The development of the conceptual understanding of first-year chemistry university students in stoichiometry using thinking skills, visualization and metacognitive strategies

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I thank my Creator who gave me the opportunity to discover my calling in life and for giving me the talents to pursue the life calling of teaching.

“Your work is going to fill a large part of your life, and the only way to be truly satisfied is to do what you believe is great work. And the only way to do great work is to love what you do. If you haven’t found it yet, keep looking. Don’t settle. As with all matters of the heart, you’ll know when you find it. And, like any great relationship, it just gets better and better as the years roll on. So keep looking until you find it. Don’t settle.”
PREFACE

Introduction

This dissertation was submitted in article format, as required by the North-West University (NWU). This entails that the article is added into the dissertation as it will be submitted for publication (chapter 3). The relevant information is summarised in the article. Separate background and motivation (chapter 1), literature (chapter 2) and project evaluation (chapter 4) were included in the dissertation, even though some of this information was summarised in the article. This will result in some repetition of text in some of the chapters and the article itself. chapter 5 consists of the summary, conclusion and recommendations. The figures and tables of chapter 3 are also added at the end of the text, as prescribed by the journal.

Rationale in submitting dissertation in article format

Currently it is a prerequisite for handing in a MSc. dissertation at the NWU, that a draft article be prepared. In practice, many of these draft papers are never submitted to the peer-reviewed journals. However, in this study, the candidate decided to submit this MSc. dissertation in article format, since it is required that the candidate prepare a paper that will be submitted to an ISI-accredited journal. Therefore, the prerequisite of the NWU was complied with. The co-authors of the above-mentioned article (chapter 3) are: Dr CE Read, Dr GM Reitsma & Me M. H. du Toit.
ABSTRACT

First-year chemistry was identified by the North West University Potchefstroom Campus as one of the modules with a low pass rate. It is clear that students often memorise definitions and formulae, without understanding the underlying concepts which are necessary for problem solving. It is important that these and other related problems are addressed, before any significant change in the through-put rate for first-year students is reached. Conventional forms of lectures as teaching approach had little impact on the performance of students’ exam results. Much research has already been done on students’ misconceptions of stoichiometry, as well as problem solving strategies regarding stoichiometric problems. In addition, several alternative approaches concerning the teaching of chemistry have already been developed. Students still see this subject as very difficult and challenging. This study handles the systematic integration of visualization during lectures and the development of critical thinking and metacognition in assignments in stoichiometry teaching of first-year students at a South African University with the purpose of improving conceptual understanding.

A quantitative research approach was followed. A one-group pre-test-post-test design was initiated to determine if there were practical significant differences in the conceptualisation of students at the beginning and at the end of the study. The intervention consisted of the implementation of specific teaching techniques, which included visualization and the development of critical thinking. Slideshows, a document camera, assessment tasks, a mini-project as well as thinking skills tasks were used. The study indicated that visualization, metacognition and critical thinking had a positive influence on the learning and conceptualisation of stoichiometry in students. The promotion of the learning of by the implementation of visualization, metacognition and critical thinking techniques, was successfully applied to help first-year students of this university realise stoichiometric-conceptualisation.

Key words: visualization, conceptualisation, stoichiometry, critical thinking, metacognition, chemistry teaching.
OPSOMMING

Eerstejaar-chemie is geïdentifiseer deur die Noordwes Universiteit se Potchefstroomkampus as een van die vakke met 'n lae slaagsyfer. Dit is duidelik dat studente dikwels definisies en formules memoriseer, sonder om die onderliggende konsepte wat nodig is om probleme op te los, te verstaan. Dit is noodsaaklik dat hierdie en ander verwante probleme aangespreek word voordat enige betekenisvolle verandering aan die deurvloeisyfer vir eerstejaars bereik sal word. Konvensionele van lesings as onderrigbenadering het min impak op die prestasie van studente in eksamens. Baie navorsing is reeds gedoen oor studente se wanopvatting in stoïgiometrie asook probleemoplossing-strategieë rakende stoïgiometriese probleme. Daarbenewens is verskeie alternatiewe benaderings vir die onderrig van hierdie onderwerp van chemie reeds ontwikkel. Studente beskou hierdie onderwerp nog steeds as baie moeilik en uitdagend. Hierdie studie handel oor die sistematisiere integrering van visualisering en metakognisie tydens lesings en die ontwikkeling van kritiese denke in opdragte in stoïgiometrie-onderrig van eerstejaar chemie studente by 'n Suid-Afrikaanse Universiteit met die doel om konseptuele begripvorming te verbeter.

'n Kwantitatiewe navorsingsbenadering is gevolg. 'n Eengroep voortoets-natoets ontwerp is onderneem om te bepaal of daar beduidende verskille in die konseptualisering van studente aan die begin en einde van die studie was. Die intervensions het bestaan uit die implementering van spesifieke onderrigtegnieke wat visualisering, metakognisie en die ontwikkeling van kritiese denke ingesluit het. Daar is gebruik gemaak van skyfievertonings, 'n dokumentkamera, assesseringsopdragte, 'n miniprojek en denkvaardigheidsopdragte. Die studie het getoon dat visualisering, metakognisie en kritiese denke 'n positiewe effek gehad het op die leer en konseptualisering van stoïgiometrie by studente. Bevordering van die leer van stoïgiometrie deur die implementering van visualiserings- en kritiese denkprosesse het geleid tot suksesvolle om stoïgiometrie-konseptualisering by die eerstejaarsstudente by hierdie universiteit.

Sleutelwoorde: visualisering, konseptualisering, stoïgiometrie, kritiese denke, metakognisie, chemie onderrig.
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CHAPTER 1: BACKGROUND, MOTIVATION AND OBJECTIVES

1.1 INTRODUCTION

In this chapter, the focus and scope of the study are explained. A short discussion of the background and motivation for this study, as supported by the literature, is provided. The main concepts that are relevant to this study are clarified. An overview of the research process is also provided.

1.2 BACKGROUND AND MOTIVATION

The teaching and learning of chemistry, and mainly of stoichiometry, provide challenges to both students and lecturers on tertiary level. Stoichiometric concepts and phenomena appear throughout the field of chemistry, and form an integral part of the chemistry curriculum on first-year level. Potgieter (2010) found in a national study, that first-year students were not prepared for chemistry on tertiary level. Coupled with that, students found the field of stoichiometry particularly challenging (Abdullateef, Haidar & Al Naqabi, 2008).

Teaching strategies are seldom adjusted to assist students with the learning of stoichiometry (Arasasingham, Taagepera, Potter, & Lonjers, 2004). Stoichiometry teaching usually takes place according to a traditional algorithmic approach, which seldom addresses or improves the understanding and critical thinking of students (Abdullateef et al., 2008). It is clear from a report of Potgieter (2010) that chemistry-teaching of students should urgently be looked at. Innovative and effective alternative teaching processes, which could help improve students’ conceptual understanding of stoichiometry, should be investigated. This study handles the systematic integration of visualization during lectures and the development of critical thinking in metacognitive assignments of stoichiometry-teaching of students from a South African University, with the purpose of improving conceptual understanding.

1.3 DISCUSSING THE PROBLEM

Chemistry-teaching traditionally takes place by means of lectures, coupled with the use of textbooks, the learning of theories and rules, and the principle that there is in general only one correct solution to every problem (Nakhleh, 1993). The predominant approach to teaching on school level and at universities in South Africa is a more traditional approach of the step by step solving of algorithms. As concluded from existing chemistry textbooks, this includes mainly four steps for problem solving which should be followed, according to directions in several textbooks, and illustrated by examples (Kotz, Treichel & Townsend, 2012). The student is expected to follow the same “recipe” to solve similar problems. This approach focuses solely on
the application of several algorithms, without leading the student to conceptual understanding (Pushkin, 2007). With typical traditional problem solving in stoichiometry, the student is expected to select, adapt and specifically apply algorithms to the problem (Othman, Treaugust & Chandrasegaran, 2008). Various studies also confirmed that students on tertiary level essentially make use of these traditional algorithms to solve problems (BouJaoude & Barakat, 2003; Othmen et al., 2008; Lythcott, 1990).

The study of Potgieter (2010) furthermore indicated that nearly 70% of the first-year students from the particular institution where this study was performed experienced conceptual problems in stoichiometry. The result could be similar at other universities. According to Wood (2006) previous exposure to stoichiometry is the strongest defining factor for conceptual understanding. If students never form a conceptual understanding of stoichiometry on school level, or wrong concepts are formed, their conceptual understanding on university level will necessarily be handicapped. Huddle and Pillay (1996) found in an earlier study among South African students that misconceptions of stoichiometry were very difficult to correct.

The main concepts that are relevant to this study are the following:

**Thinking skills:** A major component of the current reforms in science education worldwide is the shift from the dominant traditional teaching for algorithmic, lower-order cognitive skills, to teaching for the development of higher-order thinking skills (Zoller, 2000).

Higher-order thinking skills can be conceptualised as a non-algorithmic, complex mode of thinking that often generates multiple solutions (Ben-Chaim, Barak, Overton & Zoller, 2005). Recalling of information is an example of lower-order thinking skills, whereas analysis, evaluation and synthesis would be considered as higher-order thinking skills (Ben-Chaim et al., 2005). Learning experiences associated with higher-order thinking skills focus on analysis, evaluation and synthesis and develop skills in problem solving, inferring, and estimating, predicting, generalizing and creative thinking. Other examples of such skills include: question posing, decision making, critical and systemic thinking (Ben-Chaim et al., 2005).

**Visualization** is central to learning, especially in chemistry, for students have to learn to navigate between modes of representation. It is therefore, argued that science students must become metacognitive in respect to visualization (Gilbert, 2005). Visualization is the systematic and focused visual display of information in the form of tables, diagrams, graphs, videos, and models.

Chemistry is commonly portrayed at three different levels of representation: macroscopic
(observable chemical phenomena), sub-microscopic (explain the macroscopic phenomena in terms of the movement of particles such as electrons, molecules and atoms) and symbolic representations to construct mental images. These levels combine to enrich explanations of chemical concepts (Othman, Teagust & Chandrasegaran, 2008).

**Metacognition** is defined as “cognition about cognition” or “knowing about knowing”. What distinguishes novice from expert science students is the use of metacognition (Abdulateef *et al*., 2008). Metacognitive knowledge can be described as the knowledge, awareness, and deeper understanding of one’s own cognitive processes and products. Expert science students regularly evaluate their own understanding. They generally examine the quality of their work as they go along. Metacognition is important for successful problem solving, which is a form of higher-order learning (Howard, McGee, Shia & Hong, 2000). Metacognition is also regarded as a central skill for successful learning (Abdulateef *et al*., 2008).

### 1.4 PURPOSE OF THE STUDY

The purpose of this study is to develop the conceptual understanding of first year chemistry university students in stoichiometry by:

1) Implementing learning experiences associated with higher-order thinking skills which focus around analysis, evaluation and synthesis and the development of problem solving skills, inferring, estimating, predicting, generalizing and creative thinking.

2) Visualization of concepts and their interrelationships by concretising and by explaining the meaning of concepts by making use of the macroscopic, sub-microscopic and symbolic modes of representation.

3) Using the metacognitive control skills of prediction, planning, monitoring and evaluation to develop metacognitive skills of students.

The topic of stoichiometry was selected as the subject context for this investigation. stoichiometry is an essential part of the first year chemistry curriculum, and is regarded as one of the more difficult sections in the curriculum.
In order to reach the research purpose presented above, the following research questions had to be answered:

1) What will the impact of teaching strategies, focussing on the development of higher order thinking skills, be on first year students’ conceptual understanding of stoichiometry?

2) What will the impact of visualization be as a tool on the structure and content of the students’ stoichiometry knowledge?

3) What will the effect of metacognitive regulation be on test performance of students in stoichiometry questions?

4) What will the effect of the concurrent integration of thinking skills, metacognitive strategies and visualisation be on the conceptualisation of first year students in stoichiometry?

1.5 RESEARCH METHOD

1.5.1 Literature study

A comprehensive literature study was done to determine how students conceptualise in stoichiometry and what the influence of critical thinking, visualization and metacognition was on this. Chapter 2 formed the theoretical framework for the research. From the literature study a measuring-instrument was compiled according to which the conceptualisation of students concerning stoichiometry was determined (see Annexure A).

1.5.2 Empirical study

1.5.2.1 Quantitative research

For the quantitative research an experimental design was used, where the group was subjected to a pre-test and a post-test (Creswell, 2003), to determine if significant differences between the students’ levels of conceptualisation in stoichiometry existed, after they had been exposed to critical thinking skills tasks, several forms of visualization as well as tasks aimed at the development of metacognitive skills.

Study population

The study population for the empirical research consisted of all registered chemistry first-year students (n=798) at the North-West University’s Potchefstroom Campus.
Variables

*Independent variable:* Critical thinking skills tasks, visualization and metacognitive tasks.

*Dependent variable:* Level of conceptualisation of chemistry students regarding stoichiometry.

Measuring-instrument

For this quantitative research a self-compiled concept test (from other standardised tests, adapted for the specific context) was used as a pre- and post-test to determine levels of conceptualisation.

Statistical techniques

Descriptive statistics such as averages, % improvement, p-values (statistical significance) and d-values (practical significance) were used to analyse data and to determine the significance of the differences.

1.5.2.2 Course of the research

At the beginning of the study the students wrote an unprepared concept test with regard to the levels of their conceptualisation of stoichiometry. A teaching programme where critical thinking, visualization methods and metacognitive tasks were continuously used, was followed.

After a period of approximately 3 months the same concept test was written once more, again unprepared.

After completion of the teaching and the post-test, the data were analysed, interpreted and conclusions were made, after which certain recommendations were given.

1.6 STRUCTURE OF THE DISSERTATION

In chapter 1 the orientation regarding the study, the problem statement as well as the programme of research is discussed. Chapter 2 provides a thorough literature study on the teaching of critical thinking skills, visualization and metacognition with specific reference to stoichiometry. Different approaches regarding the teaching of stoichiometry are discussed.

Chapter 3 is the article, that will be submitted to *Journal of Chemical Education*. The research plan, the research methodology and the data analysis techniques are represented more detail.
in chapter 4. Chapter 5 provides the analysis and discussion of the results and findings of the quantitative procedures which were used to answer the research questions (see 1.3).

According to the findings, recommendations for the development of the conceptual understanding of first-year chemistry students of stoichiometry are made.
2.1 INTRODUCTION

In this chapter consideration will be given to the role of visualization, critical thinking and metacognition in the formation of conceptual understanding and problem solving skills in stoichiometry. The aim of this study is to determine whether the synergistic approach of visualization, critical thinking and metacognition can develop the conceptual understanding of students in stoichiometry, thus improving their problem solving skills specifically applied to stoichiometry. The diagram below (Fig 2.1) is presented by the researcher for this study to show the integration and synergistic collaboration between visualization, critical thinking and metacognition for conceptual understanding and problem solving.

Figure 2.1: Visual presentation of the integration of critical thinking, metacognition and visualization promoting conceptual understanding and problem solving in stoichiometry
2.2 VISUALIZATION

2.2.1 Definition and description

According to the New Oxford Dictionary visualization is described as “a form of mental image or to make something visible to the eye.” According to Gilbert, Reiner and Nakhleh (2008), mainly two types of visualization can be distinguished, namely external and internal visualization.

In the case of external visualization a model is presented in one or more forms (like an object, visually, symbolically, verbally) for visual perception. The intellectual presentation of visualization by an individual is an image (Gilbert et al., 2008 and Gobert, 2007). Formulated simply, external visualization refers to presentations used in teaching and learning for instance graphs, diagrams, models, simulations and animation. These external presentations have different properties, originate from different sources and contribute to the students’ learning.

