Students' difficulties with chemical reaction types

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Glory to God alone.

Abstract

The initial problem that prompted this study was students' difficulties with chemical reaction types (CRT). In diagnostic tests in South Africa, across some of the major universities, CRT reflected as the poorest score of the basic and special topics in chemistry. Questionnaire results from both South Africa and Norway also reflected the inability of students and teachers to classify chemical reaction types and underlined the misconceptions about important CRT principles.

The aim of this study was twofold: (1) to investigate why students struggle with chemical reaction types and the extent to which textbook related problems and teacher induced problems play a role, and (2) how practical work can be used as an intervention to address CRT misconceptions. To achieve the first part of the aim, a review of 102 general chemistry textbooks on CRT was conducted. In the review, numerous CRT and inconsistent and problematic chemical reaction type terminology were identified. To achieve the second part of the aim, documented international misconceptions on CRT were collected and these misconceptions were used to teach for conceptual change with the aid of the MYLAB small scale chemistry (SSC) kits as an intervention tool.

The results of the textbook study showed no progression towards a standard in CRT classification over the years from 1661 to 2017 (year of textbook publication). Furthermore, confusing and ambiguous CRT terms are used in textbooks. Consequently, a new theoretical framework (fig.1, paper 1) and a theoretical framework model (TFM, fig.2, paper 1) were proposed to simplify and clarify the classification principles of CRT and CRT terminology. The TFM is supported by the analysis on the listed CRT and the complete chapter content analysis of the CRT chapters in the textbooks. The outcomes of the textbook investigations recommend a standard classification system and standardized terminology for CRT to assist students to understand and master a complex chemistry concept and led to the proposal of such a classification system.

The aim of the practical intervention was to attempt to reduce misconceptions in CRT by doing practical work, using structured and open worksheets, to enhance learners' understanding of theoretical work. Much of a teacher's time is taken up with identifying and correcting misconceptions during students' journey to a more complete understanding of concepts and construction of knowledge in chemistry. The SSC kit proved to be a useful tool in the intervention of teaching for conceptual change. A number of conceptual change models were successfully implemented, using the kit and the worksheets. Metacognition especially was addressed effectively, leading students to identify the incorrect concept, the correct scientific concept, the possible origin of the concept and also strategies for conceptual change. The metacognition activity highlighted the students' superficial knowledge of CRT and their inability to propose strategies for teaching for conceptual change. They often know what they must do, but not how to do it. More practice and skills training needs to take place. Thus, our basic hypothesis, that misconceptions about chemical reaction types are symptomatic of textbook related problems and problems with other related chemistry concepts, is true and SSC kits can successfully be used as intervention tools to address these misconceptions.

Keywords

First-year undergraduate, inorganic chemistry, misconceptions, textbooks, aqueous solution chemistry, terminology, chemical reaction types.

Opsomming

Die aanvanklike probleem wat aanleiding gegee het tot hierdie studie was die probleme wat studente met chemiese reaksietipes (CRT) ondervind het. In diagnostiese toetse in Suid-Afrika, by 'n paar van die groot universiteite, toon CRT die swakste punt van die basiese en spesiale onderwerpe in Chemie. Vraelysresultate van beide Suid-Afrika en Noorweë weerspieël ook die onvermoë van studente en onderwysers om chemiese reaksietipes te klassifiseer en onderstreep die wanopvattings oor belangrike CRT beginsels.

Die doel van hierdie studie was tweeledig: (1) om te ondersoek waarom studente sukkel met chemiese reaksietipes en die mate waarin handboekverwante probleme, en probleme as gevolg van onderrig, 'n rol speel; en (2) hoe praktiese werk gebruik kan word as 'n intervensie om CRT wanopvattings aan te spreek. Om die eerste deel van die doel te bereik, is 102 eerstejaars chemiehandboeke se aanbiedinge van CRT bestudeer. In die handboek-studie is talle CRT en teenstrydige en problematiese CRT terminologie geïdentifiseer. Om die tweede deel van die doel te bereik, is gedokumenteerde internasionale wanopvattings oor CRT versamel. Hierdie wanopvattings is gebruik om vir begripsverandering te onderrig deur gebruik te maak van die MYLAB klein-skaal-chemie (KSC) stelle as ingrypingsinstrument.

Die resultate van die handboek-studie het getoon dat geen vordering na 'n standaard in CRT klassifikasie gemaak is deur die jare 1661-2017 (jaar van handboek publikasie) nie. Verder het die terminologie ondersoek aan die lig gebring dat verwarrende en dubbelsinnige CRT terme gebruik word. Gevolglik is 'n nuwe teoretiese raamwerk (fig.1, artikel 1) en 'n nuwe teoretiese raamwerk model (TFM, fig.2, artikel 1) voorgestel om die klassifikasie beginsels van CRT en die CRT terminologie te vereenvoudig en te verduidelik. Die TFM word ondersteun deur die ontleding van die genoteerde CRT en die volledige hoofstukinhoudsanalise van die CRT hoofstukke in die handboeke. Die uitkoms van die handboekondersoek beveel aan dat daar 'n standaard klassifikasiestelsel en gestandaardiseerde terminologie moet wees vir CRT om studente te help om 'n komplekse chemiebegrip te verstaan en te bemeester.

