

**CHEMICAL EDUCATION: THE HEART OF THE CENTRAL SCIENCE**

**INAUGURAL LECTURE**

**PRESENTED BY**

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# Chemical Education: the Heart of the Central Science

## 1. Introduction

Allow me to express my appreciation to North-West University for giving me this opportunity to share my work and my passion with you. I embarked on a study of chemistry about 40 years ago, at a time when it was not a very popular field for girls. My journey took me from analytical chemistry, to teaching almost every branch of chemistry over the years, to many years of research into aspects of chemical education. This lecture therefore examines the nature of chemistry and chemical education, as well as my role in it.

### 1.1 Chemistry the central science

Chemistry is often called **the central science** because of its role in connecting the physical sciences, which include chemistry, with the life sciences and applied sciences such as medicine and engineering, as well as earth sciences. The phrase was popularized by Brown and LeMay, in their textbook titled *Chemistry: The Central Science*, which was first published in 1977, and expanded to seven authors and a fourteenth edition published in 2018 (Brown *et al*, 2018).

Balaban and Klein (2006) proposed a diagram (See Figure 1) showing partial ordering of sciences in which chemistry may be argued is “the central science” since this is where a significant degree of branching occurs, connecting the different sciences to each other.

Chemistry is built on mathematics, and the laws of physics that govern particles such as protons, electrons, neutrons, atoms, ions and molecules. Biology describes how these molecules and other particles combine to form living organisms (Livesay, 2007). Chemistry is fundamental to biology since it provides a methodology for studying and understanding the molecules that compose all plants and animals. I am not saying that chemistry describes everything. For instance, evolution may be described in terms of chemistry by describing mutations in the order of genetic base pairs in the DNA of an organism. However, chemistry cannot fully describe the process since concepts such as natural selection that are responsible for driving evolution are not part of chemistry (Balaban and Klein, 2006).

Chemistry and physics are both needed in the areas of physical chemistry, nuclear chemistry, and theoretical chemistry. Chemistry and biology are both involved in the areas of biochemistry, medicinal chemistry, molecular biology, chemical biology, molecular genetics, and immunochemistry. Chemistry and the earth sciences intersect in areas like geochemistry and hydrology.

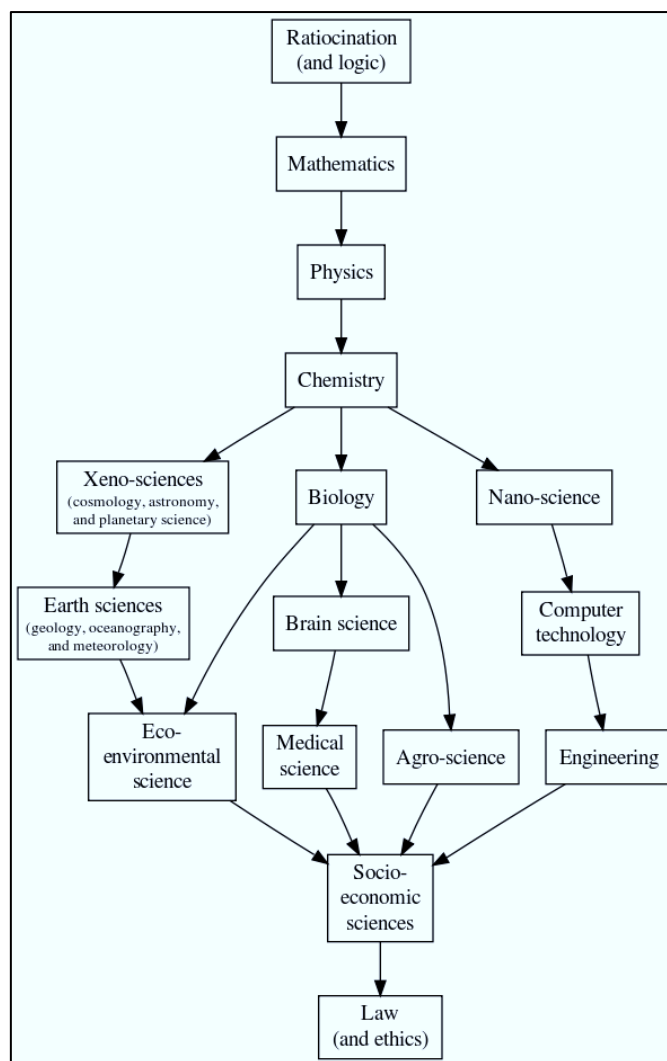


Figure 1: The “framework” partial ordering of the sciences (Source: Balaban and Klein, 2006).

## 1.2 Chemical Education – the heart of chemistry

The centre (or heart) of this central science is education – passing it on to the next generation. Without Education, the body of knowledge known to modern science would die with its researchers, and there would be no one to continue and build on their work.

When we talk about the centre of a person, we normally talk about the Heart. Not only is the heart in the middle, but it is also used as the organ from which human feelings and emotions emanate. Education puts the heart into Chemistry.

The most important document used by chemists is the Periodic Table of the elements – but the most important element in the world is the human element. In no other branch of chemistry is the human element as central as in chemical education.

## **2. Need for Research in Chemical Education**

### **2.1 Importance of science and chemistry**

Science is the engine of prosperity. Economists will tell you how much growth depends on scientific research (DiChristina, 2014). In the first introductory lecture on chemistry, this is usually pointed out to the students. The cars that got us here today, our smart phones, the electricity that lights this room, all the metal, glass or plastic objects we use, the clothes we wear, the food we eat: All of these were developed and improved through research in science, and particularly chemistry.