During internal visualization the results of external visualization are embedded in the thoughts of the individual. Internal visualization is presentations like intellectual models (brain charts/thinking models), and ideas or pictures used in solving problems regarding for instance questions about chemical bonding. Furthermore the internal presentation may also be information stored in the memory of a person to enable him/her to make deductions and decisions in addition to problem solving (Rapp & Kurby, 2008). Visualization is also used to describe spatial intelligence.

Spatial intelligence is the ability to understand the visual world correctly and to bring about transformations and changes in the observed visual world (Gardner, 1983). These last two contributions (internal visualization and spatial intelligence) correspond to a greater extent with the description of Gilbert et al. (2008) of visualization as a verb (to visualise).

Learning with external visualization normally requires that an intellectual image of the object or process to be studied be created and this also requires spatial intelligence on the side of the student (Locatelli, Ferreira & Arroio, 2010).

2.2.2 Visualization in the teaching of stoichiometry

Visualization, as described above, is relevant in science teaching, especially in the teaching of stoichiometry (Rapp & Curby, 2008).

The essence of theory-driven chemistry teaching consists of the constant shift between the different representative areas of chemical thinking, the macroscopic, the sub-microscopic and
symbolic domains (Johnstone, 1997). Since the sub-microscopic domain cannot be seen or directly visualised, it requires very specific forms of visualization. The use of visualization improves the learning of students. Niaz and Robinson (1993) emphasised that the ability of students to visualize is important for solving conceptual problems. Noh and Scharmann (1997) found that teaching with visualization of the molecular level helps students to capture scientifically correct perceptions. External sources of visualization like photos, animations and simulations are powerful instruments for teaching and learning in chemistry. According to Williamson and Abraham (1995) there is great potential in the use of these visualization techniques, since they improve the student’s understanding of three-dimensional structures and contribute to the development of the spatial intelligence of learners (Arasasingham et al., 2004). These aids may lessen the students’ misconceptions of basic chemical concepts and methods (Sanger & Greenbowe, 2000, Yang, Greenbowe & Andre, 2004), and also increase the students’ motivation for learning chemistry (Tsui & Treagust, 2004). Krieger (1997) used flow diagrams based on the three domains (macroscopic, sub-microscopic and symbolic). Witzel (2002) presented microscopic domains by using LEGO BLOCKS and Haim, Corto´n, Kocmur & Galagovsky (2003) presented the stoichiometric processes using the production of a hamburger. Photos and animations illustrate the model-based level of separate particles, atoms or molecular structures. Therefore all techniques of visualization are applied with the aim of improving the formation of stoichiometric understanding.

Researchers (Locatelli, Ferreira & Arroio, 2010; Gilbert, 2005; Rapp & Kurby, 2008; Arroio & Honorio, 2008) discuss factors relevant to visualization in science teaching like; understanding how the visual presentation is transformed into knowledge; the importance of training models of thinking skills in the interpretation and processing of an image.

The teaching of chemistry requires much abstract thinking of the students in which visualization is important. Students should have at their disposal the metacognitive skill regarding visualization, also named metavisualization. Metavisualization may be described as the process monitoring and regulating the internal visualization by the individual (Locatelli et al., 2010). In figure 2.2, this monitoring and regulating process is presented.
According to Locatelli *et al.* (2010) chemistry can generally be understood by models and presentations that may be of a visual nature. These visual presentations are then stored as knowledge. Visual presentations become internal presentations (models) monitored at metacognitive level. The metacognitive process in turn regulates the formation of internal visualizations.

Studies, focusing on visualization as external presentation, attempted to determine how learning can be supported and promoted by using these presentations as well as their role in teaching and learning. Research on spatial intelligence focuses on the role of spatial visualization skills in the learning of external visualizations, the nature of these skills and how they can be developed.

External static visualizations (like photos, sketches and flow diagrams) are more readily available in typical textbooks and they can more easily be incorporated in learning. Visualizations in textbooks often focus only on the details of experiments, but not on the scientific process and research forming the basis of the experiments that helps the learner to understand the aim of the experiment (Astudillo & Niaz, 1996). Leevie and Lentz (1982) did research on the effect of static visualization and they pointed out that the use of text-superfluous visualization does not necessarily help learners in understanding the content, especially when they are weak readers. Stieff (2011) and Plass *et al.* (2012) showed that students perform better when dynamic visualizations like animations, instead of static visualizations, are used. Mayer (2003) confirms that animated visualizations are more advantageous than static visualization since details are added that support the understanding of the sub-microscopic world. Animated visualizations enable students to visualise the dynamic nature of the sub-microscopic world and
these visualizations lead to a better understanding of the underlying chemical concepts (Sanger & Greenbowe, 2000; Kozma & Russell, 2005a, 2005b; Yang et al. 2004). The positive effect of dynamic visualizations can be further improved when students can create their own static visualizations with reference to dynamic visualizations of the study content under consideration. (Zhang & Linn, 2011).

It is important to take note that there are factors that may limit the positive effect of visualization (static or animated) (Azevedo, 2004; Schwartz, Andersen, Hong, Howard & McGee, 2004). These factors include: an inadequate demand for the use of metacognitive skills, an insufficient prior knowledge of the students, overrating of the students’ ability to recognise and use proper spatial relationships (Lee, 2007), limited attention of the learner (Ploetzner, Bodemer & Neudert, 2008); and the inability of students to see the relationship between the symbols that are used in the visualization and the chemical concepts which they represent (Jones, Jordan, & Stillings, 2005). Eilks (2003) and Hill (1988) warn that visualization may impede correct understanding of concepts or even slow down the learning process. Although students can remember well what they have seen in an animation and also make appropriate sketches they do not necessarily understand what they have seen (Kelly & Jones, 2007). Learning by visualization is based on a semantic process that can only lead to successful learning if it is properly related to the foreknowledge of the learner (Schnotz & Bannert, 2003). Visualization should also describe the scientific concept in a correct manner (Hill, 1988). For effective learning to take place by using visualization in chemistry teaching and specifically stoichiometry, it is therefore important that the concepts are visually structured correctly taking into consideration the students’ foreknowledge of the various topics or theories (Eilks, Witteck & Pietzner, 2009).

Locatelli et al. (2010) proposed that more research should still be done in the field of visualization and metavisualization to understand the process of metavisualization better as well as the importance thereof for learning in general.

In the preceding parts consideration was given to forms of visualization and the role played by external visualization and spatial intelligence in the capturing of knowledge by the student. In this study various forms of visualization, including static visualization, dynamic visualization and assignments that develop metacognition and critical thinking were used in an attempt to promote the understanding of stoichiometry by first year students. This research considers the central role played inter alia by visualization in the capturing and changing of conceptual understanding in stoichiometry. Subsequently the focus will fall on critical thinking in the teaching of stoichiometry and its application to stoichiometric problem solving.
2.3 CRITICAL THINKING

2.3.1 Definition and description

What is critical thinking and why is it so important? Critical thinking can be defined as the intellectual disciplined process of active and skilful conceptualisation, application, analysis, synthesis, and evaluation of information obtained by observation, experience, reflection and reasoning (Scriven & Paul, 2007). Tempelaar (2006) refers to critical thinking as a form of metacognition. In this study it is assumed that critical thinking and metacognition complement each other, not being one and the same process. Critical thinking is important since it enables the students to handle social, scientific and practical problems efficiently (Shakirova, 2007) and solve problems critically and effectively. To only have knowledge is not enough. It will not necessarily enable the student to solve problems. To function effectively in the working environment, the student should be able to solve problems by more effective decision-making. They should therefore be able to think critically. Critical thinking is an intellectual habit that requires the students to think about the way in which they think and how to improve this process (metacognition). Students should not only memorise data and should not accept what they read without considering it critically (Scriven & Paul, 2007 & Tempelaar, 2006). Critical thinking is a product of teaching and learning and it can be mastered by practice (Tempelaar, 2006).

Critical thinking is not an inborn skill. Although some students are inquisitive by nature they should be trained to be systematical, analytical, thorough and open-minded in their quest for knowledge. With these skills students can be full of self-confidence in the application of their ability to think critically in any field or discipline (Lundquist, 1999). Critical thinking is often compared to the scientific method: it is the systematic and step-by-step approach to the process of thinking (Scriven & Paul, 2007). In a similar way in which students manage the steps of the scientific method they should acquire the process of critical thinking (Duplass & Ziedler, 2002).

Unfortunately students are normally not taught to think and learn independently. They seldom master these skills on their own (Landsman & Gorski, 2007; Lundquist, 1999; Rippen, Booth, Bowie & Jordan, 2002).

2.3.2 Critical thinking in the teaching of stoichiometry

Critical thinking has become one of the most essential skills that individuals should have to be able to adapt to the changing world. Critical thinking in chemistry is indispensable because it promotes significant learning (Zoller, Dori & Lubezky, 2002).

The development of students’ critical thinking is one of the most important aims of teaching at all
Critical thinking is mainly applicable to the context of higher-order thinking in the promotion of learning in scientific teaching (Zoller, 1994). In the context of the teaching of chemistry critical thinking is conceptualised as an activity linked to results. With an activity linked to results, one should first decide what knowledge is correct and usable. Thereafter a plan of action to be followed is decided on, then the execution of the assignment itself and lastly accepting responsibility for the outcome (Zoller, 1994).

Research has shown that students can master critical thinking if they are taught how (Adey & Shayer, 1990; Zoller, 1994; Zoller et al., 2002; Ten Dam & Volman, 2004). It was found in studies by Adey & Shayer, (1990); Zoller, (1994); Zoller et al., (2002) and Ten Dam & Volman, (2004) that the development of students’ capacity for solving problems as well as thinking critically is attainable by employing continual purposeful higher-order thinking skills and problem solving activities. Students’ critical thinking is also developed by applying better teaching and assessing strategies (Ten Dam & Volman, 2004).

Lecturers continuously experience problems in getting students involved in critical thinking activities (Tempelaar, 2006). Students themselves seldom use critical thinking to solve complex daily problems (Rippen et al., 2002). The question is why? The answer possibly lies in the teaching methods. According to Schafersman (1991), Clement (1979) stated that “our students should learn how to think. Instead we teach them what to think”. Norman (1981) states that: “it is strange that we expect students to learn but we seldom teach them how to learn”. Although content is important, the process of learning is just as important. The best practices and methods should be incorporated in the teaching of critical thinking in stoichiometry. Hindrances in the teaching of critical thinking should be identified. Students should also be supplied with strategies and examples for the development of critical thinking skills during the teaching process (Norman, 1981).

To couple the skills of critical thinking with content, the focus should be on the process of learning. How are the students going to master the information? Research supports the fact that traditional teaching and memorisation do not lead to the formation of long-term knowledge or the capacity for applying knowledge in new situations (Celuch & Slama, 1999; Daz-lefebvre, 2004 & Kang & Howren, 2004). Traditional teaching methods often comprise too many facts and not sufficient conceptualisation; too much memorisation and too little critical thinking. Teaching methods that force students to use higher-order thinking skills lead to the development of critical thinking skills (Duplass & Ziedler, 2002; Hemming, 2000 & Wong, 2007).

Teaching that supports critical thinking uses questioning techniques that expect the student to analyse, synthesise and evaluate information thus solving problems and making decisions (to
think) rather than simply repeating information (memorise). Critical thinking can be promoted in a discussion environment by asking questions and taking students through the process of critical thinking step by step. Critical thinking activities should be based on a structure that includes four elements: a) loosely structured problems, b) criteria for assessing thinking, c) self-assessment of thinking, d) promoting the critical thinking process itself. Weakly structured questions are questions, case studies or scenarios that do not have definite correct or wrong answers; they include debatable issues requiring self-reflective judgment. An example is to ask students to compare different types of chemical processes by comparing their content, format and usefulness. There are no correct and wrong answers as long as the student supports his answer by logical reasoning.

Self-assessment of thinking supplies the student with a framework of his own thinking where other measuring instruments like formal tests or class assignments only test the extent of knowledge and its application. For instance: Why is the optimum temperature of the Haber process economical? What are the disadvantages of a higher pressure in the system? Why is the forward reaction optimal at the specific temperature? On what do you base your opinion?

The promotion of critical thinking can be obtained by using a reflective questionnaire in which students can think about their own thinking processes and practise logical constructs (Duplass & Ziedler, 2002).

In addition to this, assessments should emphasise thinking rather than facts (Ennis, 1993). Assessments, quizzes and tests should be intellectually more challenging than the mere reproduction of facts (Norman, 1981). Subjective instruments like paragraph type questions and case studies require the students to apply their knowledge in new situations and they are a better indication of understanding than objective true/false or standardised multiple choice assignments. To strengthen and develop students’ processing skills it is important to revise and to explain correct answers by modelling the critical thinking process (Brown & Kelly, 1986; Duplass & Ziedler, 2002). If the lecturer models the criteria for assessing thinking and supplies a framework, students will eventually be able to apply these techniques on their own (Lundquist, 1999).

For the purpose of this study the view was taken that the above-mentioned techniques should be incorporated in the structure of stoichiometric assignments and projects, thus forcing the students to develop their own critical thinking.
Four obstacles often prevent the achievement of critical thinking namely a) the lack of training b) the lack of information c) preconceived ideas and d) time limits.

a) Lack of training: Lecturers are not trained in the methodology of critical thinking (Broadbear, 2003). Lecturers know the content and learn the teaching methods but little (if any) training focuses specifically on how to teach critical thinking skills. Lecturers pursue additional content-based teaching but they often have no formal training in methodology (Broadbear, 2003).

b) Lack of information: There is too little teaching material that provides suitable information for critical thinking (Scriven & Paul, 2007). Certain textbooks supply chapter-based critical thinking questions for discussion, but teaching manuals often do not meet expectations regarding information for critical thinking (Scriven & Paul, 2007).

c) Preconceived ideas: Both researchers and students have preconceived ideas about the content that prevent them from thinking critically about the content. Preconceived ideas like personal prejudices prevent critical thinking since students cannot think analytically and objectively (Kang & Howren, 2004).

d) Time limit: Lecturers often have great volumes of study content that have to be dealt with in a short period. When the focus is on the content rather than on the teaching, short cuts like lectures and objective tests become the norm. This type of teaching is faster and easier than integrating project-based learning opportunities. Objective tests are faster and easier to conduct and mark than subjective assessment assignments. Research confirms that lectures are not the best method of teaching and that objective tests are not the best way of assessment (Broadbear, 2003; Brodie & Irving, 2007). Several researchers (Landsman & Gorski, 2007; Sandholtz, Ogawa & Scribner, 2004; Sheldon & Briddle, 1998 & Wong, 2007) criticise the current trend in teaching to standardise curricula with the focus on test marks rather than the teacher’s ability to address critical thinking in the classroom. The emphasis on “teaching for the test” diverts the learner’s attention from the learner-centred teaching and places emphasis on the content. If the focus is on learning the learners should be given the freedom to master the content, to analyse sources and to apply knowledge.

This study describes how an attempt was made to promote critical thinking among first year students in chemistry. Basic stoichiometric concepts were presented visually by using visualization techniques. Animations and online tutorials, as well the inclusion of metacognitive assignments and evaluation assignments, were supplied to the students on an on-going basis. These assignments required higher-order critical thinking skills of the students.
Subsequently metacognition and its role in the process of conceptualisation and stoichiometry are considered.

