as well as the demand to demonstrate a concept’s usefulness in calculation.

The Heisenberg Uncertainty Principle (HUP) is intimately connected to the particle-wave properties of the electron and so both these ideas appear in the textbook analysis in Table 5. Recent textbook authors like those appearing in Table 5 do a fairly stirring job of what even the experts agree is a complex topic. Three of the five textbooks not only state the HUP but

give an explanation of it. In order to locate the position of an electron, radiation of a very small wavelength is required because of the very small size of the electron. All textbooks in Table 5 except one introduce the wave-particle properties of radiation in the form of de Broglie's, $\lambda=h/mv$, which illustrates that radiation of very small wavelength (λ) possesses photons (particles of light) of very high momentum (mv) and energy and this is imparted to the electron when the radiation is used to locate its position. Therefore, when locating the electron, its speed cannot be accurately determined because in the process of measurement momentum is imparted to it. Conversely, if one increases the wavelength in order to reduce the momentum imparted to the electron, one loses track of its position since a very small wavelength is required to track it. The textbook by Moore et al. (2002) uses an analogy of a high speed and low speed shutter to track a racing car; the high speed shutter giving a reasonably clear picture of the car and the low speed shutter giving a blurred picture. One must, of course, be aware of the limitations of such an analogy because the HUP, while applying to all objects, becomes recognizable only in the world of atomic dimensions. So, in our macroscopic world, the process of measurement does not impart sufficient momentum to the observed object to lead to a blurring of its position or momentum so both can be measured simultaneously.

Table 5. The Heisenberg Uncertainty Principle (HUP) across five General Chemistry textbooks

Textbook	Explanation for HUP	Wave-particle Relationship
Kotz et al. 1999	HUP is stated qualitatively and mathematically but no explanation given	Evidence is given: Photoelectric effect and the Davisson and Germer experiment - de Broglie's $\lambda=h/mv$ given
Whitten et al. 2000	HUP stated qualitatively-no mathematical statement-is a short explanation	Davisson and Germer experiment - de Broglie's $\lambda=h/mv$ given
Moore et al. 2002	HUP stated qualitatively- no mathematical statement – a fairly detailed explanation given – a photographic analogy given	Davisson and Germer experiment - de Broglie's $\lambda=h/mv$ given
Spencer et al. 2006	HUP stated qualitatively-no mathematical statement-is a very short explanation	Discusses properties of waves and particles –de Broglie's $\lambda=h/mv$ not given
Silberberg, 2006	HUP is stated qualitatively and mathematically but no explanation given	Davisson and Germer experiment - de Broglie's $\lambda=h/mv$ given

The textbook by Silberberg (2006) does give a hint of some of the philosophical dimensions of this topic by way of a short historical note to the effect that some scientists of the early 20th century regarded uncertainty as unacceptable in science. The argument went that because an accurate value of the momentum of a localized particle cannot be defined by measurement, it has no place in the theory. Feynman (1963, pp.38-8, 38-9), reflecting on this question, commented that, "Just because we cannot measure position and momentum precisely does not *a priori* mean that we cannot talk about them. It only means that we need not talk about them. The situation in the sciences is this: A concept or an idea which cannot be measured or cannot be referred directly to experiment may or may not be useful.....It is not true that we can pursue science completely by using only those concepts which are directly subject to experiment".

Another philosophical argument revolves around the interpretation of the HUP. According to Baggott (1992, p.33) Heisenberg and Bohr had a different understanding of the implications of the Uncertainty Principle (UP). To Heisenberg the UP taught that there are

limits on what is measureable. The concepts of locality and momentum as far as the electron is concerned are legitimate concepts but they cannot be measured simultaneously. Bohr argued that it might be meaningless to talk about an electron's position and momentum since these are classical concepts. They only become of interest when we attempt to measure them. Baggott (1992, p.33) summarises Bohr's position as follows. "For him (Bohr) it was wave-particle duality that lay at the heart of quantum mechanics. All the rest – including the UP – were the physical and mathematical consequences of using two diametrically opposed classical concepts, waves and particles, to describe something that was fundamentally non-classical. According to Bohr, quantum theory tells us not what is measureable, but what is knowable". Fritz Rohrlich (1987, p.143) has a similar view of the implications of the wave-particle idea. "The classical physicist was confronted with the puzzle, 'how can an electron be both a particle and a wave?' With this question he had in mind the classical notions of particle and wave. The Quantum-Mechanical answer is: 'The electron is neither; it is neither a classical particle nor a classical wave. It is a quantum particle and as such it has some properties that resemble certain classical particle properties and others that resemble those of a classical wave'".

To those of us involved in the teaching of chemistry at the tertiary level there is a real dilemma here. Yes, there are important historical and philosophical issues present in this topic. But a discussion of such topics only makes sense if students are also familiar with using the concepts and much time is required for getting to this stage. Peter Atkins (2003, p.225) reaches a stage in his discussion of quanta that illustrates the dilemma we face. "Quantum Mechanics gets philosophically interesting when we start to ask what it all means. That's the subject of the rest of this chapter. If you stop here, you will know the main principles of quantum mechanics and, in principle, can use it to do any calculation; if you go on, your ability to use it won't be helped, but you will know why people find it so deeply puzzling".