### **2.2 Importance of education**

One of the most important drivers of economic advancement is education. A country cannot advance in this technological age without an educated populace. It is of vital importance that we produce chemists, both men and women. Because it is Women's Month, let me mention gender briefly. At NWU on the Mafikeng Campus we have very nearly equal numbers of male and female undergraduate students in the Faculty of Natural and Agricultural Sciences, both in BSc and Agriculture programmes (277 female, 281 male in 2017). At least in this regard we are on the right track.

Studies have shown that gender inequality in education undermines economic growth directly by failing to harness expertise and lowering average human capital and indirectly through its impact on investment and population growth. (Klasen, 2002; Klasen and Lamanna, 2009). Promoting gender equity in education may be among the few "win-win" development strategies. "It advances economic prosperity, lowers mortality and fertility and is intrinsically valuable as well" (Klasen, 2002, p.370).

## **3. State of Chemical Education**

### **3.1 Poor performance of students in South Africa**

Much has been written about the poor performance of South African students in science and mathematics. As an indicator of this, Trends in International Mathematics and Science Study (TIMSS) was first administered in South Africa in 1995 and from then on every four years, in 1999, 2003, 2011 and 2015. The Human Sciences Research Council (HSRC) analysed South African performance, in TIMSS 2015 at the Grade 9 level, relative to other countries, and examined the trends in mathematics and science achievement from 2003 to 2015. These results are important to track educational progress and the health of the education sector and to identify interventions that need to be put in place to ensure improvements (Zuze et al, 2017).

The top five ranked countries were from East Asia. The five lowest performing countries were Botswana, Jordan, Morocco, South Africa and Saudi Arabia - countries from Africa and the Middle East.

While South Africa continued to perform at the lower end of the rank order, its score improved from TIMSS 2011 to TIMSS 2015 by 20 points for mathematics and 26 points for science. From 2003 to 2015 South Africa improved by 87 points for mathematics and 90 points for science, an

improvement of about two grade levels. Of the 25 countries who participated in both TIMSS 2003 and 2015, South Africa showed the biggest improvement (Zuze et al, 2017).

This shows that educational change is possible, but the pace of change must be accelerated if we are to have the requisite skills and capacities to meet the societal and economic needs of the future.

### **3.2 The need to improve chemistry teaching and learning**

Much has been written on the need to improve chemistry teaching and learning, and innovative ways of teaching chemistry have been suggested. Many researchers have come up with ideas to improve chemistry teaching. Some have suggested that chemistry should be made more attractive to students, there have been many curriculum changes, and the mode of presentation has changed.

There has been great concern about curriculum development in science over a long period of time. Two aims of science education since the 1960s have been the creation of a scientifically-based work force and a scientifically literate citizenry (Fensham, 1988). Chemistry can be made more attractive to students both by changing the curriculum and by changing the manner of teaching and learning (Eilks, 2005). Some innovations try to make the content more interesting by rearranging it. Curriculum development has many aspects: changes in subject content; changes in the way in which subject content is taught and learned (e.g. by introducing modules on food, energy etc). Instead of teaching organic chemistry, teach food chemistry. Teach modules on the use of alternative fuels or drug synthesis. The Salters Chemistry Course is a notable example of this (Salters Advanced Chemistry, 2018).

Another suggestion is that chemistry should be taught through practical work. Practical work is a vital part of any chemistry course. However, a study by Abrahams and Millar (2008) showed that practical work was generally effective in getting students to do what is intended with physical objects, but much less effective in getting them to understand and use the intended scientific ideas.

It has been suggested that chemistry should be taught in context, and by different teaching methods. It should be linked to indigenous knowledge. A context-based approach to chemistry education may help to develop a sense of wonder and curiosity of young people about the natural world (Ültay and Çalık, 2012).

Many innovations focus on using different media and changes in the medium of presentation (e.g. by using films, computers, games etc).

Gabel (1999) imagined how chemistry would be taught in the 21<sup>st</sup> century. She wrote “As information grows, ... this will require an increased use of technology. With students immersed in virtual reality, the richness of the immersion may produce more efficient learning, creating another rich area for research. We have already seen the positive effects of using technology in teaching” (Gabel, 1999, p.553).

Now that technology is available, we should incorporate it in our teaching and learning. We cannot afford to be left behind by technology, and to send students into the world of work unequipped to face the demands of the 21<sup>st</sup> century.

We know that students of today are much more comfortable using smart phones or laptops than pen and paper, even at a very young age.

At present some of the buzz words in teaching and learning are flipped classroom and blended learning.

- **Flipped classroom** is a model in which direct instruction takes place in the environment usually reserved for “homework” while time in class is used for active problem solving in one-to-one or small group interaction with the teacher (Bergmann and Sams, 2012). For example, students may download a video that goes through the key points of a coming lecture beforehand, to mentally prepare them. Ideally, with the use of efficient and effective digital learning tools, students become more engaged in the classroom (Brown, 2018).
- **Blended learning** is an education program that combines online digital media with traditional classroom methods. It requires the physical presence of both teacher and student, with some elements of student control over time, place, path, or pace. While students still attend face-to-face sessions, these are combined with computer activities (Friesen, 2012; Strauss, 2012; McGee and Reis, 2012; El-Mowafy, Kuhn and Snow, 2013).

There is a push in this university to go for more online and distance learning. It is true that students are comfortable with computers and technology. However, the teacher is still needed to guide their learning. After the recent disruptions in 2016, many universities in South Africa, including our own, devised coping strategies, by putting material on eFundi, for example. However, a study at the University of Pretoria (Potgieter, 2018) showed that students, particularly the most at-risk students, struggled to pace their learning. One lecturer said “I am the metronome in my module - I set the pace of learning.”