2.4 METACOGNITION

2.4.1 Definition and description

The meaning of cognition is to acquire knowledge by perception. Cognition entails active monitoring and guidance regarding the task under consideration (Everson & Tobias, 1998). Metacognition differs from cognition since metacognition is necessary to understand how a task should be executed, while cognition will try to ensure that an aim has been reached (Livingston, 1997). For instance: A student has the task to present water molecules by means of a sketch (cognitive process) and immediately thereafter to think about the internal presentation by using a diagram or drawing only (cognition). Reflection on the number of bonds between hydrogen and oxygen, the geometry of the molecule and the number of hydrogen bondings compels the student to change the original planning. If the student acts cognitively he will only draw the molecule as it was observed and memorised from the study content. This emphasises the importance of metacognition in the process of construction of knowledge (Locatelli et al., 2010).

Flavell (1978) defined metacognition in 1976 as “Metacognition refers to one’s knowledge concerning one’s own cognitive process and products or anything related to them...” Later he added the function of regulating and monitoring to the definition “...metacognition refers, among other things, to active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects...” (Flavell, 1978).

From the definition of Flavell, and from further literature three different aspects of metacognition can be deduced, namely knowledge of cognition (to know what thinking is like), monitoring of cognition (to observe) and regulating of cognition (to control) (Flavell, 1978, 1979 & Tobias & Everson, 2002).

In the past researchers like Cavanaugh and Pelmutter (1982) considered regulating and monitoring as essential. Knowledge was the focus point as explained by the following statement: “inclusion of executive process as an aspect of metamemory is counterproductive, since it adds little to understanding of memory knowledge per se and heightens perceptual confusion...” Study of more recent sources shows that regulating and monitoring play a more prominent role and that the primary focus is no longer on knowledge only (Cooper, Sandi-Urena & Stevens, 2008).
Later research acknowledged the important role of metacognition in learning (Cooper et al. 2008). There is consensus that the metacognition skill plays a very important role in problem solving (Antonetti, Ignazi & Perego, 2000; Cooper et al., 2008 & Sandi-Urena). As soon as the student is able to apply metacognition he can accelerate his own learning and will have knowledge of his own cognition. He himself can regulate his learning and accept ownership for his future learning. Knowledge can then be kept up to date dynamically and they can plan the future themselves (Everson & Tobias, 1998). Everson and Tobias proposed the pyramid below (Fig. 2.3) as a hierarchical model of metacognition.

![Model of metacognition](image)

**Figure 2.3: Model of metacognition (Tobias & Everson, 2002)**

At the base below, knowledge is first monitored so that more advanced metacognitive processes can take place, namely evaluation of knowledge, selection of strategies for solving problems and planning problem solving. Tobias and Everson (2002) emphasised that it is important first to identify what the student knows and does not know before moving upwards in the pyramid, in other words, being able to regulate and control his learning by himself. This concurs with what Cavanaugh and Pelmutter said already in 1982 about the importance of knowledge. It serves as a building block for the succeeding metacognitive processes. This model of metacognition is considered as the most effective and applicable for this study where the role of metacognition in stoichiometry was studied. During the process of metacognition in stoichiometry, existing knowledge should first be monitored to ensure that students have the correct and adequate knowledge. Subsequently it should be evaluated whether learning was adequate and whether students have the correct and suitable problem solving skills to solve the stoichiometric problem under consideration. Thereafter strategies may be chosen that can be
applied in the problem solving. Lastly the suitable planning of strategies can be done, giving rise to effective solving of a given stoichiometric problem.

From the above-mentioned discussion it is clear that the development and teaching of metacognitive skills are very important for students in their ability to solve scientific problems (Haidar & Naqabi, 2008 & Howard et al., 2000).

2.4.2 Metacognition in the teaching of stoichiometry

Schraw (2001) states clearly that metacognition can be taught. It should take place purposefully to help students to become conscious of their own metacognition (Martínez-Jimenez, Pontes-Pedrajas Polo & Climent-Bellido, 2003). Teaching that encourages students to reflect on how and why they think, remember, learn and perform tasks, can help students to have more control of their own learning. Teaching is more effective when the lecturer presents metacognitive strategies in the context of the subject. The student should be given an opportunity for applying and integrating it in general learning activities (Schraw, 2001). In a study by Abdullateef et al. (2008) it clearly came to the fore that every step in the solution of stoichiometric problems forced the students to work metacognitively. In this specific study the students had to monitor and evaluate the new information, regarding the context of the information, during the metacognitive process. The students record the concept internally by an integrated natural process of conceptualisation and internal visualization that are continuously regulated by metacognition.

Abdullateef et al. (2008) studied the relationship between the understanding of stoichiometry and the use of metacognitive strategies for Grade 11 students. The results of this study emphasised that students’ understanding of stoichiometry can be predicted by considering the extent to which they use their metacognitive strategies. They further proposed that chemistry teachers should teach metacognitive strategies to their students.

There are two aspects from the research of Abdullateef et al. (2008) that pave the way for future study. First, the stoichiometric problems that are used to test the students’ understanding of the concept are extremely algorithmic. It implies that students master the steps in the process of solving problems but they do not necessarily understand what they are doing. Secondly a more direct link between metacognitive skills and problem solving can be investigated.

One of the techniques to help developing metacognition is by questioning. Baird (1998) helped physical science students to become better thinking learners by including purposeful questioning in the learning activities. He supplied his students with a checklist of questions that
helped them in solving problems. Key questions that were included were questions like: “What do I know about this topic? Have I read the supplied information thoroughly? How are the parts of the topic related? How am I going to approach this assignment? What do I need to execute this assignment fully? How does the new knowledge relate to my previous thoughts?”

Students’ metacognition can be measured by using an inventory of metacognitive self-regulation (Howard, McGee, Shia & Hong, 2000). This inventory has been adapted for the purpose of this study (Annexure A). Planning questions include: “What is my objective? What information and strategies are needed? Evaluation questions include: Have I reached my objective? Will I do it differently next time?” (Howard et al., 2000).

In this study an attempt was made to bring about a link between metacognition and problem solving. Problems given to students in assignments and projects were of such a nature that students were forced to “think about how they were thinking” in solving problems.

2.5 PROBLEM SOLVING

2.5.1 Definition and description

Stoichiometry problems are fundamental chemistry problems in which the amount of reactants and products in a chemical equation are compared by using ratios obtained from balancing the equation. The calculations are based on the mole concept, mole ratio and proportionality. Students will meet these concepts in chemistry where conservation of mass, solutions and concentrations, gas laws, rate of chemical reactions, chemical equilibrium and electrochemistry are addressed (Abdullateef et al., 2008).

Chemical problems can be of a qualitative or a quantitative nature. In the case of qualitative problems students have to give an explanation of the conceptual knowledge they have. In the case of quantitative problems it is expected of the students to integrate conceptual knowledge with mathematical skills (Abdullateef et al., 2008).

In chemistry the mole is a fundamental concept that forms the basis of various chemical calculations especially in stoichiometry. A study of the literature gives insight into the reason why students still have problems with calculations regarding the mole concept.

2.5.2 Teaching problem solving in stoichiometry

With traditional teaching of stoichiometry at secondary level, the lecturer usually starts explaining the four general steps in solving problems typically found in in the textbook.
Stoichiometry is further illustrated by examples. Lastly students are expected to solve problems. This plan of action is exclusively based on the application of various algorithms that does not promote conceptualisation (BouJaoude & Bakarat, 2003). This was confirmed by research that showed that students are considerably more successful with solving problems that require application of an algorithm than with problems that require a deeper conceptual understanding (Arasasingham et al., 2004; BouJaoude & Bakarat, 2003; Mason et al., 1997; Mulferd & Robinson, 2002; Sanger, 2005; Schmidt, 1990, 1997; Wolfer & Lederman, 2000). Students are taught to tackle problems in a certain stepwise manner. As soon as the problems are of such a nature that critical thinking and proper understanding of the concepts -- instead of the algorithmic approach -- are needed to solve them, the students have difficulties in solving the problems (Sanger, 2005).

Wolfer and Lederman (2000) conducted interviews with first year students to determine their success in calculation and conceptual questions. They found that students have various misconceptions regarding mole ratios (stoichiometric coefficients) as well as a weak link between sub-microscopic and macroscopic levels of chemistry. Similar findings were obtained by Mulferd and Robinson (2002). They analysed first year students’ understanding of various chemical concepts, inter alia stoichiometry. They found that students have wrong concepts of the topics studied. Abdullateef et al. (2008) found in their study that 44% of the students confuse subscripts with coefficients when they have to write down visualised reactions in balanced chemical equations. Previously Schmidt (1990) found that students confuse mole when they have to rewrite visualised reactions into balanced chemical reactions and that students become confused with the molar masses and reactant masses in reactions. Schmidt found in another study (1997) that the inability of students to solve problems originates in the lack of understanding the mole concept. From the results of the above-mentioned research it can be deduced that there are various problems regarding the understanding of basic concepts of stoichiometry.

Students should be taught to understand concepts and to be able to apply them in problem solving. BouJaoude and Bakarat (2003) studied the problem solving strategies in stoichiometry in relation to the conceptual understanding and learning approach of Grade 11 Lebanese students. Arasasingham et al. (2004) investigated the relation between learning-space theory and the students’ understanding of the stoichiometric concept. Both found that the students’ frameworks of conceptual understanding were very weak. Students had certain factual knowledge but they could not apply it to solve conceptual problems. The researchers ascribed this deficit to a lack of comprehensive teaching. On the other hand Chiu (2001) studied the ability of Grade 11 Taiwanese students to solve algorithmic problems and their conceptual
understanding. He found that students performed notably better in questions comprising problem solving than in questions testing conceptual understanding. Mason et al. (1997) investigated the difference in methods used by students in algorithmic problem solving and in conceptual problem solving. Findings showed that inexperienced problem-solvers had greater success in solving algorithmic problems than conceptual problem-solvers. Nakhleh (1993) did a study to identify students' conceptual understanding of chemistry. She found that students experienced more problems in answering conceptual questions than algorithmic questions. It is clear from these studies that students in general have adequate factual knowledge but they are incapable of applying it.

Further problems in the teaching of stoichiometry include:

a) Students’ long-term memory is inadequate and they have an inability to recall knowledge. Students have a chemical knowledge base that is stored in their long-term memory. They should find the link between the current problem and the knowledge stored in their long-term memory. Previous knowledge should be integrated in the process of solving the problem. This process is specifically challenging for students that are confronted with open-ended questions since they are unsure whether already existing knowledge is applicable in an unknown problem (Reid, 2009).

b) Students lack mathematical skills. They understand the basic chemical concepts but they cannot do the mathematical manipulations correctly (Abdullateef et al., 2008).

c) Students are totally dependent on algorithms, where the algorithm is considered as the only problem solving technique. They learn the steps by heart and do not understand what they are doing. As soon as they are confronted with problems which upset the normal algorithmic order, they cannot solve the problem (Hand, Yang & Bruxvoort, 2007).

The development of teaching methods to help students to obtain a better understanding of stoichiometry has been well researched. The researcher used two methods of teaching: teaching according to prescribed algorithms and teaching to develop conceptual understanding. Results confirmed that these teaching methods promoted the problem solving ability of students.

It is clear from the above-mentioned research that alternative approaches regarding the solving of problems have a definite influence on the general solving of stoichiometric problems.
2.6 SUMMARY

In this chapter literature on the role of visualization, critical thinking and metacognition in the conceptualisation and problem solving of stoichiometry was uncovered. It is clear from the literature that each of these skills plays a significant role in problem solving in stoichiometry.

The whole process of visualization begins as an external action where after visualization takes place internally, where the student forms intellectual images that are regulated metacognitively. A learning environment, where students can develop critical thinking by participating actively in the investigation of knowledge and its application, is favourable for the development of critical thinking. The end result is where students can think for themselves and can solve problems.

The findings from the literature in this chapter were used to adapt the teaching-learning approach of first year students in stoichiometry. In the following chapter the research project, as it was done, is presented in the form of an article.
CHAPTER 3: THE IMPACT OF CRITICAL THINKING, VISUALIZATION AND METACOGNITIVE STRATEGIES ON THE CONCEPTUAL UNDERSTANDING OF STOICHIOMETRY OF FIRST-YEAR CHEMISTRY STUDENTS.

ABSTRACT

The purpose of this study was to develop the conceptual understanding of first year chemistry university students in stoichiometry by implementing learning experiences associated with higher-order thinking skills, visualization of concepts and using the metacognitive skills.

A quantitative research and experimental design was used. The group was subjected to a pre-test and a post-test. The main aim was to determine if significant differences between the students’ levels of conceptualisation in stoichiometry existed, after they had been exposed to critical thinking skills tasks, several forms of visualization as well as tasks aimed at the development of metacognitive skills.

Although research has shown that conceptual understanding of students in stoichiometry can be improved by visualization, critical thinking skills and metacognition, there is no indication in literature of what the impact of the synergetic implementation is on conceptualisation in stoichiometry with students.

From the quantitative data-analyses in this study, the observation can be made that first-year chemistry students who were actively taught in critical thinking, showed a remarkably improved conceptual understanding in stoichiometry.

The visualization techniques to which students were exposed, improved their conceptualisation in stoichiometry. The development of students’ metacognitive skills improved their planning strategies for problem solving and their ability to achieve a successful solution.

From the quantitative data-analysis, the conclusion can be made that students’ conceptualisation in stoichiometry visibly improved. The synergetic implementation of critical thinking, visualization and metacognition indeed made a difference in the conceptualisation of stoichiometry and the test performance of students.

Key words: visualization, conceptualisation, stoichiometry, critical thinking, metacognition, chemistry teaching.
3.1 INTRODUCTION

Stoichiometry is the study of the numerical relationship between chemical quantities in a balanced chemical reaction equation. Stoichiometry involves the calculation of the amounts of products formed if the amounts of reactants are known or the amounts of reactants necessary to give a certain amount of products. Stoichiometry is also used to determine how much of one reactant is required to react completely with another reactant to give the expected products. Stoichiometry is based on the laws of definite proportions, and on the laws of conservation of mass and matter (Kotz et al., 2012). Concepts and common terminology in stoichiometry are: the mole concept; mole ratios; mass-mole calculations; limiting reagents; mass percent; percent yield (theoretical yield and actual yield); formula determinations (empirical and molecular formulas); concentration and titration calculations; and analysis of mixtures (Kotz et al., 2012).

The teaching and learning of chemistry, and especially stoichiometry, are very challenging for students and lecturers at tertiary level. Stoichiometry concepts and phenomena appear throughout the subject area of chemistry. Therefore, stoichiometry forms an integral part of the chemistry curriculum at first-year level. Students find stoichiometry challenging and difficult due to the complexity of chemistry as a subject (Arasasingham et al., 2004).

In South Africa researchers such as Huddle and Pillay (1996) and Potgieter, Davidowitz & Venter, (2008) and Potgieter, (2010) found, in different studies that first-year students are not prepared for chemistry at tertiary level. Huddle and Pillay highlighted misconceptions like:

(a) “limiting reagent implies lowest stoichiometry” and
(b) “ignoring the stoichiometry of the balanced equation, lowest calculated moles indicated limiting reagent” (Huddle & Pillay, 1996).

Potgieter, Davidowitz & Venter, (2008); Potgieter, (2010) found misconceptions and mistakes such as:

(a) confusion of coefficients versus subscripts,
(b) no conservation of atoms,
(c) confusion between mole and molecule,
(d) “using the mole as counting unit for atoms, molecules and ions”,
(e) solution weighs less than the solvent plus the solute, and
(f) conservation of mass is incorrectly applied to reactions (mass, atoms, molecules).

Internationally the most common misconceptions in stoichiometry were identified as the following:
(a) Students “equate the mass ratio of atoms in a molecule with the ratio of the number of these atoms, and the mass ratio with the molar mass ratio” (Schmidt, 1990).

(b) Students “calculate the molar mass of a given substance by summing up the atomic masses and then multiplying or dividing this sum by the coefficient of the substance in the chemical equation; others do not understand the significance of the coefficients in a chemical equation at all” (BouJaoude & Barakat, 2000).