Die doel van die praktiese ingryping was om wanopvattings in CRT te probeer verminder deur praktiese werk, met behulp van gestruktureerde en oop werkkaarte, asook om leerders se begrip van teoretiese werk te verbeter. Baie van 'n onderwyser se tyd word in beslag geneem deur die identifisering en regstelling van wanopvattings van studente gedurende die bemeestering van konsepte en die konstruksie van kennis in Chemie. Die KSC stel is as 'n effektiewe hulpmiddel as ingrypingsinstrument vir die onderrig van konseptuele verandering aangetoon. 'n Aantal konseptuele veranderingsmodelle is suksesvol geïmplementeer met behulp van die KSC stelle en die werkkaarte. Metakognisie, veral, is effektief aangespreek, wat daartoe gelei het dat studente die verkeerde konsep, die korrekte wetenskaplike konsep, die moontlike oorsprong van die konsep en ook strategieë om te onderrig vir konseptuele verandering, kan identifiseer. Die metakognisie aktiwiteit beklemtoon die oppervlakkige kennis van CRT wat die studente en onderwysers het en hul onvermoë om strategieë voor te stel vir die onderrig vir konseptuele verandering. Hulle weet wat hulle moet doen, maar nie hoe om dit te doen nie. Meer oefening en vaardigheidsopleiding moet plaasvind. Dus, ons basiese hipotese, dat wanopvattings oor chemiese reaksietipes simptomaties van handboek-verwante probleme en probleme met ander verwante chemie konsepte is, is waar en KSC stelle kan suksesvol gebruik word as ingrypingsinstrument om hierdie wanopvattings aan te spreek.

Sleutelwoorde

Eerstejaar voorgraads, anorganiese chemie, miskonsepsies (wanopvattings), handboeke, chemie oplossings in water-medium, terminologie, chemiese reaksie tipes

Preface

- This is to state that I, Maria H du Toit, have chosen the article format for submitting my thesis.

- The work was done by myself, Maria H du Toit, with editing done and suggestions given by Dr CE Read and Dr M Lemmer as respectively supervisor and co-supervisor of my M.Sc.

- Paper 1 (Ch 2) : *A new proposed theoretical framework to standardize classification and terminology of inorganic chemical reaction types in general chemistry textbooks to reduce misconceptions* has been formatted according to the ACS style for submission to the Journal of Chemical Education.

- Paper 2 (Ch 3) : *Chemistry for the masses: the value of small scale chemistry to address misconceptions (in especially chemical reaction types) and re-establish practical work in diverse communities* was submitted to the ACRICE proceedings for a peer reviewed Springer publication.

Abbreviations

CRT	Chemical reaction types
SSC	Small scale chemistry
TF	Theoretical framework
TFM	Theoretical framework model
TG	Textbook group

Table of Contents

Chapter 1: Introduction and objectives

1.1 Problem statement and substantiation

Chemistry education has grappled with misconceptions from its earliest beginnings. Perusal of the literature reveals that textbook related problems, time constraints and teacher induced problems, are some of the root causes of students' misconceptions in chemistry.[1-8] Therefore, teachers should be consistent and careful with their use of scientific language, because it can be a source of misconceptions for students.[1, 3, 9] Moreover, literature reveals that even the word 'misconception' has several alternative terms pertaining to the same concept. For example, different terminology such as naïve conceptions, pre-conceptions and alternative conceptions are often proposed, further obscuring the issue. In this research the word misconceptions will be used with the understanding that it includes all types of unscientific conceptions and also incomplete conceptions.[6, 10]

The origin of misconceptions can be "preconceived notions; non-scientific beliefs; conceptual misunderstandings; vernacular misconceptions and factual misconceptions".[11] If the student is "on his way" to deeper understanding, any or all of these conceptions play a role along the way to complete deeper understanding.[10] Due to the abstract nature of chemistry, students' misconceptions are not so much the result of pre-conceptions as most scientific knowledge in chemistry will be new knowledge. Misconceptions in chemistry might more usually or possibly be due to instructed misconceptions.[8] Teachers must use their words and models of instruction very carefully because the instruction can be the cause of misconceptions.[6, 12] The simplification and clarification of chemistry concepts are also important if we want to minimize working memory overload for students.[13]

Subsequently, there are many conceptual change models to address misconceptions.[10, 14-18] Students differ in learning styles and also with regard to the misconceptions they have, therefore, more than one conceptual change model should be followed.[6, 10] Furthermore, the individual paths students follow in their progression towards deeper understanding of any topic are different.[8, 11] Rather, there is a need for multiple conceptual change models to be implemented because students have multiple misconceptions from multiple origins. Teachers and lecturers should become "diagnostic learning doctors" to address the range of misconceptions experienced by their students.[8] Furthermore, teachers are challenged to "bring about significant conceptual change in student knowledge".[10] Teachers should use and develop various skills and tools to help them identify misconceptions, endeavour to eliminate misconceptions and teach for deeper understanding. That is why hands-on practical work and individual experiments are excellent opportunities to identify misconceptions and teach for conceptual understanding.[5, 10, 19-20]