### 3.3 The complex nature of chemistry

Chemical knowledge and understanding of our world is generated, expressed, taught, and communicated at three different “levels”, traditionally called the macroscopic, the submicroscopic, and the symbolic levels (Johnstone, 1982, 1991). The triplet relationship, as it has been called by Gilbert and Treagust (2009), has served as a framework for many research studies in the field and guided the work of chemistry instructors, curriculum and software developers, and textbook writers across the world (see Figure 2).

Macrochemistry, or the macro level, refers to the entities and phenomena that we can see and touch, submicrochemistry refers to the particulate models of matter, and the representational level, also referred to as the symbolic level, encompasses both chemical and mathematical signs and their relationships (i.e. equations). Students need to understand phenomena on all these different levels.

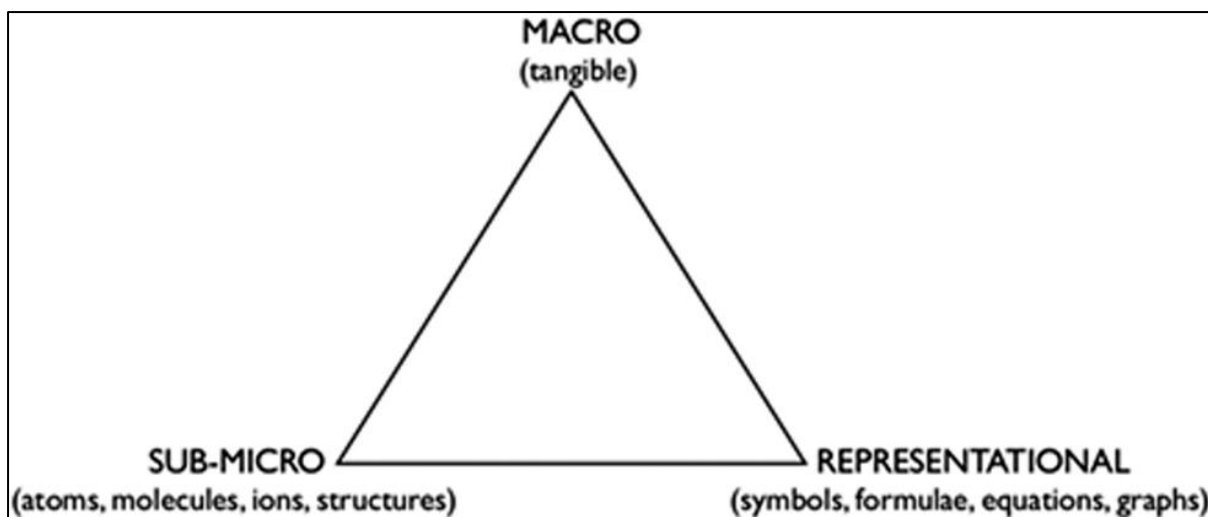


Figure 2: The chemistry triplet (Source: Johnstone, 1982, 1991)

Understanding of concepts is extremely important in chemistry, and is rightly the focus of most teaching. Much has been written on misconceptions, often euphemistically called “alternative conceptions” and various other names (Taber, 2002; Talanquer, 2006). Strategies such as revising topics from lower grades before teaching more advanced topics has been shown to reduce misconceptions (Molaakgosi, 2017; Molaakgosi and Drummond, 2018).

#### 4. Teaching and Learning of Skills

Although concepts are important, if students don't learn the skills needed, they will never master chemistry. So I favour a skills based approach to teaching chemistry.

##### 4.1 Goals of education

It is important to teach students how to learn. “Helping students to handle ... their own thinking processes is a major goal of our educational system that will only increase in importance in the future” (Weinstein and Mayer, 1986, p.315). Two types of goals of instruction can be specified:

- (a) goals concerning the products of learning, which focus on what students should know or be able to do as a result of learning, or “teaching what to learn”,
- (b) goals concerning the processes of learning, which focus on techniques and strategies students can use to accomplish learning, or “teaching how to learn”.

Goals of education should be formulated concerning subject content and also intellectual skills, processes and strategies. Five general goals are listed by Marzano *et al* (1988, p.130). Students should:

- (a) attain high levels of knowledge in the subject area;
- (b) have cognitive and metacognitive skills and strategies that they can call on as they engage in various cognitive processes;

- (c) be able to use these skills and strategies with increasing independence and take responsibility for their own learning;
- (d) be aware of the nature of thinking and be able to control their attitudes, dispositions and development;
- (e) have standards for evaluating what is “good” thinking and be able to think critically and creatively.

Many researchers believe that intellectual skills cannot and should not be taught apart from content because content is inseparably linked with cognition (Glaser, 1985; Marzano *et al*, 1988). Skills may be impossible if students do not have enough prior knowledge, and understand the “language of chemistry” (Ver Beek and Louters, 1991). There is “no such thing as expertness without extensive and accessible knowledge” (Simon, 1980, p.82). Although transfer of skills is possible from one area to another, it is more efficient to teach skills in the specific situation in which they are needed (Glaser, 1984; Drummond, 2003, Drummond and Selvaratnam, 2009). According to Glaser (1984), the task is to produce “an environment in which there is a new relationship between students and their subject matter, in which knowledge and skill become objects of interrogation, inquiry, and extrapolation. As individuals acquire knowledge, they also should be empowered to think and reason” (Glaser, 1984, p.103).

## **5. My Philosophy of Chemistry Teaching**

According to my teaching philosophy, chemistry teaching should take a guided approach. Content must be taught in a logical progression, along with skills and strategies, which should be taught by their component steps. Thus my motto in chemistry teaching is “Focus on the goal, and proceed step by step.”