(c) Students “confuse the concepts of conservation of atoms and possible non-conservation of molecules or do not take into account the conservation of atoms or mass at all” (Mitchell & Gunstone, 1984).

(d) Students “cannot determine the ‘limiting reagent’ in a given problem, when one substance is added in excess” (Huddle & Pillay, 1996).

(e) Students “confuse or do not know the definitions of and relationships between stoichiometric entities in general” (Furió et al., 2002).

(f) Students “believe that one mole means the same as one particle” (Fach, De Boer & Parchmann, 2007).

Teaching strategies are rarely tailored to support students with the learning of stoichiometry. Stoichiometry teaching mostly occurs according to the traditional algorithmic approach. The algorithmic approach does not address or improve the students’ comprehension and critical thinking skills (BouJaoude & Barakat, 2003 & Hafsah, Rosnani, Zurida, Kamaruzaman & Khoo, 2014). There is an urgent necessity for research in chemistry teaching to students. Research should cover innovative and effective alternative teaching strategies that promote the conceptual understanding of stoichiometry in first-year students (Hafsah et al., 2014). The current research focused on the improvement of conceptual understanding through systematic integration of visualization during lectures and the development of critical thinking and metacognition in stoichiometry assignments of first-year chemistry students at a South African university.

In order to reach the research purpose presented above, the following research questions had to be answered:

1) What will the impact of teaching strategies, focussing on the development of higher order thinking skills, be on first year students’ conceptual understanding of stoichiometry?

2) What will the impact of visualization be as a tool on the structure and content of the students’ stoichiometry knowledge?

3) What will the effect of metacognitive regulation be on test performance of students in stoichiometry questions?
4) What will the effect of the concurrent integration of thinking skills, metacognitive strategies and visualisation be on the conceptualisation of first year students in stoichiometry?

3.2 LITERATURE REVIEW

3.2.1 The teaching of chemistry and stoichiometry in general

Chemistry teaching traditionally takes place according to the lecture method, with concomitant use of textbooks, learning unambiguous and authoritative theories and rules, and the principle that in general only one correct solution for each problem is possible (Nakhleh, 1992). The predominant approach, to teaching at school and at university in South Africa, is a more traditional approach of stepwise solving of algorithms. The solving of algorithms involves four main steps as prescribed in textbooks and highlighted by examples (Kotz et al., 2012). This method requires the student to follow the same "recipe" for similar problems. This approach focuses solely on the use of various algorithms, without guiding the student to conceptual understanding (Pushkin, 2007). With typical traditional problem solving in stoichiometry, it is expected of the student to select algorithms, to adapt the algorithm to the specific problem, and to apply the algorithm to the specific problem (Othman et al., 2008). Several studies have confirmed that students, at tertiary level, mainly use these traditional algorithms to solve problems (BouJaoude & Barakat, 2003; Othmen et al., 2008 & Lythcott, 1990).

A number of studies have been done on the teaching and learning of stoichiometry in chemistry. Some studies concentrated on teaching, and other studies concentrated on learning.

Examples of studies on learning stoichiometry are:

- “Students’ understanding of stoichiometry and the influence of metacognition on their understanding” (Haidar & Naqabi, 2008).
- “High school chemistry content background of introductory college chemistry students and its association with college chemistry grades” (Tai et al., 2006).
- “Depth versus Breadth in high school science content relates to success in college chemistry coursework” (Schwartz, Sadler, Sonnert & Tai, 2008).
- “Students’ strategies in solving algorithmic stoichiometry problems” (Schmidt & Jignéus, 2003).
- “Students’ problem solving strategies in stoichiometry and their relationships to conceptual understanding and learning approaches” (BouJaoude & Barakat, 2003).
Examples of studies on teaching stoichiometry are:

- Constructivist instruction (Okanlawon, 2012).
- Understanding the underlying conceptual foundation of stoichiometry before introducing algorithmic problem solving (Hafsah et al., 2014 & Nakhleh, 1992).
- “Exploring and acknowledging chemistry teachers’ pedagogical content knowledge i.e. how teachers understand and teach reaction stoichiometry” (Okanlawon, 2010).
- Teaching to enhance problem solving (Phelps, 1996).
- “The development of Stepped Supporting Tools for stoichiometry problems” (Fach et al., 2007).
- Using audience response systems during interactive lectures to promote active learning and conceptual understanding of stoichiometry (Cotes & Cotua, 2014).
- “Interactive demonstrations for mole ratios and limiting reagents” (Wood & Breyfogle, 2006).

These studies represent a wide variety of different methods and teaching strategies, and one or more aspects of these studies have been used in the current study.

3.2.2 Problems in stoichiometry

The Potgieter (2010) study showed that nearly 70% of first-year students at a South African university experienced conceptual problems in stoichiometry. It may be that this result will be similar at other universities. The strongest determinant of conceptual understanding of stoichiometry is previous exposure to stoichiometry (Wood, 2006). If students already lack conceptual understanding at school level or formed erroneous concepts, it will seriously handicap the student's conceptual understanding formation at university level (Yang et al., 1988 & Tai, Ward & Sadler, 2006). Huddle and Pillay (1996), in an earlier study among South African students, found that misconceptions about stoichiometry are very difficult to correct.

Researchers studied students’ stoichiometry concept formation (Arasasingham et al, 2004; BouJaoude & Bakarat, 2003 & Schmidt, 1997), and found students were significantly more successful in solving problems involving the application of algorithms than with problems that required deeper conceptual understanding and critical thinking (Phelps, 1996). Bailin (2002) also suggested that students often lack the necessary skills of self-directed learning to perform chemistry assignments that require critical thinking.
3.2.3 Effective teaching of stoichiometry

Several studies have been conducted to try to determine what teaching approaches will promote learning and conceptual understanding of stoichiometry (Nurrenbern & Pickering, 1987). Students use various problem solving strategies, but they turn mostly to algorithmic problem solving even when they do not understand the relevant chemistry concepts (BouJaoude & Barakat, 2003). Students achieve better results with algorithmic problem solving than with problems that require conceptual understanding of chemistry concepts (BouJaoude & Barakat, 2003). These results indicate a lack of conceptual understanding, which students try to bypass by using “recipes”. The focus in teaching should be on the understanding of chemistry concepts rather than on the memorizing of chemistry concepts.

3.2.3.1 Critical thinking

According to Zoller (1993) several teachers saw the development of students’ critical thinking as one of the main goals of education at all levels, especially in the context of higher-order thinking in the advancement of learning in science education. In chemistry education, critical thinking is conceptualised as a result-guided activity, which should first decide what knowledge is correct and useful, secondly, what procedures will be followed, thirdly, the output of the command itself, and finally the acceptance of responsibility for the outcome (Zoller, 1993).

Students can learn critical thinking if they are taught to think critically (Ten Dam & Volman, 2004). Ben-Chaim, Barak, Overton & Zoller, (2005) and Ben-Chaim, Barak, Lubezky and Zoller, (2006) found that the development of students’ problem solving ability and critical thinking is attainable through the use of persistent purposeful higher-order thinking- and problem solving activities and the use of better teaching and assessment strategies. Critical thinking in chemistry is crucial because it promotes meaningful learning.

This article describes how critical thinking among first-year chemistry students was promoted by first showing basic stoichiometry concepts visually and by enabling the use of visualization, animation and online tutorials, as well as the inclusion of evaluation tasks and metacognitive activities on an on-going basis. All the activities and assignments required higher-order thinking skills of the student.
3.2.3.2 Visualization in Chemistry

The foundation of theoretical chemistry education is the continuous change between the different domains of chemical thinking: the macroscopic, sub-microscopic and symbolic domains (Johnstone, 1997). Because the sub-microscopic domain cannot be seen or cannot be visualised directly, it requires very specific types of visualization. Niaz and Robinson (1993) emphasized that the ability of students to visualise is important for solving conceptual problems. The use of visualization is important to promote students’ learning. Noh and Scharmann (1997) found that teaching, with visualization of the molecular level, helps students to obtain more scientifically correct perceptions. Photos, animations and simulations are powerful visualizing instruments that promote students’ understanding of three-dimensional structures (Williamson & Abraham, 1995). Visualization also contributes to the development of learners’ spatial abilities (Arasasingham et al., 2004). Visual aids help to reduce students’ misconceptions about basic chemical concepts and methods (Sanger & Greenbowe, 2000 & Yang et al., 2004), and increase students’ motivation for learning chemistry (Tsui & Treagust 2004). Krieger (1997) made use of flow charts, based on the three domains. Witzel (2002) represented microscopic domains by using LEGO blocks and Haim et al. (2003) compared the stoichiometric processes to making a hamburger. Photos and animations illustrate that individual particles, atoms, or molecular structures are based on chemical models and help to improve stoichiometric conceptual understanding.

Static visualization (such as photos, diagrams and flow charts) is usually found in textbooks, and can easily be incorporated into learning. Visualization in textbooks often focuses only on the details of the experiments, and not on the explanation of the scientific process and the investigations that support these experiments. The processes and the prior investigations can help the learner to understand the purpose of the experiment (Niaz, 1998). Levie and Lentz (1982) noted that students are not necessarily helped by the use of text-redundant visualization to understand the content. This is particularly true in the case of poor readers. Stieff (2011) and Plass et al. (2012) have shown that students perform better when dynamic visualizations instead of static visualizations are used. In dynamic visualization concepts are added that support the understanding of the sub-microscopic world (Mayer, 2003). Students can then visualise the dynamic nature of the sub-microscopic world and this can help students to understand the chemistry concepts relevant to the topics (Sanger & Greenbowe, 2000; Kozma & Russell, 2005a, 2005b & Yang et al., 2004).

It is important to realise the factors that may limit the positive effect of visualization (static or animated). Some of these factors, that limit the positive effect of visualization, may be the lack of metacognitive skills (Azevedo, 2004 & Schwartz et al., 2004); a lack of students’ fore
knowledge; overestimating the ability of learners to recognize and use proper spatial relationships (Lee, 2007); limited learner attention (Ploetzner et al., 2008); and the inability of students to make the correct relationships between the symbols used in the visualization and the chemical concepts they represent (Jones et al., 2005). Eilks (2003) and Hill (1988) warned that the visualization can impede correct concept formation or even delay the learning process. Students can correctly recall what they have observed in an animation and make the appropriate sketches, but that is not to say that they understand what they have observed (Kelly & Jones, 2007). Learning through visualization is based on a meaningful process that can only lead to effective learning if the relationship between the visualization and the prior knowledge of the learner is clearly indicated (Schnotz & Bannert, 2003). Visualization should also describe the scientific concept correctly (Hill, 1988). It is therefore important that the concepts should be structured visually correct; taking into account the learners’ prior knowledge of the subject, for effective learning to take place. The relationship between the scientifically correct explanation, the sub-microscopic model for the task, and the nature of the explanation itself must be clear (Eilks et al., 2009).

3.2.3.3 Metacognition in chemistry

Metacognition is very important for the development of good problem solving skills and achieving conceptual understanding of chemistry (Cooper et al., 2008).

“Metacognition involves three dimensions. These are knowledge about oneself, knowledge about the thinking process, and controlling of one’s commitment, attitude and attention to learning new or complex tasks” (Pulmones, 2003).

Controlling the thinking process involves planning, regulating and evaluating (Pulmones, 2003).

These skills and actions are all part of a self-directed learner’s tool kit. They are also part of the process of successfully executing an assignment or task. If students think about what they are doing and are committed to complete a task or learning activity to the best of their ability, these would be the steps they would follow and the attitudes they would bring to the task at hand.

The research question for this study is: How will visualization and the inclusion of assignments that require critical thinking and metacognition influence first-year students’ understanding of stoichiometry? This paper considers the central role that critical thinking, visualization and metacognitive strategies play in the reinforcement and modification of conceptual understanding in stoichiometry.

In the next part of the article the empirical research are presented. Specific visualization
techniques have been used to improve understanding of stoichiometry and innovative assessment tasks and thinking skills exercises were included to improve critical thinking skills of first-year chemistry students.

3.3 METHODOLOGY

A quantitative research approach was followed to determine the impact of critical thinking, visualization and metacognitive strategies on the conceptual understanding of stoichiometry of students. The same group of students completed a pre-test and a identical post-test (Creswell, 2003), (Annexure A), which consisted of 24 multiple choice questions. The test is based on knowledge and application of important stoichiometric principles. This test should be an indication of the student's previous exposure to and retention of specific stoichiometric subject matter that is considered important for the conceptual understanding of various stoichiometric problems. Both the pre-test and post-test was given to students to write without prior test preparation.

A purposive sample was used for this study. All the students, registered for the first-year chemistry module, were asked to participate. A total of 798 students wrote the pre-test before the start of the intervention, and 713 students completed the identical post-test about three months later. Although the intervention took place consistently over the entire semester covering all the study modules, the post-test was only conducted three months after completion of the study unit on stoichiometry. The intervention consisted of the implementation of specific teaching visualization techniques, the development of critical thinking skills and the practicing of metacognitive strategies. The teaching media used were PowerPoint slides, a document camera, computer animations, an electronic Learning Management System (LMS) and textbooks. The assignments were evaluation assignments, thinking skills assignments, and a mini-project. The tests were pre- and post-tests.
3.3.1 Critical thinking

In the mini-project, several higher-order questions were given to students. These questions consisted of stoichiometric problems based on the subject matter, and the various steps of interpretation, planning, presentation and execution were required. The students had not been exposed to these questions previously, and more was required from the student than knowledge and simply the application of algorithms. Questions in the mini-projects required the student to acquire new knowledge in the process of solving the problems.

After each question was answered, students also had to demonstrate and verbally describe exactly how they arrived at the answer. In this way, students were forced to be more critical about how they think about the solution of the problem, the challenges they experienced and the meaning or purpose of the answer of the problem.

Four evaluation tasks were given during the course of the semester, to learn, to practice and to get used to the process of critical thinking. Initially the students found the evaluation tasks confusing. The students were not accustomed to working on higher-order thinking problems. During the evaluation tasks, higher order skills of Bloom’s taxonomy were required of the student. Skills such as synthesis, where a memorandum and mark scheme must be set up, and evaluation, where they had to evaluate other students’ answers, and scoring, where they had to submit a mark for students’ responses, were required of the students.

For the first phase of the evaluation tasks, students worked together in groups and an evaluation role was fulfilled. The students had to set a complete memorandum with a mark scheme for the questions (from previous years’ examination papers) asked. During the second phase, the students received written responses of a previous year’s student’s (anonymous) question paper, to mark. The written responses, on previous papers, were legitimate responses from real students. Some written responses were correct, others partially correct and others were completely wrong. The student had to mark the written responses according to their marking schemes and give a score for the relevant answers.

The lecturer assessed the correctness of the marking scheme of the student, and the correct application of the marking scheme to the written responses. In the next phase, the students were given the opportunity to compare their memos and their marking scheme application to the correct memo and mark scheme of the lecturer. They were allowed to improve their memo and marking application before final submission of the tasks.
In the **thinking skills tasks**, a similar approach was followed where students had to describe their problem solving process in words. Two similar thinking skills tasks (questions from the textbook) were given to the students over the course of the semester in which their thinking skills were exercised. One of the questions asked the students to describe how they would make a solution, with a specific concentration, of a given chemical compound, by using a volumetric flask. This assignment only allowed a verbal description of the process and not a numerical calculation. The focus was on the thinking skills and the thought process, not on the calculations.