Conclusion

Chemistry educators as a professional group recognize the importance of teaching for understanding rather than just the skill of calculation with a set of algorithmic procedures. The IHPST and ISPC groups are all about assisting teachers in this quest by providing historical and philosophical analyses of the concepts we have to teach and learn. However, we have made very little progress in incorporating historical and philosophical elements for understanding in our curricula although some brave attempts are being made. Wandersee and Griffard (2002, p.31) note this deficiency but encourage us to be courageous in this matter. "Much of the research that has been peer-reviewed and published is prescriptive of approach, rather than being descriptive of implementation and bulwarked by evidence of effectiveness. We may be currently limited by this imbalance, but we hope that chemists and chemical educators will increasingly document their experiences in publication form".

There are a number of difficulties we face in teaching for understanding, for conceptual depth and meaning. The first difficulty is that most of us have never experienced this type of education ourselves. Most of the curricula we have studied have been loaded with information and standard exercises to be learned for a final examination. Consequently, we have naturally tended to perpetuate our own experience with our students. Wandersee and Griffard (2002, p.33) believe that this "rush to abstraction and the final form science.....evident in chemical

education today actually short-circuits deep understanding by cutting off all human and epistemological contexts...We think rigour is comprised less of breadth than it is of depth and that both take much more time to develop than current chemistry curricula allow”.

A second difficulty lies with the complex nature of historical and philosophical study. Students generally have enough difficulty handling the skills associated with calculation and problem-solving without having to deal with questions of historical and philosophical significance. IHPST and ISPC are making courageous efforts to help teachers and students in this regard and such efforts are to be encouraged and applauded. The fact that an international effort is being made to solve this problem augers well for the future.

A third difficulty is associated with the nature of the historical and philosophical elements that should be included in a chemistry course. Our accreditors rightly insist that we are responsible for teaching chemistry, not history and philosophy of science, which means that we must choose elements that *enhance* an understanding of the chemistry topics at hand and not elements that, although important, do not address the content being studied.

A fourth difficulty is related to how to find space in a content-rich curriculum for issues of historical and philosophical relevance. It is agreed that less breadth and more depth is required. The challenge is how to accomplish this.

My own initial response to these difficulties was to write a series of historical/philosophical case studies drawn from my own research and that of others and to use these as part of the assignment load each semester of my chemistry course. The idea was to use one of these case studies each semester so there was no great impingement on the course content covered. The case study would particularly relate to a chemistry topic for that semester. This approach met with mixed success. I overestimated the students' capacity to link historical ideas with the current ideas even though I tried to make these explicit. Using genuine historical data proved a stumbling block because of the units used for quantities like pressure and volume for example. The data had to be reworked for student use. This is currently an ongoing project. My immediate revised response has been to be more modest in my attempts and to include an extra question or exercise on a tutorial sheet and a laboratory report that impinges on the topic but which attempts to deepen a student's understanding of the topic. This extra question or exercise often depends for its content on historical/philosophical data. On some occasions a decision has been made to reduce the breadth of topics or laboratory exercises to allow time for more reflection. A sample exercise, pertinent to the concepts discussed in this paper, is shown in Figure 3. Ultimately one has to move beyond the evidence of personal experience as far as demonstrating the effectiveness or ineffectiveness of including historical/philosophical elements in chemistry teaching is concerned to a more encompassing research agenda, but at least it is a starting point. It is not clear at the moment what the nature of such a research agenda might be and this remains a major challenge to chemistry education researchers.

In Australia, as elsewhere, there has been great debate about the nature of the modern university and the political pressures put by government to enhance the role of the modern university in a nation's economic progress. Professor Alan Gilbert (2003), Vice Chancellor of the University of Melbourne at the time, in response to such pressures on the university of the 21st century asked, “But what of the other enduring characteristics of universities: the valuing of knowledge and inquiry for their own sake, and the civilizing mission of sustaining well-founded civil societies? When, arguably, the world needs powerful civilizing institutions more than ever, universities seem to be losing the capacity and even the will, to tackle the

great philosophical and moral questions through which humankind seeks meaning and guidance, and through which humane, sustaining civil societies are built". Though the task of enhancing the soul of chemistry education, the depth of meaning, and clarity of understanding is a stupendous one as we have outlined, it is ultimately, as Alan Gilbert infers above, a deeply civilizing one.

Identify what you think is wrong or incomplete about these statements and rewrite the statement in a way you think corrects the errors or incompleteness.

1. When 50 J of heat is added to the system, the internal energy rises by 50 J.
2. When 20 J of work is done by the system, the internal energy falls by 20 J.
3. Common salt contains sodium and chlorine.
4. 6×10^{23} molecules of O_2 is one mole of O_2 .
5. An electron is both a wave and a particle.