### **5.1 Hypothesis:**

- All skills are teachable.
- Skills (e.g. representation of knowledge, mathematical skills) can be broken down into their component steps, and strategies (e.g. problem solving) into their component skills, each of which can be taught. They can then be put together.
- Note that each step should not be mindless, but must be thoroughly understood, otherwise the overall skill or strategy will not be mastered.

## **6. Skills Needed in Learning Chemistry**

An analysis of the textbooks and the syllabus reveals that a large number of skills and strategies are needed to learn and apply matric chemistry effectively (Drummond, 2003). These include the ability to:

- (1) classify concepts according to important criteria
- (2) arrange items in a logical order
- (3) represent information as figures, graphs and tables
- (4) extract information from tables and graphs
- (5) extract information from equations



- (6) assign explicit symbols to data
- (7) visualize the particles present in matter and their properties to explain phenomena
- (8) select relevant information from many pieces of information
- (9) recognise the conditions under which laws and principles are valid
- (10) make logical deductions from facts and principles
- (11) use inductive reasoning to generalise from particular data
- (12) focus on the goal and select appropriate information for problem solving
- (13) express statements as equations
- (14) obtain information from balanced equations
- (15) give correct relationships between variables
- (16) recognise quantities which remain constant
- (17) derive equations
- (18) rearrange and combine equations
- (19) substitute numbers for symbols in equations
- (20) use self-consistent units when performing calculations
- (21) manipulate exponential numbers
- (22) perform calculations
- (23) perform operations in a logical order
- (24) check whether answers are reasonable
- (25) visualise three-dimensionally.

## **7. Competence in Skills**

Studies have been undertaken to test students' competence in a wide range of skills (Tuckey, 1989; Drummond, 2003, Drummond and Selvaratnam, 2008, 2009, Jele, Drummond and Selvaratnam, 2015). The skills tested include

- language skills, mathematical skills, graphical skills, three-dimensional visualization skills, information processing skills and reasoning skills.

The studies showed that the competence of most students in intellectual skills is poor. This lack of competence could be expected to lead to negative attitudes and a lack of self-confidence that would seriously handicap their learning, and may also be an important reason for the observed high failure rate of students in science courses (Drummond and Selvaratnam, 2009, p.183).

A few of these skills will be discussed in subsequent sections.

### **7.1 Ability to explain phenomena in terms of the type of particles present in a system and their properties.**

The most important approach to explanations in chemistry is in terms of the particles present. Many students, however, do not recognise the fundamental difference between descriptions (which involve macroscopic properties) and explanations (which involve the properties of sub-microscopic particles). Since matter is built up of particles (molecules, atoms, ions, electrons, protons and neutrons), it

“logically follows that all properties of matter must ultimately depend on, and hence be explicable in terms of, the properties of the constituent particles. By recalling the type of particles present in a given system, and then by identifying the properties of those particles that are appropriate, it should be possible to interpret/explain any property of the system considered” (Selvaratnam, 1998, p.2).

### Example 1

Explain why copper conducts electricity

- Using the particle approach:
- The types of particles present are positive ions and delocalized electrons.
- The relevant property of the particles is that the delocalized electrons are free to move.

Some typical answers that do not provide explanations:

“Copper is a metal and metals conduct electricity.” “Copper contains electrons.”

A study was conducted to test BSc chemistry students’ competence in the use of the strategy of explaining the facts, principles and laws of chemistry in terms of the properties of the constituent sub-microscopic particles (Serobatse, Selvaratnam and Drummond, 2014). More than half of the students had difficulty in answering the questions. Worryingly, performance did not improve as they progressed from year to year in their BSc course. Many students did not identify clearly the problem that had to be solved and did not use the relevant principles and reasoning to solve the problems. Instead, most students tried to solve problems by *recalling* knowledge, procedures and solutions they had learnt. However, when students were directed to consider the particles and their properties, the correct answers increased from 27% to 43% (Drummond, 2003).

## 7.2 Language skills

There is heated debate in South Africa regarding the language of instruction in most tertiary institutions (e.g. Abongdia, 2015, Nudelman, 2015), The Minister for Higher Education and Training called for comments on the draft policy (DHET, 2017, 2018), which sparked a very lively debate within NWU. NWU is in the process of finalising its language policy, which advocates functional multilingualism. In reality, on the Mafikeng Campus, the language of instruction is English, which is the second (or third) language for the majority of students.

Students need to understand the language used in order for them to make decisions and conclusions when considering verbal statements in chemistry. The language used in chemistry often makes learning difficult, as the meanings of some words in chemistry are different from their meanings in everyday language. For example “base” might mean the bottom of something in everyday language, but in chemistry it is the opposite of an acid. “Organic” means the chemistry of carbon compounds, but many people use the term nowadays to mean food that is grown without fertilizers or pesticides. I have even heard the term “organic” applied to spring water! (H<sub>2</sub>O and the dissolved salts present in spring water, are, of course, inorganic.)

Students struggle to read and comprehend chemistry texts in English, and to extract the important information and key ideas from texts (Abranches, 2014). The abstract nature of chemistry means that chemistry classes require a high level skill set (Taber, 2002, 2013; Zoller, 1990). Verbal reasoning involves the understanding of the verbal information given; and using it to carry out thinking and reasoning tasks. A study of language skills tested students' competence in simple language skills and verbal reasoning skills (Jele, 2017; Jele, Drummond and Selvaratnam, 2015). The results showed that many students had difficulties with language skills and verbal reasoning skills. For example

- the meanings of some important non-technical words/phrases, such as “analyse”, “deduce”, “dissociation”, “emission”, “fraction”, “ratio”, “variable” (30%);
- the difference between descriptive and explanatory statements; qualitative statements and quantitative statements (30%);
- the meanings of some important words used in scientific context, (such as “heat is absorbed”, “percentage” and “constant” (50%);
- the conversion of quantitative statements into equations (45%);
- representation of verbal information in the form of a diagram (70%);
- using verbal information to draw conclusions (60%).