### 3.2.2 Visualization

A document camera was used as visualization instrument. The purpose was to show students visually the solution step by step of the problems. Examples and illustrations from textbooks were also shown directly to the class. A visual information bridge was created for students between learning materials used in class and the subject matter that had to be mastered later, outside the classroom. Digital images of relevant and appropriate stoichiometry problems were made electronically available to students on the LMS. The lecturer had also consistently made use of additional visual animations and Power Point slides. Students were encouraged to use the online sites of the textbook, as indicated via the LMS, for additional teaching support. All supporting study materials were also made available to the students on the LMS.

There were 19 Khan videos placed on the LMS with topics: stoichiometry and solution chemistry (mole ratios and concentration); limiting reagents explained; limiting reagent problems; definitions and basic principles of stoichiometry; and the mole concept and Avogadro’s number.

There were also 21 complete class examples, done by the lecturer, and placed as digital images on the LMS. The topics were: examples from the study guide; mass percent; theoretical yield and actual yield; percentage chlorine in a complex; percentage crystal water in copper (II) sulphate or other hydrated compounds; and limiting reagent problems.

### 3.3.3 Metacognition

The **mini-project** (Annexure B) consisted of four questions (Q1 – basic stoichiometry principles; amount of reactant A necessary to react completely with reactant B; total mass of products produced [11 marks])(Q2- atom-mass relationship; mass-mole relationship; formulas; molar mass; balanced equation; mass-mass relationship; limiting reagent calculations; actual yield-mass relationship; empirical formula; mass reactant-mass product [24 marks])(Q3-empirical
formula; mass reactant-mass product [13 marks])(Q4-concentration problems [8 marks]). Each question was followed by two types of reflection: first three open questions (concepts; planning; steps followed) and then 21 questions answered according to a Likert scale. The students had to reflect on each question they answered. The mini-project was an individual assignment, but students could use resources or discuss possible solutions with peers.

The main measuring instrument of the research project was the pre-test-post-test questionnaire with the different interventions (visualization techniques, evaluation tasks, thinking skills assignments and the mini-project) to provide an impact on the research results.

3.4 RESULTS AND DISCUSSION

3.4.1 Critical thinking

The results of the first evaluation task (atoms, ions, molecules) were ignored and did not contribute to the final participation marks of the students. There were too many uncertainties and problems among students about the assignment that may have influenced the reliability of the data. In the second task (chemical reactions), more reliable data were obtained and the class average was 54% (n = 908). The third evaluation assignment (stoichiometry) had a class average of 75% (n = 905) and the fourth evaluation assignment (equilibrium) had an average of 83% (n = 905). It is clear from these results that the students gradually become accustomed to the process of evaluation and critical thinking, however, a single twelve-week semester alone is not sufficient to enhance critical thinking. Research indicated that teaching general “critical thinking skills” should be in combination with the learning of content knowledge to enable students to transfer the thinking skills to new situations and new problems. The transfer of thinking skills only take place successfully if it is taught under the right teaching conditions (Rickey & Stacy, 2000).

In the thinking skills assignment about solution concentrations: 40% of the students used the volumetric flask incorrectly. They mix the salt and solvent before transferring the solution to the volumetric flask. Some students view the white salt that dissolves into a colourless solution as a chemical reaction because of the “colour change”. Many students want to write down a balanced chemical equation and immediately calculate the number of moles of salt that will dissolve in the number of moles of water. (They argue according to a set recipe instead of according to the problem set before them.) They want to calculate mole ratios to determine how much water is needed for the salt to dissolve. Others want to heat the volumetric flask to obtain
the “product” faster. The students consider the solvent as the limiting reagent of the "reaction". Results of the assignment indicate a lack of practical skills as well as a lack of thinking skills and logical argumentation.

3.4.2 Visualization

From a total of 942 students registered on the electronic (LMS) 930 students (99%) have visited the environment in the course of the study. Only 11 students (1%) did not visit the LMS site at all. The students' confidence in the lecturer’s authority is instructive. Despite the fact that the online videos (prescribed by the textbook) are audio-visual and the lecturer’s resources are only photos (digital images), the students chose to use the photos as learning support material. Of the 19 published online videos related to stoichiometry, the video that most students opened, were opened by only 160 students (a video about Avogadro’s number and the mole concept). The video least opened, were opened by only 50 students (solution stoichiometry with mole ratios and concentration calculations). On the contrary, the photos provided by the lecturer on LMS were opened much more. Of the 21 photographs that relate to stoichiometry, the photo that were opened most, were opened by 767 students (mass percent of chlorine in a complex chemical compound). The photo that were opened the least, were opened by 279 students (mass percent of sulphur in a chemical compound). If these results are compared with the results of the mini-project, the noted frequency is related to the problems students experienced with the concepts in the mini-project.

3.4.3 Metacognition

The mini-project was completed by 868 students, and a class average mark of 64% was obtained. The results of the mini-project were interesting. The class average for question 1 (mole ratios) was 62%, the average for question 2 (limiting reagents) was 74%, the average for question 3 (empirical formula) was 63 % and the average for question 4 (solution stoichiometry) was 32.8%. The questions students considered as less challenging, received the poorest results. The questions the students considered challenging were tackled with more attention and consequently achieved better scores. According to the project results, limiting reagents remain a guessing game rather than a conceptual understanding achievement. The answers to the three open metacognitive questions posed difficulties for the students.

- Which chemistry concepts came to mind first when you read the question?
- How did you argue or plan to solve the problem (tell your story)?
Write down the steps you followed to solve the problem?

Identifying the correct chemistry concepts proved to be a problem. Some students are very general and vague (like stoichiometry and organic chemistry) and some report unrelated concepts (like rounding off, fuel, motorcars, engines). Some students think about concepts that are given in the question (like “how toluene’s formula looks and how I will get it?”). Very few students show evidence of a logical and analytical mind. Evidence of a logical and analytical mind in this study is taken as a student who can correctly and concisely give the relevant concepts, show good planning and execute all the necessary steps to solve the problem.

In the 21 question metacognitive task the following were some of the results: students are very dependent on the lecturer; 30% don’t understand the problem they have to solve; students think they can identify the main concepts, but in actual fact they have the concepts wrong; 37% never review steps they have taken in problem solving; 42% don’t check for mistakes in problem solving; 30% don’t consider the meaning of the answer obtained; 53% cannot immediately identify the correct formula to use in problem solving; 79% stated that they obtained new understanding by solving the problems; 95% stated that the questions forced them to think in greater depth about the problems; 53% were only interested in calculating the answer and not in the meaning and purpose of the answer; 32% said the assignment was challenging.

The main results were students’ overconfidence in their problem solving abilities. The students’ evaluation of their skills does not correspond with their real achievement scores. Students often think there is only one method to solve the problem (47%). Students (63%) cannot think of a different method to solve the same problem. Students have an inability to think and describe the problem solving in words. This result can be attributed to a number of reasons, but language difficulties should not be a hindrance because most students in this study are mother tongue learners. As deeper conceptual understanding of stoichiometry is the aim of the study, lecturers should include more and regular metacognitive tasks during the general chemistry course (Rickey & Stacy, 2000).

3.4.4 Total impact of critical thinking, visualization and metacognition strategies as determined by the questionnaires of the pre-test and post-test

The results of the pre-test and post-test showed that there were improvements in the misconceptions students had in stoichiometry. The results of the pre- and post-test are given in Table 1. The percentage of correct answers in the pre- and post-test was compared with each other. Statistical significance (p-values) and practical significance (d-values) were determined (Ellis & Steyn, 2003).
The students' pre-test-post-test responses were analysed by three chemistry lecturers to identify possible reasons for the students' performance. Statistical analysis for the complete test shows that students scored significantly higher marks in the post-test than in the pre-test. The number of students that performed poorly in the pre-test is significantly reduced in the post-test.
Table 3.1: Results of the stoichiometry pre-test and post-test of the first-year chemistry students.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Question nr</th>
<th>Pre-tests (n = 798)</th>
<th>Post-tests (n = 713)</th>
<th>Improve</th>
<th>p-value*</th>
<th>d-value**</th>
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<tbody>
<tr>
<td></td>
<td>% correct</td>
<td>% correct</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>15</td>
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<td>0.28</td>
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* p-value ≤ 0.5, statistically significant (Ellis & Steyn, 2003)
** d-value 0.5 (medium) - 0.8 (high): practically significant (Ellis & Steyn, 2003)

All the p-values are statistically significant according to Table 3.1, and the d-values of the grey coloured questions are of practical significance. In questions 4, 10, 11, 13, 15, 16, 23 and 24 there was a marked improvement of more than 23%. In questions 3, 8, 17, and 20 the average marks for the questions were below 50% after the interventions, indicating problems with the conceptual understanding. Questions 3, 17 and 20 showed improvements of 15%, but in question 8 there was no improvement.

In figures 3.1 to 3.12 the results of the individual questions (Annexure A) where an improvement of more than 23% were noticed, are presented and the underlying misconceptions are discussed.
Consider the graphs of individual question results with improvement above 23%:

Figure 3.1: Question 4 – Conservation of matter

The correct answer is option 3, and the strongest misconceptions are found in 1 and 2. The misconception in 1 was that the iron becomes lighter when it rusts (due to a macroscopic view of the phenomenon). The misconception in 2 was that there is no difference in mass before or after the rusting process (only conservation of iron and no conservation of balanced reaction). In the post-test there was an improvement in the correct conception, but still a significant number of students kept to misconception 1 even after intervention.

The possible reasons for conceptual improvement in post-test Q4 (question 4) can be the videos on conservation of mass, mini-project Q1, and stoichiometry problem solving in class.
The correct answer is option 1 and the strongest misconceptions are found in 3 and 4. The wrong answers are the results of incorrect calculations of mole, molar mass, concentrations or incorrect unit conversions. An improvement of 45% is observed (Table 1) after the intervention.

The possible reasons for conceptual improvement in post-test Q10 can be the Khan videos on mole concept and mole calculations, mini-project Q4, the lecturer’s class examples and digital images for review.
The correct answer is option 3 and the strongest misconceptions were found in 1 and 4. The misconception 1 is possibly the result of incomprehension or inattention when reading a question. The student has 40 mL and he dilutes the solution and gets 6.67 ml. The meaning of the word dilute is “to add more water”, however the student’s answer indicates a misconception of volume.

The possible reasons for conceptual improvement in post-test Q11 can be the Khan videos on solutions, mini-project Q4, the lecturer’s class examples and digital images for review.
Figure 3.4: Question 13 – The Mole concept

The correct answer is Option 1, and the strongest misconceptions are found in 2 and 3. The misconception 3 is the result of putting mole and molecules as equal amounts. Students calculate the number of moles and declare the number of moles as equal to the number of molecules. They ignore the significance of Avogadro’s number. Misconception 4 was a number equal to Avogadro’s number, an indication of students with no conception. Misconception 2 is the result of calculation mistakes.

The possible reasons for conceptual improvement in post-test Q13 can be the Khan videos on mole concept, mini-project Q1-Q4, the practice of more stoichiometry problems.
Figure 3.5: Question 15 – Mole Ratios

The correct answer is option 3, and the strongest misconceptions are found in 1 and 2. The misconception 2 is possibly the result of equating the mass and the molar mass of AlBr₃. The other misconceptions are due to incorrect mole ratios and an inability to understand the concept of ratios in chemistry.

The possible reasons for conceptual improvement in post-test Q15 can be the Khan videos on mole concept and mole calculations, mini-project Q2 and Q3, and more practice problems in stoichiometry.
Figure 3.6: Question 16 – Limiting reagents

The correct answer is option 2, and the strongest misconceptions are found in 1, 4 and 5. The misconception 1 is the result of taking the reagent with the lowest mass as the limiting reagent. Misconception 4 says that neither of the reagents is the limiting reagent and misconception 5 says that both of the reagents are the limiting reagents. These misconceptions are a clear indication that students do not know the chemical argument about why a reagent is considered a limiting reagent. The same results were found in the mini-project (Question 2).

The possible reasons for conceptual improvement in post-test Q16, Q23 and Q24 can be the Khan videos on limiting reagents, mini-project Q2, the lecturer’s computer animations, class examples and digital images for review.
Figure 3.7: Question 23 – Limiting reagents

The correct answer is option 2, and the strongest misconceptions are found in 1 and 5. The misconception 5 is the result of equal masses of limiting reagents, and therefore, the limiting reagents are present in equal amounts. Limiting reagents are a guessing game and not based on good conceptual understanding.
The correct answer is option 3, and the strongest misconceptions are found in 2, 4 and 5. The misconception 5 is possibly the result of believing that all chemical reactions go to completion and therefore the percent yield of the product must be 100%. The masses of the reagents are the same and in this case the smallest number of moles was legitimately the limiting reagent. Misconception 4 was the result of taking the moles of the one reagent the same as the moles of the product (ignoring the balanced equation) and thus calculated the percent yield incorrectly.

**Figure 3.8: Question 24 – Limiting reagents**
Consider the graphs of individual question results with average marks below 50%:

**Figure 3.9: Question 3 – Mole ratios**

Choosing O1 (option 1) implies no conservation of atoms and an incorrect molecular formula. O2 implies an incorrect molecular formula and conservation of atoms. O3 implies correct molecular formula, but no conservation of atoms. O4 is the conservation of atoms and correct molecular formula. O5 indicates confusion between subscripts and stoichiometric coefficients and incorrect molecular formula. Only 34% chose the correct distracter O4. The students had difficulty in correctly interpreting the visual images.
Figure 3.10: Question 8 – Mole concept

O1 (option 1) implies students have the misconception of seeing the mole as equal to the mass. O2 is the correct answer. In O3 students see mole as equal to Avogadro’s number never mind the mole ratios. The answer indicates a lack of conceptual understanding of the mole concept. O4 implies that atoms or molecules are equal to moles (a well-acknowledged misconception). Only 23% of the students indicated the correct answer and the interventions made no difference at all.
Figure 3.11: Question 17 – Limiting reagents

O1 implied that students equate mole ratios with mass ratios (as 17 moles is to 16 moles, so 73.3 gram is to X gram). O2 indicated that students used the correct limiting reagent to calculate the theoretical yield. O3 indicated that the wrong limiting reagent was used. The lowest moles, lowest mass reagent is seen as the limiting reagent. O4 students had the wrong concept about conservation of mass. They added the masses of the reagents to give the mass of the product without considering the limiting reagent or the moles at all. O5 is an indication of wrong calculations. Only 39% students had the correct answer although there was a 16% improvement after interventions.
O1 confuses the atoms (2 Al + 3 S + 12O = 17 atoms) with ions. O2 may possibly multiply the subscripts to get 6. O3 is the correct answer for a soluble ionic compound in water (2Al$^{3+}$ + 3SO$_4^{2-}$ = 5 ions). O4 may possibly just consider the polyatomic ions (3SO$_4^{2-}$). O5 see the compound as an iron and shows confusion between ions and ionic compounds. Most of the students had this misconception. Only 46% of the students chose the correct answer after interventions.

The class average for the concepts concerned with conservation of matter and mass are 68.5% (post-test). Only 54% of the students had Q1 (question 1) correct after interventions. Students are still uncertain about the definitions of the conservation of mass and matter and the deeper understanding of the meaning of the concepts. The 66% for Q4 indicates that students still believe the mass of iron decreases when the iron rusts.