Figure 3. A sample exercise designed to assist understanding of concepts.

References

- Atkins, P. (2003). *Galileo's Finger-The Ten Great Ideas of Science*. Oxford: Oxford University Press.
- Baggott, J. (1992). *The Meaning of Quantum Theory*. Oxford: Oxford University Press.
- Bodner, G.M. & Herron, J.D. (2002). Problem-Solving in Chemistry. In Gilbert, J.K., De Jong, O., Justi, R., Treagust, D.F., & Van Driel, J.H. (Eds.). *Chemical Education: Towards Research-based Practice* (pp.235-266). Dordrecht: Kluwer Academic Press.
- de Berg, K.C. (1986). Textbook Analysis of the Mole and Its Underlying Concepts: A Teaching-Learning Perspective. *The Australian Science Teachers Journal* **31**(4), pp.33-43.
- de Berg, K.C. (1989). The Emergence of Quantification in the Pressure-Volume Relationship for gases: A Textbook Analysis. *Science Education* **73**, pp.115-134.
- de Berg, K.C. (1997). The Development of the Concept of Work: A Case where History can inform Pedagogy. *Science & Education* **6**, pp.511-527.
- de Berg, K.C. (2006). Chemistry and the Pendulum – What have they to do with each other? *Science & Education* **15**, pp.619-641.
- Domenach, J.L., Gil-Perez, D., Gras-Marti, A., Guisasola, J., Martinez-Torregrosa, J., Salinas, J., Trumper, R., Valdes, P., & Vilches, A. (2007). Teaching of Energy Issues: A Debate Proposal for a Global Reorientation. *Science & Education* **16**(1), pp.43-64.
- Erduran, S., & Scerri, E. (2002). The Nature of Chemical Knowledge and Chemical Education. In Gilbert, J.K., De Jong, O., Justi, R., Treagust, D.F., & Van Driel, J.H. (Eds.). *Chemical Education: Towards Research-based Practice* (pp.7-27). Dordrecht: Kluwer Academic Press.
- Feynman, R.P., Leighton, R.B., & Sands, M. (1963). *The Feynman Lectures on Physics*. Reading, Massachusetts: Addison-Wesley.

- Gabel, D.L., Sherwood, R.D., & Enochs, L. (1984). Problem-Solving Skills of High School Chemistry Students. *Journal of Research in Science Teaching* **21**, pp.221- 233.
- Gilbert, A. (2003). Barbarians at the Gate. In *The Australian Higher Education Section*, October 15, p.29.
- Holton, G., & Brush, S.G. (2001). *Physics, the Human Adventure*. New Brunswick: Rutgers University Press.
- Hudson, M.J. (1981). A Tested Approach for Introducing the Mole. *Source Book for Chemistry Teachers*. Sixth International Conference on Chemical Education, p.113.
- Kotz, J.C., & Treichel, P. (1999). *Chemistry and Chemical Reactivity* (4th ed.). Fort Worth: Saunders.
- Mendeleev, D.I. (1891). *The Principles of Chemistry* (5th Russian ed.)(Vol.1)(1st English Trans. by G. Kemensky). New York: Collier.
- Moore, J.W., Stanitski, C.L., & Jurs, P.C. (2002). *Chemistry – The Molecular Science*. Fort Worth: Harcourt.
- Reif, F. (1983). How can Chemists Teach Problem-Solving? *Journal of Chemical Education* **60**, pp.948-953.
- Rohrlich, F. (1987). *From Paradox to Reality*. Cambridge: Cambridge University Press.
- Scerri, E.R. (1997). Are Chemistry and Philosophy miscible? *Chemical Intelligencer* **3**, pp.44-46.
- Scerri, E.R. (2007). *The Periodic Table – Its Story and its Significance*. Oxford: Oxford University Press.
- Silberberg, M.S. (2006). *Chemistry – The Molecular Nature of Matter and Change* (4th ed.). Boston: McGraw Hill.
- Solomon, J. (1992). *Getting to know about ENERGY in School and Society*. London: The Falmer Press.
- Spencer, J.N., Bodner, G.M., & Rickard, L.H. (2006). *Chemistry – Structure and Dynamics* (3rd ed.). New Jersey: John Wiley & Sons.
- Stenhouse, D. (1985). *Active Philosophy in Education and Science*. London: Allen & Unwin.
- Wandersee, J.H. & Griffard, P.B. (2002). The History of Chemistry – Potential and Actual Contributions to Chemical Education. In Gilbert, J.K., De Jong, O., Justi, R., Treagust, D.F., & Van Driel, J.H. (Eds.). *Chemical Education: Towards Research-based Practice*(pp.29-46). Dordrecht: Kluwer Academic Press.
- Whitten, K.W., Davis, R.E., & Peck, M.L. (2000). *General Chemistry with Qualitative Analysis* (6th ed.). Fort Worth: Saunders.
- Winchester, I. (1989). Editorial – History, Science, and Science Teaching. *Interchange* **20**(2), p.(i).