An intervention programme led to a significant improvement in the verbal reasoning skills of these students (Jele, 2017). Time should thus be spent helping students with these skills. If this results in better performance in chemistry, then it is worthwhile.

### **7.3 Three-dimensional visualisation skills**

Several studies (El Farra, 1982, Seddon, Tariq and Dos Santos Veiga, 1982, Pribyl and Bodner, 1987) have indicated that students tend to experience difficulty with many aspects of three-dimensional thinking required for the learning and understanding of chemistry. Attempts to circumvent or rectify these difficulties over many years have used teaching aids such as models (Oyediji, 1978), stereodiagrams (Rozelle and Rosenford, 1985), shadows of rotating molecules (Seddon, Eniaiyaju and Jusoh, 1984), diagrams showing successive stages in rotation and reflection (Seddon and Shubber, 1984), videotapes of rotating models (Seddon and Moore, 1986), and more recently computer animations (Kokalj, 2003; Tasker and Dalton, 2006).

A study was undertaken to test and improve students understanding of three-dimensional structures, rotation and reflection in chemistry (Tuckey, 1989, Tuckey, Selvaratnam and Bradley, 1991) The approach adopted in this study, concerning the identification and rectification of these difficulties, was different from the studies mentioned above, because it was based on the hypothesis that a stepwise approach must generally be used for the logical solution of three-dimensional problems and that difficulties in this field are due either to not using a stepwise approach or to incompetence in one or more of the required elementary steps. It was found that even at university level many students have difficulties with three-dimensional thinking. These difficulties were attributed to incompetence in just a few relatively simple concepts and skills. That these concepts and skills are mastered, without much

difficulty, by most students was demonstrated by the fact that just a 2-hour remedial workshop program was sufficient to improve student performance significantly.

### Example 2

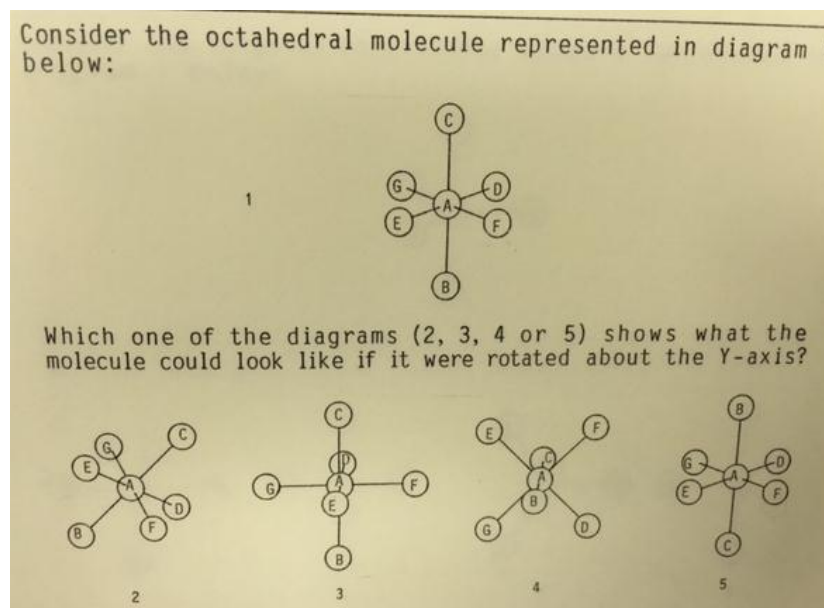


Figure 3: Three-dimensional visualisation example (Source, Tuckey, 1989).

The steps needed to answer the question:

- visualize which atoms in diagram 1 are in the plane of the paper and which atoms are farther away and which are closer to us than the plane of the paper, by making use of the depth cues (overlap, foreshortening of lines and distortion of angles) provided in the diagram;
- recognize the orientation of the Y-axis;
- recognize the meaning of the phrase "rotation about the Y-axis";
- visualize, three-dimensionally, how the positions of the various atoms would change when the molecule is rotated about the Y-axis;

### 7.4 Mathematical skills

Mathematical skills deal with relationships between quantities, using numbers, symbols and equations. Even when students have calculators, they need to be able to perform various mathematical skills. For example,

- (1) focus on the goal and select appropriate equations for problem solving;
- (2) express statements as equations;
- (3) obtain information from equations;
- (4) derive, rearrange and combine equations;
- (5) substitute numbers for symbols in equations;
- (6) use self-consistent units when performing calculations;

- (7) recognise correct relationships between variables;
- (8) recognise quantities which remain constant;
- (9) manipulate exponential numbers;
- (10) perform operations in a logical order;
- (11) check whether answers are reasonable.

## Variables and constants

### Example 3

The rate of decomposition of a substance A is directly proportional to the square of its concentration ( $c_A$ ). This information can be represented by the equation  $rate = k c_A^2$ .

- (a) If the rate is  $r$  at concentration  $c$ , the rate when the concentration is doubled to  $2c$  will be: (
- (i)  $4r$     (ii)  $2r$     (iii)  $r$     (iv)  $(\frac{1}{2})r$     (v)  $(\frac{1}{4})r$     (vi) none of the above
- (b) How will  $k$  change if the concentration of A is *doubled*?