The class average for mole ratios is 81.75%. Chemistry as images is problematic as shown by Q3. Only 36% of the students had correct answers. Students either have problems with visualization, or with the concepts of mole ratios, or conservation of mass and matter are not understood. The problems, with familiar chemical reaction equations due to prior exposure at school, were easily solved because students were familiar with the reaction equations and not necessarily because there was conceptual understanding of mole ratios. Similar questions with unfamiliar chemical reaction equations were wrongly interpreted by students (Q6). After the interventions students became more familiar with calculations that involve the ratio concept in chemistry (Q15). The other questions (5, 6, 7, 14, 18, and 22) posed no problems in the post-test.
The class average for the **mole concept** is still only 49.75% (post-test). Students’ prior knowledge of the mole concept was poor as indicated by the pre-test (38.5%). The improvement after interventions was also limited except for Q13 at 23%. The relationship between moles and Avogadro’s number is still unclear to many students. There is the possibility that students did not understand what they read and therefore could not interpret the question correctly. In Q8 "moles" and "molecule" is regarded as synonyms regardless the mole ratios. Little improvement in the mole concept is observed in Q9. “Moles” and “molecules” is again seen as the same thing (a well-known misconception). These answers indicate a lack of conceptual understanding about molecules, atoms and the mole concept. In Q13, only 60% students indicated the correct answer and the biggest misconception was declaring moles and molecules as equal amounts. Only 46% of students had Q20 correct and the misconception that students had, was about the number of ions in a soluble ionic compound and the confusion about the distinction between ions and atoms.

The class average for **mole and solution concentration calculations** is 86.3%. There is little exposure to solution concentration calculations at the school level. It is evident from the increased performance of students in these questions (Q10, 11 and 12) that the interventions were very successful in this topic. Students that still performed poorly might confuse molar mass and concentration and neglect unit conversions.

The class average for the **limiting reagents problems** was 61.0% for the post-test. The students’ average for the pre-test was 34.8%. This result is an indication of the students’ poor conceptual understanding about limiting reagents. In the post-test Q16, 23 and 24 improved with 23% and higher. In Q16 and Q17, the understanding of the concept is still too low, 51% and 39% respectively. Students cannot argue logically in their decision about the limiting reagent in a chemical reaction. The lowest mass or lowest moles are taken as limiting reagent without logical calculations and exact determinations. There is a 50:50 chance of being correct with the limiting reagent and very few students give the correct argument for their choice of a limiting reagent.

If only the class averages per concept is considered, conservation of mass and matter, the mole concept and limiting reagents, are still the difficult concepts. Questions 3, 8, 17 and 20 still received low scores even in the post-test.
The following general misconceptions were evident:

(i) **limiting reagent** implies lowest stoichiometry; lowest calculated moles or lowest mass indicated limiting reagent; “cannot determine the ‘limiting reagent’ in a given problem, when one substance is added in excess” (Huddle & Pillay, 1996). [found in Q16O1O4O5, Q17, Q23o5, Q24O2O4O5 and MPQ2]

(ii) don’t understand the **mole concept**; using “mole as counting unit for atoms, molecules and ions”, (Potgieter, Davidowitz & Venter, 2008; Potgieter, 2010). [found in Q13O4, Q8, Q20]

(iii) conservation of mass in **solutions**; solution weighs less than the solvent plus the solute, (Potgieter, Davidowitz & Venter, 2008; Potgieter, 2010). [found in thinking skills assignment, Q10O3O4, Q11, and MPQ4]

(iv) equate the mass ratio of atoms in a molecule with the ratio of the number of these atoms, and the **mass ratio with the molar mass ratio**” (Schmidt, 1990). [found in Q15O2, Q15O1 and MPQ2]

(v) “calculate the molar mass of a given substance by summing up the atomic masses and then multiplying or dividing this sum by the coefficient of the substance in the chemical equation; others do not understand the significance of the coefficients in a chemical equation at all” (BouJaoude and Barakat, 2000); confusion of **coefficients versus subscripts** (Potgieter, Davidowitz & Venter, 2008; Potgieter, 2010). [found in Q3O5]

(vi) “confuse the concepts of **conservation of atoms and possible non-conservation of molecules** or do not take into account the conservation of atoms or mass at all” (Mitchell and Gunstone, 1984); no conservation of atoms; conservation of mass are incorrectly applied to reactions (mass, atoms, molecules) (Potgieter, Davidowitz & Venter, 2008; Potgieter, 2010). [found in Q1, Q3O1O3, Q4O1O2]

(vii) “confuse or do **not know the definitions** of and relationships between stoichiometric entities in general” (e.g. Furió, *et al.*, 2002). [found in mini-project(MP) in reflection 2]
3.5 CONCLUSION

This current research focused on the improvement of conceptual understanding through systematic integration of visualization during lectures and the development of critical thinking and metacognition in stoichiometry assignments of first-year chemistry students at a South African university. Interventions in the form of a mini-project and assessments on evaluation and thinking skills were done and visualization strategies were used. The total impact of the interventions was tested by a pretest and a post-test.

Interventions cannot be pinpointed and ascribed to certain results. The students mostly use algorithms as a crutch when problems need to be solved without understanding. As soon as problems become more complex, students have no cognitive scaffolding system which can be applied to solve these higher-order problems. Because of a variety of undefined factors and variables a direct line cannot be drawn between interventions and results. The research results, in general, indicated an increase in conceptual understanding that lead to better achievement in the stoichiometry problem solving.

Metacognition is generally thought to play an important role in deeper understanding, and more meaningful learning (Rickey & Stacy, 2000). The process of thinking about why you are learning, what you are learning, how you are learning, will make the process of learning and knowledge acquisition more meaningful and useful to students. When students take the metacognition questions more seriously; their conceptual understanding will improve with the concurrent improvement in stoichiometry problem-solving skills. Metacognition strategies showed promising results, but continuous practicing of these strategies need to be exercised in future classes or courses. The metacognition exercises indicated a number of weaknesses in the students’ problem-solving skills.

Misconceptions and conceptual understanding that still need further improvements are definitely the mole concept and limiting reagents. Despite all the interventions and practice problems the mole concept showed little improvement in the post-test and the mini-project results. Students are confronted with the basic mole concept only in the grade 10 syllabus of secondary school in South Africa and then to a lesser extent in Grade 12 where the concept is examined. Some special attention and time should be invested in clear and concise explanations of the concept. It might be that the fuzzy concepts students have as prior knowledge are resistant to change at
a later date. Limiting reagents, from thorough screening of question 2 (Q2) of the mini-project, are a guessing game with a 50:50 chance of being correct. Students cannot correctly motivate their choice of the correct limiting reagent for a chemical reaction. Only 7% gave the correct reasoning for choosing the limiting reagent. 20% chose least mass or least moles as the reason for the limiting reagent. 10% calculated the mass by stating that the mole ratios are the same as the mass ratios. Confusion between the meaning of coefficients and subscripts in chemistry are also substantial (2Br₂ is considered the same as 4Br) and calculating molar mass then becomes a problem.

The results of the study showed that critical thinking skills, visualization and metacognition exercises had a positive effect on the conceptualization of stoichiometry for the students. These results correspond well with the results of previous studies (Potgieter, 2010; Potgieter et al., 2008; BouJaoude & Barakat, 2003; Rickey & Stacy, 2000).

BouJaoude and Barakat (2003) concluded that lecturers should choose instructional strategies and teaching materials that encourage students to develop meaningful learning. Student should strive for conceptual understanding of any chemistry topic rather than using algorithmic solutions without understanding (Phelps, 1996). If students are persuaded that conceptual understanding is important, that would enhance the road to more meaningful learning for them. Therefore, how students read the problem, decide on a problem-solving strategy and execute the problem have an influence on their success in stoichiometry problem-solving and consequently on their conceptual understanding of stoichiometry. Interventions that improved the conceptual understanding of stoichiometry cannot be isolated; it is more a holistic approach that made the difference. Another possibility is that different interventions may have supported different student’s learning styles.
REFERENCES


CHAPTER 4: METHODOLOGY – RESEARCH PLAN, RESEARCH METHODOLOGY AND DATA-ANALYSIS TECHNIQUES

4.1 INTRODUCTION

In chapter 2 the teaching of stoichiometry, by making use of critical thinking, visualization and metacognition, was elaborated on to provide more detail information. Chapter 3 is the article, as it will be presented to Journal of Chemical Education. In this chapter, the empirical study, including the research plan and methodology that were used for data collection and analysis, is discussed in detail to provide a more comprehensive view than the information shared in the article.

4.2 THE PURPOSE OF THE EMPIRICAL RESEARCH STUDY

The purpose of the empirical research study was to determine the influence of critical thinking, visualization and metacognition on the conceptualisation of first-year chemistry students in stoichiometry. Based on the results and findings, a summary, conclusions and recommendations are given in chapter 5.

4.3 RESEARCH PLAN

4.3.1 Orientation

A research plan was used to give structure to the research. It demonstrated how the main components of the research project, namely population, data-collection instruments, programmes or interventions and methods, formed a whole to address the central research questions.

4.4 RESEARCH METHODOLOGY

4.4.1 Quantitative research

4.4.1.1 Experimental design

Maree and Pietersen (2007) defined quantitative research as a systematic and objective process where the numerical data of a selected sub-group, chosen from an overall group, was used to subsequently make generalisations which were applicable on the bigger group.
4.4.1.2 Population

Availability population is described by Johnson and Christensen (2004) as the group of students who was available to the researcher for participation in the research. In this case the population for the experimental group consisted of first-year chemistry students from the School of Physical and Chemical Sciences at the North West University, Potchefstroom Campus.

4.4.1.3 Data-gathering instruments and variables

In this experiment, the independent variables were the application of critical thinking strategies and tasks, visualization techniques, metacognitive activities and assignments, which the students were exposed to throughout the semester. The dependent variable was the conceptualisation of the key concepts in stoichiometry.

A quantitative research approach, according to a one-group pre-test-post-test design (Creswell, 2003), was used to determine what the impact of critical thinking, visualization and metacognition was on the conceptualisation of stoichiometry concepts of first year chemistry students.

An identical pre- and post-test was compiled (Annexure A) from existing research questionares, which consisted of 24 multiple choice questions. The test was founded on the knowledge and application of important stoichiometry principals. This test gave an indication of the student’s previous exposure to and retention of specific stoichiometric subject-matter, which was considered important to the conceptual understanding of various stoichiometric problems. Both the pre-test and the post-test were written unprepared by students.

An availability test sample was used for this study. All the students that were registered for the first-year chemistry module were asked to participate. A total of 798 students took the pre-test prior to the commencement of the intervention, and 713 students took the identical post-test. Although the intervention was applied on all the study units of the module, the post-test was written 3 months after completion of the study unit which dealt with stoichiometry.

The interventions consisted of the implementation of specific teaching techniques which promoted the development of critical thinking. Presentation of Power Point slideshows, a document camera, a mini-project, assessment and thinking skills tasks were all used as part of the teaching intervention.
Teaching techniques for critical thinking

With the mini-project (Annexure B), various high-order questions were given to students. The questions consisted of stoichiometric problems, based on the module content and it required various steps of interpretation, planning, and implementation. The students had never before been exposed to these types of questions, and more than just knowledge and application of algorithms was required. Questions in the mini-projects required from students to obtain new knowledge in the process of solving problems. After every question had been answered, students had to indicate and describe in words exactly how they obtained their answer. Thus students were forced to be more critical in how they were going to solve a question.

For the assessment tasks' (Annexure C) first phase, students worked together in groups and took on an assessment role. The students had to compile a complete memorandum with a marking schedule for questions from previous exam papers. During the second phase, students had to mark/correct the previous year group’s questions of the particular question papers. They therefore worked with original answers of real students (anonymous) from previous year groups. Some of the answers were correct, other partly correct and others incorrect. They then had to award marks to the particular answers, according to their own marking schedule. The lecturer assessed the correctness of the memorandum as well as the correct application of the memorandum on the answers. The students then had the opportunity to compare their own memorandum and the application thereof with that of the lecturer, and to make corrections.

With the thinking skills assignments, a similar approach was followed, where students had to describe the process of problem solving in their own words. Two similar thinking skills assignments (questions from the prescribed textbook) were given to the students during the semester, where they had to exercise their thinking skills. One of the questions asked them to describe how they would prepare a solution, the concentration as well as the volume of a given compound, by making use of a volumetric flask. This assignment only allowed for a description of the process, and not a numerical calculation. Thus the focus was on the thinking and thought process and not on calculating skills.

Teaching techniques for visualization

During teaching a document camera (Annexure D) was applied as visualization instrument. The purpose of this was to enable students to visually observe how problems can be approached and solved step by step. Examples and illustrations from the prescribed textbook were showed to the class directly. A visual information-bridge was created between learning material, with which the student was confronted in class, and the learning material which later
had to be mastered outside the classroom. Photos of the appropriate stoichiometric problems which were studied in class and displayed on screen were taken during class and made available to students electronically on the learning management system. The lecturer also continuously made use of additional **visual slide material and Power Point animations**. Students were also encouraged to visit the online Webpages which were indicated in the prescribed textbook, via the electronic learning management system, as additional study material.

Study material was also made available to students on the learning management system.

**Teaching strategies for metacognition**

The **mini-project** consisted of four questions (Q1 – basic stoichiometry principles; amount of reactant A necessary to react completely with reactant B; total mass of products produced [11 marks])(Q2- atom-mass relationship; mass-mole relationship; formulas; molar mass; balanced equation; mass-mass relationship; limiting reagent calculations; actual yield-mass relationship; empirical formula; mass reactant-mass product [24 marks])(Q3-empirical formula; mass reactant-mass product [13 marks])(Q4-concentration problems [8 marks]). Each question was followed by two types of reflection: first three open questions (concepts; planning; steps followed) and then 21 questions answered according to a Likert scale. The students had to reflect on each question they answered. The mini-project was an individual assignment, but students could use resources or discuss possible solutions with peers.

The main measuring instrument of the research project was the pre-test-post-test questionnaire with the different interventions (visualization techniques, evaluation tasks, thinking skills assignments and the mini-project) to provide an impact on the research results.

**4.4.1.4 Statistical analysis**

In this study it was decided to use effect sizes (Cohen’s d-values) to determine if the difference between high- and low-group-achievers is significant in practice. According to Steyn (2005), the determination of effect sizes is sometimes the only way to evaluate the practical usefulness, where full populations are concerned. If $\mu_1$ and $\mu_2$ are the two populations’ averages, $\sigma$ is the maximum standard deviation and $\delta$ is the standardised difference ($\delta$):

$$\delta = \frac{\mu_1 - \mu_2}{\sigma}$$
This value is also called the effect size of the difference in population averages. Cohen, Manion & Morrison (2007) calls this value \( d \), and it is the value which is used to determine if there is a practical useful difference between the pre- and post-test of the experimental group. Cohen et al., (2007) uses the following scale for the \( d \)-values (Steyn, 2005):

1. \( d = 0.2 \): Small effect: such a result is not viewed as significant
2. \( d = 0.5 \): Medium effect: may indicate significance
3. \( d = 0.8 \): Large effect: this result is viewed as significant and of practical interest
4. Cohen’s guideline values are used here, for the interpretation of effect sizes, where 0.5 suggests a visible difference and 0.8 a difference which is of interest in practice. The discrimination of each question must be high (\( \geq 0.8 \)), as more successful students should probably answer the question correctly, and less successful students should answer the question or most of the question incorrectly.

### 4.4.1.5 Validity of measuring instruments

Validity refers to the degree in which the instrument really measures what it is supposed to measure (Maree & Pietersen, 2007). The evaluation of a measuring instrument thus always takes place with reference to its specific uses (Maree et al., 1997). Because a measuring instrument is usually mounted for different purposes, the validity of each of the possible purposes for which it is used, has to be determined.

Face validity refers to the manner in which the instrument looks valid, in other words, whether the instrument looks as if it's measuring what it should. This kind of validity cannot be quantified or tested, but has to be traced by someone skilled to ensure a high degree of validity (Maree & Pietersen, 2007). The concept test of which the questions were chosen from previously standardised questionares (resources indicated on Annexure A) was analysed by the researcher and the study leaders to determine if the test complied with the purposes for which it was applied for this study. This concept test, of which the questions were, was submitted to study leaders and skilled colleagues, to ensure face validity.

Content validity refers to the manner in which the instrument is representative of the field it is supposed to measure (Maree & Pietersen 2007). Content validity refers to the content of the measuring-instrument and is not expressed in terms of quantitative indexes. The following steps were taken to ensure the content validity of the concept test (Maree et al., 1997):

- A comprehensive literature study of stoichiometry was initiated.
• The terminology and positioning of items in the fields were supervised by various skilled persons.

4.4.1.6 Data gathering process

The pre-test of stoichiometry was conducted with the experimental group at the beginning of the semester. This was done by means of the Learning Management System. An identical pre- and post-test (Annexure A) was composed, which consisted of 24 multiple choice questions. The test was based on the knowledge and application of important stoichiometric principles. This test should give an indication of the student's previous exposure to and retention of specific stoichiometric subject-matter, which is considered important for the conceptual understanding of various stoichiometric problems. Both the pre- and post-tests were written unprepared.

4.4.1.7 Analysis of data

Data of the concept test was analysed electronically. All the questions were multiple choice questions.

4.5 SUMMARY

In this chapter, the empirical part of the research process was explained. The research plan and methodology were explained by means of the techniques that were used for the gathering and analysis of data. In chapter 5 the conclusion will be provided.
CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The purpose of this chapter is to provide a summary of the theoretical and empirical research, and to give the most important findings and conclusions from the theoretical and empirical study. The limitations of the study, recommendations for further research and the contribution of the study, are also provided.

5.2 SYNOPSIS

The teaching and learning of chemistry, and in particular stoichiometry, present challenges to both students and lecturers on tertiary level. Stoichiometric concepts and phenomena are found throughout the subject of chemistry and form an integral part of the chemistry curriculum on first-year level. Potgieter (2010) found in a national study, that first-year students weren't prepared for chemistry-teaching on tertiary level at all. Coupled with this, students found the field of stoichiometry particularly challenging.

Teaching strategies are seldom adapted to support students with the learning of stoichiometry. Stoichiometry teaching usually takes place according to a traditional algorithmic approach, which seldom addresses or improves students' understanding and critical thinking. It is clear from the Potgieter-report (2010), that chemistry-teaching of students should urgently be looked at. Innovative and effective alternative teaching processes, which can help improve students' conceptual understanding of stoichiometry, should be examined. This study comprises of the systematical integration of visualization during lectures and the development of critical thinking and metacognition in stoichiometry assignments of first-year students from a South African University, with the purpose of improving conceptual understanding.

The research questions that were addressed were:

1. What will the impact of teaching strategies focussing on the development of higher order thinking skills be on first year students’ conceptual understanding of stoichiometry?
2. What will the impact of visualization be as a tool on the structure and content of the students’ stoichiometry knowledge?
3. What will the effect of metacognitive regulation be on test performance of students in stoichiometry questions?
The purpose of this study was to determine whether the development of the critical thinking abilities can be enhanced through the use of visualization tools and metacognitive strategies by:

1. Implementing learning experiences associated with higher-order thinking skills which focus on analysis, evaluation and synthesis and the development of problem solving skills, inferring, estimating, predicting, generalizing and creative thinking.
2. Visualization of concepts and their interrelationships by concretizing and by explaining the meaning of concepts by making use of the macroscopic, sub-microscopic and symbolic modes of representation.
3. Using the metacognitive control skills of monitoring and evaluation to develop metacognitive skills of students.

With the literature study in chapter 2, an attempt was made to explain students’ approach to stoichiometry in general and also the traditional approach in teaching. The influence of critical thinking, visualization and metacognition on conceptualizing in the teaching and learning of stoichiometry was also examined separately. In chapter 3 the journal article is submitted.

The research plan and methodology were discussed in chapter 4. To provide answers to the research questions, a quantitative research plan was used. For the empirical research, a one-group experimental design was used, which consisted of a single first-year chemistry group of students, who was subjected to a pre- and post-test. A concept test with 24 multiple choice questions was completed electronically by each student.

The results of the quantitative research are captured here in chapter 5.

The most important findings and conclusions are discussed in the following paragraph.

5.3 CONCLUSIONS

5.3.1 Theoretical conclusions

From the literature study, it is clear:

**Critical thinking:**

- Critical thinking is a form of metacognition.
- Critical thinking helps students to critically and effectively solve social, scientific and practical problems.
- Critical thinking is an intellectual habit, a product of teaching and learning which can be acquired with practice.
- Just like students have to master the steps of the scientific method, they also have to acquire the process of critical thinking.

**Visualization:**

- The ability of students to visualise is important for the solving of conceptual problems.
- Students perform better when dynamic visualizing, like animations, is used instead of static visualizations.
- Animated visualization is more profitable than static visualization, because detail is added, which support the understanding of the sub-microscopical world.
- The positive effect of dynamic visualization can be improved when students create their own static ideas contributory to dynamic visualizations regarding the particular curricula.
- Much research still has to be done in the field of visualization and metavisualization, to better understand the process of metavisualization, as well as its importance in the theory.

**Metacognition:**

- Metacognition can be taught.
- One of the techniques to help metacognition develop, is questioning.
- Students’ metacognition can be measured by making use of an inventory of metacognitive self-regulation.
- Metacognition is important for the development of good problem solving skills and achieving conceptual understanding.

**Problem solving in stoichiometry:**

With the traditional teaching of stoichiometry on secondary level, the lecturer usually starts with explaining problem solving in the textbook, by means of four general steps. This procedure is solely based on the application of various algorithms, but it does not promote conceptualisation.

**5.3.2 Empirical conclusions**

Although research has shown that conceptual understanding of students in stoichiometry can be improved by visualization, critical thinking skills and metacognition, there is no indication in literature of what the impact of the synergetic implementation thereof is on conceptualisation in stoichiometry with students.
From the results, the conclusion can be made that first-year chemistry students, who were actively taught in critical thinking, showed a remarkably improved conceptual understanding in stoichiometry.

The visualization techniques to which students were exposed, contributed to their conceptualisation in stoichiometry. The development of students’ metacognitive skills leads them to planning a solution for a problem, and planning strategies which they had to use to solve a problem.

From the quantitative data-analysis, the conclusion can be made that students’ conceptualisation in stoichiometry visibly improved with 18%, from an average of 56% in the pre test to 74% in the post test. The conclusion is that the concurrent implementation of critical thinking, visualization and metacognition indeed made a difference in the conceptualisation of stoichiometry and the test performance of students.

5.4 LIMITATIONS OF THE STUDY

A true experimental design with an experimental and control group was not possible. Students may not be deprived of effective teaching for the sake of research. Using a control group would have deprived these students of exposure to critical thinking activities, visualization and metacognitive tasks.

The taking of the pre- and post-test, could only be done under limited control. It was not taken formally under full examination supervision. Students completed the tests on-line in limited time supplied by the LMS. Some dishonesty could indeed have taken place between students, which could not be controlled.

5.5 RECOMMENDATIONS

This study can be used again in future, in order for a tendency to be monitored over several years.

It is recommended that this approach also be applied to other chemistry disciplines.

5.6 CONTRIBUTIONS OF THIS STUDY

Little is known regarding the influence of critical thinking, visualization and metacognition, which can be applied synergistically to improve conceptualisation in chemistry, and more specifically in stoichiometry. This study consequently provides an important contribution to sufficiently equip lecturers in order for their students to profit by alternative teaching methods in the tertiary
teaching environment. The implementation of critical thinking, visualization and metacognition may lead to a better conceptual understanding of students of stoichiometry. With the necessary adaptations and changes, this approach can also be used in other fields of study.
BIBLIOGRAPHY


ANNEXURE A

Concept Test

[References Questions 1-4]

Journal of Chemical education (online)

http://www.jce.divched.org/jcedlib/qbank/collection/CQandChP/CQs/ConceptsInventory/pConcepts_Inventory.html

Question 1 (Single Correct)

Which of the following must be the same before and after a chemical reaction?

a) The sum of the masses of all elements involved.

b) The number of molecules of all elements involved.

c) The number of atoms of each type involved.

d) Both (a) and (c) must be the same.

e) Each of the answers (a), (b), and (c) must be the same.

Question 2 (Single Correct)

What is the mass of the solution when 1 kilogram of salt is dissolved in 20 kilograms of water?

(a.) 19 kg. (b.) 20 kg. (c.) Between 20 and 21 kg. (d.) 21 kg. (e.) More than 21 kg.

Question 3 (Single Correct)

Please see attachment for question 3 and possible answers to question 3.

2S + 3O₂ → 2SO₃

attachment for question 3 and possible answers to question 3.
(a.) Diagram a. (b.) Diagram b. (c.) Diagram c. (d.) Diagram d. (e.) Diagram e.

**Question 4 (Single Correct)**

Iron combines with oxygen and water from the air to form rust. If an iron nail were allowed to rust completely, one should find that the rust weighs:

a) less than the nail it came from.

b) the same as the nail it came from.

c) more than the nail it came from.

d) It is not possible to predict what the rust will weigh.

**[References Questions 5-7]**

Journal of Chemical education (online)


**Question 5 (Single Correct)**

How many moles of hydrogen gas are needed to react completely with two moles of nitrogen gas according to the following chemical equation? \(3H_2 + N_2 \rightarrow 2NH_3\)

a) 3 moles.

b) 6 moles.

c) 9 moles.

d) 12 moles.
**Question 6 (Single Correct)**

How many moles of potassium chloride are produced from the decomposition of six moles of potassium chlorate? \(2\text{KClO}_3 \rightarrow 2\text{KCl} + 3\text{O}_2\)

a) 2 moles.  
b) 3 moles.  
c) 4 moles.  
d) 5 moles.  
e) 6 moles.

**Question 7 (Single Correct)**

How many moles of hydrogen gas are produced from the reaction of three moles of zinc and an excess of hydrochloric acid? \(\text{Zn} + 2\text{HCl} \rightarrow \text{ZnCl}_2 + \text{H}_2\)

a) 3 moles.  
b) 4 moles.  
c) 6 moles.  
d) 8 moles.

[References Questions 8-9]

Marietjie Potgieter (post-test A)


**Question 8 (Single Correct)**

One molecule of sulphur contains 8 S atoms. Then one mole of sulphur molecules (\(S_8\)) will contain?

a) 8 g sulphur.  
b) 8 mol sulphur atoms.  
c) 6.02 x 10^23 sulphur atoms.  
d) 8 sulphur atoms.
**Question 9** (Single Correct)

A mole of \( \text{H}_2\text{O} \) molecules and a mole of \( \text{O}_2 \) molecules have ...

- a) contain one molecule each.
- b) have a mass of 1 g each.
- c) contain the same number of molecules.
- d) have the same mass

[References Questions 10-12]

Jiskha Homework help

http://www.jiskha.com/display.cgi?id=1309732676.html

**Question 10** (Single Correct)

An antacid tablet containing 0.50g NaHCO\(_3\) is dissolved in water. The total volume of the solution is 250mL. What is the molarity of the NaHCO\(_3\) solution?

- a) 0.024 M
- b) 2.22 x 10\(^{-4}\) M
- c) 0.0060 M
- d) 0.0041M

**Question 11** (Single Correct)

40.0 mL of an HCl solution with concentration of 0.60 M is to be diluted to a concentration of 0.10 M. What would be the final volume after dilution?

- a) 6.67 mL  
- b) 667 mL  
- c) 240 mL  
- d) 60.0 mL  
- e) 500 mL
**Question 12 (Single Correct)**

When 25.0 mL of a 0.400 M H₂SO₄ and 50.0 mL of a 0.850 M H₂SO₄ solution are mixed, what is the molarity of sulphuric acid in the final solution?

a) 0.350 M H₂SO₄

b) 0.700 M H₂SO₄

c) 3.50 M H₂SO₄

d) 7.00 M H₂SO₄

e) 10.0 M H₂SO₄

[References Questions 13-14; 16-24]

University of Purdue, exam questions

http://www.chem.purdue.edu/gchelp/115exams/stoich2.html

**Question 13 (Single Correct)**

How many H₂O molecules are there in a snow flake that weighs 4.0 x 10⁻⁴ g?

a) 1.3 x 10¹⁹

b) 2.4 x 10²⁰

c) 2.2 x 10⁻⁵

d) 6.02 x 10²³

e) it cannot be determined
**Question 14** (Single Correct)

For the following combustion reaction, what is the stoichiometric coefficient for oxygen that balances the reaction?  \[ \text{C}_3\text{H}_8 + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2 \]

(a) 1  (b) 2  (c) 3  (d) 4  (e) 5

**[References Questions 15]**

Questions


**Question 15** (Single Correct)

What is the mass of \( \text{AlBr}_3 \) in grams produced by the reaction of 1.5 mol of HBr according to the following balanced equation:  \[ 2\text{Al} + 6\text{HBr} \rightarrow 2\text{AlBr}_3 + 3\text{H}_2 \]

and given the following relative atomic masses: \( \text{Al} = 27 \text{ amu}; \text{Br} = 80 \text{ amu}; \text{H} = 1.01 \text{ amu} \)?

(a) 520.5 g  (b) 260 g  (c) 133.5 g  (d) 65.0 g  (e) 79.9 g

**Question 16** (Single Correct)

Which is the limiting reagent when 62.0 g of \( \text{P}_4 \) and 128 g of \( \text{S}_8 \) react according to the following balanced equation:  \[ 4\text{P}_4 + 5\text{S}_8 \rightarrow 4\text{P}_4\text{S}_{10} \]

and given the atomic weights: \( \text{P} = 31.0 \text{ amu}; \text{S} = 32.0 \text{ amu} \)?

(a) \( \text{P}_4 \)

(b) \( \text{S}_8 \)

(c) not enough information.

(d) neither \( \text{P}_4 \) nor \( \text{S}_8 \).

(e) both \( \text{P}_4 \) and \( \text{S}_8 \).
Question 17 (Single Correct)

The theoretical yield of CO$_2$ ($CO_2 = 44 \text{ g.mol}^{-1}$) from a reaction mixture containing 45.6 g of vanillin ($C_8H_8O_3 = 152.08 \text{ g.mol}^{-1}$) and 73.2 g O$_2$ ($O_2 = 32 \text{ g.mol}^{-1}$) is: The balanced reaction equation is given below. $2 C_8H_8O_3 + 17 O_2 \rightarrow 16 CO_2 + 8 H_2O$

(a) 63.2 g  (b) 94.8 g  (c) 1.05 x 102 g  (d) 118.6 g  (e) none of the above mentioned.

Question 18 (Single Correct)

How many moles of H$_2$O are produced when 2.5 moles of O$_2$ react in the following balanced reaction? $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

(a) 5.0  (b) 4.0  (c) 3.0  (d) 2.5  (e) 2.0

Question 19 (Single Correct)

What is the % by weight of carbon in ascorbic acid, $C_6H_8O_6$, also known as Vitamin C, given the following relative atomic weights: C = 12.01 amu; H = 1.008 amu; O = 16.00 amu?

(a) 40.9%  (b) 4.58%  (c) 54.5%  (d) 30.0%  (e) 12.0%

Question 20 (Single Correct)

How many moles of ions are there per mole of Al$_2$(SO$_4$)$_3$?

(a) 17  (b) 6  (c) 5  (d) 3  (e) 1

Question 21 (Single Correct)

What is the product of the following hypothetical reaction: $3A_2B_3 + B_3 \rightarrow 6 ?$

(a) $AB$  (b) $AB_2$  (c) $AB_3$  (d) $A_2B$  (e) $A_3B$

Question 22 (Single Correct)

What is the stoichiometric coefficient for sulphuric acid in the following reaction?