This question tests students' understanding of the concepts: direct proportion, square, constant. Because  $rate$  is directly proportional to  $c_A^2$ , it will change by a factor of  $2^2 = 4$  when  $c_A$  is doubled.  $k$  is a constant; it will not change when the concentration is changed.

In part (a), only 14% of the students correctly reasoned that the rate increases by a factor of 4, 35% of the students thought incorrectly that the two quantities are directly proportional, and that rate would be doubled if the concentration of A is doubled, 2% thought that the rate would stay the same, and 10% said it would be halved. In part (b), 43% of students recognised that the rate constant  $k$  was a constant

### Example 4

- The density of 2.0 g of a solid is  $4.6 \text{ g cm}^{-3}$ . What will be the density of 4.0 g of the same solid, under the same conditions?

This question tests whether students focus sharply on the goal and, in addition, also whether they recognize the importance of clarifying and getting a 'clear picture' of the problem. When the mass ( $m$ ) of a solid increases, its volume ( $V$ ) will also increase in the same proportion. The ratio  $m/V$ , which is equal to the density, will therefore not change. The density of the solid will therefore not change when the mass is doubled. Student performance was very poor. Only 6 % of the students recognized that the density of a solid will not change when its mass is changed. 52 % of the students thought incorrectly that the density would double to  $9.2 \text{ g cm}^{-3}$ ; they implicitly assumed that density is directly proportional to mass, while 2 % assumed an inversely proportional relationship. 40 % of the students seem to have merely manipulated (divided, multiplied, added) the data given, without much thought, and obtained incorrect answers.

In order to ascertain whether their difficulty was due to lack of understanding of the concepts of variable and constants, this question was asked again in a second test, together with the following hint:

Hint: Deduce the answer by using the defining equation for density ( $d$ ), which is  $d = m/V$ , which shows that density depends not only on the mass  $m$  but also on the volume  $V$ . Recognize that  $V$  will also change when  $m$  changes from 2.0 g to 4.0 g.

Despite this hint, 90 % of the students did not recognize that density will not change. They made the same errors as before. Since getting a clear picture of this problem does not seem to be a difficult task, it appears that students' difficulty may be due to their rushing into the solution without sufficient mental effort.

## 7.5 Information processing skills

### Example 5

- The rate of diffusion of a gas is directly proportional to the square of the temperature and is inversely proportional to the square root of its molar mass. Express this statement as an equation.

This question tests students' ability to process the information given in a statement and give it as an equation. Processing includes identifying the quantities involved, giving them symbols (e.g. symbol  $r$  for the rate of diffusion,  $T$  for temperature,  $M$  for molar mass) and relating these quantities by using the mathematical expressions that correspond to the words 'directly proportional' and 'inversely proportional'.

$$r = \frac{kT^2}{M^{1/2}}$$

About 60 % of students were unable to convert the information into an equation. Many students have difficulties with the use of verbal reasoning for calculations and a useful method for 'by-passing' verbal reasoning would be first to represent the information provided by statements as equations and then use the equations for calculations.

## 8. Competence in Strategies

Intellectual strategies in chemistry include decision making and problem solving. Because problem solving is especially important in chemistry, it has been widely studied. Klausmeier (1985) defines a problem as a situation for which we do not have immediately available the information, methods or general plan to reach a solution. Educators use the term "problem solving" more narrowly to refer to the performance of tasks, which are generally well-structured or convergent problems: "the kind of problem which is clearly presented with all the information needed and with an appropriate algorithm available that generates a correct answer" (Frederiksen, 1984, p.303). Many problems are ill-defined, however, and require divergent problem solving, in which attempts are made to reach solutions that are novel or unconventional.

Many strategies have been suggested for problem solving. Each strategy involves a sequence of steps. Some of these strategies include “classical” strategies (Rossman, 1931; Dewey, 1933; Polya, 1945), strategies based on information processing (Guilford, 1967; Mayer, 1977) and some strategies which are specific to science (Reif and Heller, 1982; Selvaratnam and Frazer, 1982; Selvaratnam, 1990).

### 8.1 Problem solving strategy

A step-by-step procedure for solving quantitative problems has been proposed (Selvaratnam, 1990). This strategy involves the following steps:

- Step 1: Identify and give explicit symbols for the data and the goal, and organize them.
- Step 2: Focus on the goal and select the "starting equation".

“The odds of hitting your target go up dramatically when you aim at it” (Mal Pancoast). Students often use the “*Spray and Pray Approach*”. Take a random selection of the numbers given in the question, and multiply or divide them by each other.

- Step 3: Proceed step by step to derive the "calculation equation".
- Step 4: Calculate using the calculation equation.
- Step 5: Check, review and learn from the solution.

The competence of 300 first year chemistry students at North-West University in four intellectual strategies (clarification and clear presentation of the problem; focussing on the goal and identifying a strategy for moving towards the goal; identification of the principles needed for solution; proceeding step by step) was investigated, over a period of four years, by comparing their performance in ‘standard’ questions and ‘hint’ questions. The ‘standard’ and the ‘hint’ questions were the same but the ‘hint’ questions, in addition, suggested the strategies which should be used to solve the problems. Performance in all test items was poor, but improved in the ‘hint’ questions. The results indicate that about 80 % of the students were unable to use the required strategies, and also that many students who have the competence to use the strategies did not recognize the necessity for doing so. The results also suggest negative attitudes and lack of self-confidence in problem solving. There is therefore a need for specific training of students in the use of intellectual strategies. This should be integrated with the learning of subject content (Drummond, 2003).

### 8.2 Clarification and clear presentation of the problem

#### Example 6

Atom A is heavier than atom B but is lighter than atom C. Atom D is lighter than atom A but is heavier than atom B. Atom B is heavier than atom E. Which atom is the heaviest?

This question tests students’ ability to compare five items of information to decide which atom is the heaviest. To store five items of information in our short-term memory and compare them mentally is a difficult task. The following hint was then given:

Hint: Use the information given in the data, to arrange the atoms in the order of increasing masses on the line given in the figure, before answering the question. The first piece of information (atom A is heavier than atom B) has been indicated in this line (See Figure 4).

The solution is much easier if the items of information are coordinated together in a line diagram, as shown in Figure 4. The answer may then be read directly from the line.

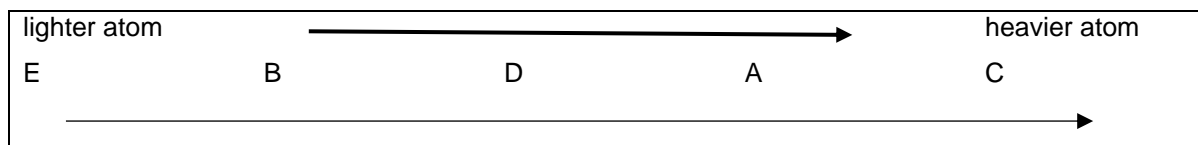


Figure 4: Arrangement of information (Source: Drummond, 2003).

In the first test, 60 % of the 300 students tested solved the problem. When the question had a hint suggesting the strategy of representing all the data on one line, there was a significant improvement in student performance. Of the students who failed in test 1, 25 % were able to answer the test 2 question correctly. This suggests that these students had the ability to represent the information given pictorially, but failed in test 1 because they did not recognize the necessity for doing this. Despite the suggestion in the hint to arrange all the data on one line, about 30 % of the students did not do so. These students may either have language difficulties that resulted in their being unable to carry out the simple instructions given or they lacked self-confidence which prevented them from even trying to proceed with the instructions. There is therefore a need for checking, and then ensuring, whether students are able to carry out simple instructions and tasks, without assuming that they can do so (Drummond and Selvaratnam, 2008).

### 8.3 Focussing on the goal and Identifying principles needed for solution

#### Example 7

- 3.00 g of phosphorus pentachloride (vapour) are heated in a closed 1.00 dm<sup>3</sup> container at 300°C. It then partially dissociates according to the equation



to give 0.50 g of Cl<sub>2</sub>. Calculate the density of the *gaseous mixture* present in the vessel after dissociation.

(Note: Density is defined as the mass per unit volume.  $P = 31.0$ ;  $\text{Cl} = 35.5$ .)

This question tests whether students start the solution with the defining equation for the required quantity,  $d_{\text{mixture}} = m_{\text{mixture}}/V$ , where  $d_{\text{mixture}}$ ,  $m_{\text{mixture}}$  and  $V$  are respectively the density, mass and volume of the mixture of gases in the vessel. The simple principle of conservation of mass means that mass does not change during any chemical reaction, thus  $m_{\text{mixture}} = 3.00$  g. From the data  $V = 1.00$  dm<sup>3</sup> and therefore  $d_{\text{mixture}} = 3.00 \text{ g}/1.00 \text{ dm}^3 = 3.00 \text{ g dm}^{-3}$ . Although the solution is easy, only 29 % of the students answered the problem correctly. About 30 % of the erring students used the defining equation for density for the calculation but they substituted incorrect masses: some substituted 0.50 g (the mass of Cl<sub>2</sub> given in the data), and some added or subtracted the masses (3.00 g and 0.50 g) given in the data.



A few students even multiplied the mass of each gas by its molar mass. It appears from these answers that many students try to solve problems by merely manipulating the data given; they do not try to get a picture of the problem and identify the principles needed for the solution.

The same question was given with a hint in the second test:

- *Hint:* Calculate the density of the gaseous mixture ( $d_{\text{mixture}}$ ) by using the equation  $d_{\text{mixture}} = m_{\text{mixture}} / V_{\text{mixture}}$  where  $m_{\text{mixture}}$  and  $V_{\text{mixture}}$  are respectively the mass of the mixture and the volume of the mixture.

Student performance in the hint question was much better; 24 % of the students who failed in test 1 were successful in test 2. These students' failure in test 1 may therefore be attributed to their not using the strategy of starting the solution with the defining equation for the required quantity.

### 8.4 Proceeding step by step

A study was undertaken to test students' ability to solve problems which required several steps. Analysis of the scores revealed that many students struggled with the problems, but when they were guided through the steps by means of a flow chart, they were able to solve the problems (Thibedi, 2016)

#### Example 8

10.00g of glucose,  $\text{C}_6\text{H}_{12}\text{O}_6$  (180.1 g/mol) is dissolved in water and the solution is made up to  $0.500 \text{ dm}^{-3}$ . Calculate the concentration of Glucose.