$\_\_ Fe_2O_3(s) + \_\_ H_2SO_4 \rightarrow \_\_ Fe_2(SO_4)_3 + \_\_ H_2O$

(a) 1  (b) 2  (c) 3  (d) 4  (e) 5
**Question 23** (Single Correct)

Which is the limiting reagent when 10.0 g of H\(_2\) and 10.0 g of Cl\(_2\) react according to the reaction?

\[ \text{H}_2(g) + \text{Cl}_2(g) \rightarrow 2\text{HCl}(g) \]

(a) H\(_2\)

(b) Cl\(_2\)

(c) HCl

(d) Not enough information.

(e) None of the above. They are present in equal amounts.

**Question 24** (Single Correct)

When 12.0 g of hydrogen reacts with 12.0 g of chlorine according to the following balanced reaction, \( \text{H}_2(g) + \text{Cl}_2(g) \rightarrow 2\text{HCl}(g) \), 5.53 g of HCl are recovered. The percent yield of HCl is?

(a) 1.27%  (b) 2.55%  (c) 45.0%  (d) 89.9%  (e) 100%
ANNEXURE B

STOICHIOMETRY MINI PROJECT.

MARCH 2012.

CHEM 111

MARK OUT OF 56: %

Title: __________ Initials: _______________ Student number: ____________________

Surname: ________________________________________________________________________________

Instructions:

➢ The mini project must be completed and handed in individually.
➢ Answers to questions MUST be answered in the spaces that are provided in pen. NO answer sheets that are completed in pencil will be marked and persons that do this will receive zero for the assignment. No excuses will be accepted later on.
➢ Show ALL your calculations. You also receive marks for the steps.
➢ The mini project consists of two parts, namely. (1) the stoichiometric problems and (2) a thinking strategy questionnaire (educational research) after each question.
➢ The stoichiometric part consists of four stoichiometric problems – each with sub divisions. Make sure that you answer each division completely as well as the reflection part and the thinking strategy questionnaire AFTER EACH QUESTION.
➢ Bonus marks can be earned if the reflection part and thinking strategy questionnaire are completed to satisfaction.
➢ The answers that you give in the reflection part and the thinking strategy questionnaire after each question is your own opinion and not an opinion that you think that I would like. Please answer these parts truthfully. Your truthful opinion and feeling is really important.
➢ The results of the educational part are very important to me because it will give me insight about the thinking strategies and problem solving strategies of students. I only use averages and does not look at individual results.
➢ Please also read the trust agreement / permission form underneath and please sign it.
➢ The completed assignment must be handed in at Dr. Read before 13:00 on Wednesday 28 March 2012.
Thank you in advance for your participation, it is appreciated!

Good luck

**Trust agreement. / Permission form.**

I acknowledge that:

* It is the purpose of this study to determine thinking strategies and patterns as well as problem solving strategies in chemistry for new students to the university.

* Any personal information that is accumulated about me during this study will be handled in the strictest confidentiality and will not be part of my permanent record at this university.

* I do not give up any human rights or law rights by participating in this study.

* I participate out of my own will in this study which is done to improve chemistry education.

I acknowledge by signing underneath that I read and understood the above mentioned prerequisites.

Signature: _________________________________________________________________

Date: _________________________________
QUESTION 1. [11 MARKS]

One of the compounds used to increase the octane rating of gasoline is toluene (Figure 1). Suppose 20.0 mL of toluene (d = 0.867 g/mL) is consumed when a sample of gasoline burns in air.

a. How many grams of oxygen are needed for complete combustion of the toluene?

b. How many total moles of gaseous products form from the combustion of the toluene?

c. How many moles of water vapour form from the combustion of toluene?

"REFLECTION ON QUESTION 1".

Answer the following 3 questions shortly:

1. Which concepts came to mind when you first read the question?

2. How did you reason/planned to solve the problem (tell your story)?

3. Write down shortly the steps you used to solve the problem.
### Reflection on Question 1. Only draw a cross in the appropriate space.

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QUESTION 2.  [24 MARKS]

Consider titanium. It is a metal that is just as strong as steel, but is 45% lighter. It is also resistant against corrosion (rust) by seawater and is used in the propeller shafts of ships.

a. How many titanium atoms are in one nanogram of titanium?

b. How many grams of titanium are in 0.0217 mol?

c. Write the formula for titanium(III) oxide. What is the molar mass?

d. When titanium reacts with bromine gas, titanium(IV) bromide is obtained. Write a balanced equation for this reaction. Show the physical states of all the reagents and products.

e. How many grams of bromine are required to completely react with 22.1 g of titanium?

f. Thirteen grams of titanium react with 60.0 g of bromine. How many grams of titanium(IV) bromide are produced, assuming 100% yield? How many grams of excess reagent are present after the reaction?

g. The reaction in (g) is later found to have 79.3% yield. How many grams of titanium(IV) bromide are actually obtained?

h. The mineral perovskite is an excellent source for titanium. It is made up of 29.4% Ca, 35.2% Ti and 35.3% O. What is the simplest formula for perovskite?

i. How many kilograms of the mineral are required to produce 5.00 kg of titanium?

"REFLECTION ON QUESTION 2".

Answer the following 3 questions shortly:

4. Which concepts came to mind when you first read the question?

5. How did you reason/planned to solve the problem (tell your story)?

6. Write down shortly the steps you used to solve the problem.
**Reflection on Question 2. Only draw a cross in the appropriate space.**

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QUESTION 3. [13 MARKS]
A sample of an oxide of vanadium weighing 4.589 g was heated with hydrogen gas to form water and another oxide of vanadium weighing 3.782 g. The second oxide was treated further with hydrogen until only 2.573 g of vanadium metal remained.

a. What are the simplest formulas of the two oxides?

b. What is the total mass of water formed in the successive (second) reaction?

"REFLECTION ON QUESTION 3".

Answer the following 3 questions shortly:
7. Which concepts came to mind when you first read the question?
8. How did you reason/planned to solve the problem (tell your story)?
9. Write down shortly the steps you used to solve the problem.

REFLECTION ON QUESTION 3. ONLY DRAW A CROSS IN THE APPROPRIATE SPACE.

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Cocaine (C_{17}H_{21}O_{4}N; Figure 1) is a natural substance found in coca leaves, which have been used for centuries as a local anaesthetic and stimulant. Illegal cocaine arrives in the United States either as the pure compound or as the hydrochloride salt (C_{17}H_{21}O_{4}N\text{HCl}). At 25°C, the salt is very soluble in water (2.50 kg/L), but cocaine is much less so (1.70 g/L).

a. What is the maximum amount (in g) of the salt that can dissolve in 50.0 mL of water?

b. If the solution in question (a) is treated with NaOH, the salt is converted to cocaine. How much additional water (in L) is then needed to dissolve the cocaine?

"REFLECTION ON QUESTION 4".

Answer the following 3 questions shortly:

10. Which concepts came to mind when you first read the question?
11. How did you reason/planned to solve the problem (tell your story)?

12. Write down shortly the steps you used to solve the problem.

**Reflection on Question 4. Only draw a cross in the appropriate space.**

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<td>67. Do you understand the problem?</td>
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<tr>
<td>68. Are you able to address the key concepts addressed by this problem</td>
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<tr>
<td>69. Did you divide the problem in the steps that must be followed to solve the problem?</td>
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<tr>
<td>70. Did you revise the steps needed to solve the problem and did you change them if necessary?</td>
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<tr>
<td>71. Did you check each step for possible mistakes?</td>
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<tr>
<td>72. Was there any irrelevant information that you was supposed to eliminate before you could start with the solution?</td>
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<td>73. Did you rethink about the answer and did it make sense?</td>
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<td>74. Did you learn anything in solving this problem?</td>
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<td>75. Could you immediately identify the formulae needed to solve this problem?</td>
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<td>76. Did you gain any new insights on the work?</td>
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<td>77. Did the question force you to think in depth about the problem?</td>
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<tr>
<td>a. Are there other ways to solve the problem?</td>
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<td>b. Can you identify them?</td>
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<td>78. Did you recall related prior knowledge correctly?</td>
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<tr>
<td>79. Do you think prior subject related knowledge was relevant for the completion of this assignment?</td>
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<tr>
<td>80. Were you able to apply the subject knowledge to this problem?</td>
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<td>81. Was the aim of this question important to you or were you simply interested in solving the problem?</td>
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<tr>
<td>82. Did you read the question more than once before you started solving it?</td>
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<tr>
<td>83. Does the answer have any meaning?</td>
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</tbody>
</table>
84. Did you find the problem extremely difficult?

THANK YOU FOR YOUR PARTICIPATION. You can now hand in this mini project.
ANNEXURE C

EVALUATION ASSIGNMENT 3

INSTRUCTIONS:

➢ The assignment must be done in groups of at least two but not more than three students. You decide by yourself who will work together. You choose a group leader who will coordinate the times that you will get together to work on the assignment. Everybody in the group gets the same mark for the assignment. Make sure that everybody in your group participates. Everybody in the group must work together on ALL THE QUESTIONS. This means that you may not divide the questions between the group members. One of the purposes of the assignment is also to initiate collaboration and conversation about chemistry with other students. So, chat to each other about potential solutions to the problems and try to get to the answers together – learn from each other!!!

➢ You must evaluate (mark the answers and give a mark allocation as though you are the lecturer) the three questions with answers underneath. Make clear correct marks and/or incorrect marks on the answer sheets. The three questions come from old examination papers and the answers are real answers from previous 1st year students.

➢ In this case question 1 with sub questions count eight marks in total and question 2 five marks. First compile your own memorandums for each question in the spaces that are allocated for that and make clear mark allocations for each answer. Decide as a group for what you are going to give marks in the answers to get to the mark allocation that I gave you. Then go and mark the given answers. You can also make written remarks if you feel like it.

➢ The given answers can be totally correct, or partly correct or totally incorrect.

➢ I also recommend you to consult with other groups to discuss the problem. You can make use of any other form of help as well.

➢ You hand in one assignment answer sheet as a group. Make sure that the titles, full initials, surnames, student numbers and signatures of everybody that collaborated in your group are clearly indicated on the answer sheet. The answer sheets MUST be answered in the space provided in pen. NO answer sheets that are answered in pencil will be marked and groups that answer in pencil will receive zero for this assignment. No excuses will be accepted later.

➢ Make photo copies for yourself of this completed assignment which you can store and then hand in the original evaluated and completed assignment before 13:00 on Tuesday 15 May 2012.

MARK ALLOCATION:

✓ = 1 mark

✓ = ½ mark

✗ = wrong (0 marks)
MEMORANDUM FOR QUESTION 1.

DDT is a poison that is harmful to fish, birds and humans. It is produced by the following balanced chemical reaction:

\[ 2\text{C}_6\text{H}_5\text{Cl} + \text{C}_2\text{HOCl}_3 \rightarrow \text{C}_{14}\text{H}_9\text{Cl}_5 + \text{H}_2\text{O} \]

In a governmental laboratory, 1142 g of chlorobenzene is reacted with 485 g of chloral. Answer the following questions with regard to the above information. The following molar masses are given to you: \( \text{C}_6\text{H}_5\text{Cl} = 112.5 \text{ g.mol}^{-1} \), \( \text{C}_2\text{HOCl}_3 = 147.36 \text{ g.mol}^{-1} \), \( \text{C}_{14}\text{H}_9\text{Cl}_5 = 354.34 \text{ g.mol}^{-1} \), \( \text{H}_2\text{O} = 18.02 \text{ g.mol}^{-1} \).

1.1 Which reagent is the limiting reagent? [4]

1.2 Calculate the mass of DDT that is formed. [1]

1.3 Calculate the mass of the excess reagent that is left over after completion of the reaction. [2]

1.4 Calculate the percent yield of DDT if the actual yield is 200.00 g. [1]

QUESTIONS AND ANSWERS FOR EVALUATION:

QUESTION 1. [Marks = 8]

DDT is a poison that is harmful to fish, birds and humans. It is produced by the following balanced chemical reaction:

\[ 2\text{C}_6\text{H}_5\text{Cl} + \text{C}_2\text{HOCl}_3 \rightarrow \text{C}_{14}\text{H}_9\text{Cl}_5 + \text{H}_2\text{O} \]

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1.1 Which reagent is the limiting reagent? [4]
1.2 Calculate the mass of DDT that is formed. [1]

\[
\begin{align*}
\text{Chlorobenzene:} & \quad \frac{1142}{1627} \times 100 = 70.2 \% \\
\text{Chloraal:} & \quad \frac{485}{1627} \times 100 = 29.8 \%
\end{align*}
\]

\[1142 \text{ g chlorobenzene} + 485 \text{ g chloraal} = 1627 \text{ g DDT}\]

1.3 Calculate the mass of the excess reagent that is left over after completion of the reaction. [2]

\[
m = n \cdot M = (6.58)(112.6) = 740.25 \text{ g}
\]

\[
1142 \text{ g} - 740.25 \text{ g} = 401.75 \text{ g}
\]

1.4 Calculate the percent yield of DDT if the actual yield is 200.00 g. [1]

\[
\% \text{ opbrengs} = \frac{200.00 \text{ g}}{1167.78 \text{ g}} \times 100 = 17.13 \approx 17 \%
\]
MEMORANDUM FOR QUESTION 2.

Hydrochloric acid is sold as a concentrated aqueous solution. If the molarity of commercial HCl is equal to 12.0 M and the density of this solution is 1.18 g/cm³, calculate the molality of the solution. Show all your steps. The molar mass of HCl is 36.46 g·mol⁻¹.

QUESTION AND ANSWER FOR EVALUATION:

QUESTION 2.  [Marks = 5]

Hydrochloric acid is sold as a concentrated aqueous solution. If the molarity of commercial HCl is equal to 12.0 M and the density of this solution is 1.18 g/cm³, calculate the molality of the solution. Show all your steps. The molar mass of HCl is 36.46 g·mol⁻¹.

\[
\begin{align*}
M &= 12 \text{ mol·L}^{-1} = 12 \text{ mol HCl per liter solution} \\
\text{Moles of solution} &= d \times V = 1.18 \text{ g cm}^{-3} \times 1000 \text{ mL} \\
&= 1180 \text{ g} \\
&= 1.180 \text{ kg solution} \\
M_{HCl} &= n \times M = 12 \text{ mol} \times 36.46 \text{ g·mol}^{-1} \\
&= 437.52 \text{ g HCl} \\
&= 0.438 \text{ kg HCl in solution} \\
M_{H_2O} &= M_{\text{solution}} - M_{HCl} \\
&= 1.180 \text{ kg} - 0.438 \text{ kg} \\
&= 0.742 \text{ kg H}_2\text{O} \\
\text{Molality} &= \frac{12 \text{ mol}}{0.742 \text{ kg}} = 16.1 \text{ mol·kg}^{-1}
\end{align*}
\]
Problem in Class 4

2. Al + 3 Cl₂ → 2 AlCl₃

Limiting reagent? Cl₂. Beprove

\[ \frac{2.70}{27.0} = 0.100 \text{ mol Al} \]

\[ \frac{4.05}{70.90} = 0.057 \text{ mol Cl₂} \]

Mass AlCl₃ = ?

\[ \frac{133.35}{1} \]

\[ n_{AlCl₃} = \frac{0.057 \text{ mol Cl₂}}{2} \]

\[ = 0.033 \text{ mol AlCl₃} \]

\[ m_{AlCl₃} = 0.033 \text{ mol} \times 133.35 \text{ g mol}^{-1} \]

\[ = 4.467 \text{ g AlCl₃} \]

\[ n_{Al} = 0.033 \text{ mol} \]

\[ m_{Al} = 0.033 \text{ mol} \times 27.0 \text{ g mol}^{-1} = 0.886 \text{ g Al} \]

\[ m_{\text{Al wet, sample}} = 2.70 \text{ g} - 1.026 \text{ g} = 1.674 \text{ g Al} \]