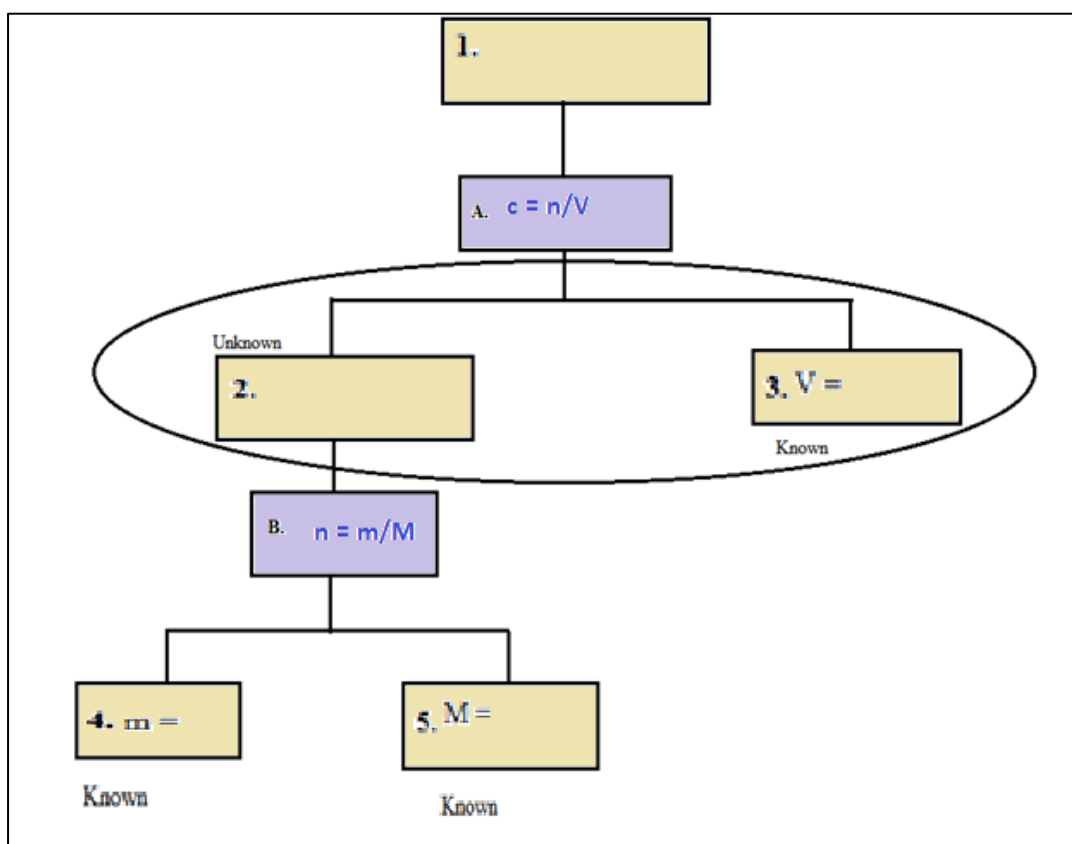


Figure 5: Flow chart used for problem solving (Source: Thibedi, 2016).

This question was generally well answered, indicating that the students were familiar with the required equations  $C = \frac{n}{V}$ ,  $n = \frac{m}{M}$  and calculations. 78 students (89%) answered correctly while 10 students (11%) answered incorrectly. All students were able to answer correctly when they used the flow chart.

## 9. Conclusion

Studies by the author, her colleagues and her students, as outlined above, have shown that many students fail chemistry not only because of lack of chemical knowledge but also because they are incompetent in basic intellectual skills and strategies. This suggests that students should be trained in intellectual skills and strategies as they learn subject content. Many teachers feel, because the content of the chemistry syllabus is large, that they do not have sufficient time to train students in skills and strategies in their courses. Although time is required to develop student competence in skills and strategies, this would decrease, in the long term, the time spent teaching subject content, because the learning of content would then be more efficient (Drummond, 2003).

The matric examination, as well as internal tests and examinations at schools and universities, should test not only content but also intellectual skills/strategies. Unless skills and strategies are tested, there will be no incentive for teachers to train students in them, or for students to spend time learning them.

Drummond (2003) showed that, although there was a significant correlation between the results of students in their first year university course, and their performance both at matric, and at the skills/strategies tests conducted in this research, the correlation was much better ( $r = 0,46$ ) between first year university performance and the performance in skills/strategies test (Drummond, 2003), than that between first year university and matric performance ( $r = 0,28$ ). This indicates that the skills/strategies test is a better indicator of success at university level than matric performance. This is in agreement with research results elsewhere, over a long period of time, which indicate that high school grades were poorer predictors of success in science at university than mathematical ability and logical thinking ability (Ozsogomonyan and Loftus, 1979; Menis and Fraser, 1992; Bunce and Hutchinson, 1993; Spencer, 1996; Nicoll and Francisco, 2001, Hahn and Polik, 2004).

Although universities are under pressure to broaden access, particularly to students from disadvantaged backgrounds, it is important that their admission policies select students who are likely to succeed. Admitting students who are likely to fail is a major problem, both for the institution and for the students. Time and money is wasted by such students, many of whom make considerable sacrifices to pay university fees.

A test of skills could also be used by teachers or lecturers, during a course of study, to identify those "at-risk" students who are likely to fail. These students could then be given extra help and tutoring, and this should help to lower failure rates.

Unlike many other syllabus changes and programmes which have been suggested for improving chemistry teaching and making chemistry more accessible to students, this approach of teaching

through the medium of skills and strategies does not require much change in subject content of the chemistry syllabus. This approach could therefore be implemented by individual teachers and lecturers using the existing textbooks and syllabus. Students who are competent in intellectual skills and strategies generally perform better both in secondary and tertiary level chemistry courses, and also in solving problems encountered in their daily lives. This alone should be incentive for teachers to concentrate on skills and strategies, when they teach subject content.

Many studies concerning the skills and strategies needed for learning chemistry effectively have been reported in this lecture. However, there is still scope for many more studies. The list of skills and strategies presented here is by no means exhaustive, particularly as more technology is incorporated into chemistry teaching. Most of these studies have concentrated on students at matric and undergraduate level. However, students at different levels of their studies can be tested, and intervention or remedial programmes can be devised to assist them with their learning. There is a need to improve the skills of students at lower grades at school, and also at all levels of their university studies.

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