> Knowledge acquisition does not cause behavior change. People learn through experience, through making mistakes, through trying things out, through talking things through with others. The teachers' role is to provide meaningful exercises and activities that can help to 'cause' learning. Bozarth[21]

One of the key problem areas regarding chemistry concepts are chemical reaction types (CRT).[22-23] Reactions are the basis of chemical scientific language and as such problems experienced at the level of reaction equations have a significant influence on deep understanding and problem-solving in chemistry at advanced levels. In two studies by Potgieter and Davidowitz[22-23], one on grade 12 learners' results in chemistry and one on preparedness for tertiary chemistry of South African students, students showed poor results in chemical reactions. Questionnaire results from South Africa and Norway supported these results.[24] CRT have a significant influence on further chemistry concepts and knowledge; it is the basis or cornerstone of a sound knowledge base. Misconceptions in chemistry are an overarching problem in teaching first year chemistry at tertiary level. Therefore, in this research the specific focus is on chemical reaction types (CRT) and chemical equations. Chemistry experts often forget the wealth of information and concepts that are imbedded into a simple chemical formula. According to Schummer[25] "chemical theory is the language of structural formulas." He further says "the chemical sign language is actually one of the most powerful predictive theories of science". A chemical equation tells an expert chemist much about its properties, its production, its classification, its reactants and products, but it does not imply the same information to a novice.[25] Therefore it is deemed necessary to strive for greater clarity and simplicity especially on the topic of CRT.

In the process to -attempt to eliminate confusion and to -optimize the basic chemistry knowledge necessary for CRT, the first step in this research was the study of general chemistry textbooks. The aim was to determine a standard classification system and standard terminology for CRT. The CRT terminology from all the textbooks was documented and compared. Old obsolete terminology was excluded. Some synonyms for chemical terms have a slight difference in meaning, real or imagined by authors, and the best, most preferred terminology had to be identified. The CRT needed to be investigated for as many textbooks as possible. Two analyses were proposed, one analysis of the explicitly listed CRT and another analysis of the complete CRT chapter contents. The purpose of the analyses was to identify one useful classification system and a set of standard terminology for all CRT terms.

The next step of the study was to use practical work to identify misconceptions and address them. Practical work provides excellent opportunities to create cognitive conflict, to ask students about their thought processes used to resolve a problem. The practical work can also be used to lead students along a thought path and to indicate inconsistencies in their thought processes about the problem.[5, 26] Experiments that do not work are good opportunities to elicit student response. Different misconceptions were used as examples in the workshops. The first series of misconceptions used in the workshops came from internationally documented lists of misconceptions. [27-28] The next series of misconceptions came from misconceptions diagnosed for South African students.

1.2 Basic Hypothesis

Misconceptions about chemical reaction types are symptomatic of textbook related problems and problems with other related chemistry concepts.

1.3 Aim and objectives

The aim of this study was twofold: (1) to investigate why students struggle with chemical reaction types and the extent to which textbook related problems and teacher induced problems play a role, and (2) how practical work can be used as an intervention to address CRT misconceptions.

Objectives:

1. To conduct a review of textbook representations of chemical reaction types.
2. To identify inconsistent and problematic chemical reaction type terminology
3. To compile a list of documented international misconceptions on CRT
4. To evaluate the MYLAB small scale chemistry kit as intervention tool to teach for conceptual change to overcome misconceptions.

1.4 Study outline

The research problem, students' difficulty with chemical reaction types, is introduced in chapter 1. A motivation for the textbook study and the article: "A new proposed theoretical framework to standardize classification and terminology of inorganic chemical reaction types in general chemistry textbooks to reduce misconceptions" is included in chapter 2. A motivation for the use of practical workshops to address misconceptions and the article:

"Chemistry for the masses: the value of small scale chemistry to address misconceptions and re-establish practical work in diverse communities" is included in chapter 3. The study is concluded with general remarks and recommendations from both articles in chapter 4.

1.5 Methodology of the study

The development of the concept of chemical reaction types and the classification of chemical reaction types in textbooks were studied to accomplish objectives 1 and 2. The study included textbooks from earliest chemistry (1661) through the years to 2017, with special emphasis on the last twelve years as their classification will have the largest impact on the current students. The reason for the extended textbook study is the confusion or ambiguity that exists around chemistry reaction types and the mixing of classification methods when identifying reactions. Two analyses were made about CRT: one analysis using the listed CRT in the textbooks and another analysis using the complete contents and supporting explanations of the textbook chapters on CRT. A new theoretical framework (fig.1, paper 1) and theoretical framework model (fig.2, paper 1) is proposed.

General misconceptions on CRT were identified through literature studies (objective 3) and used to confront South African students as an intervention to endeavour to effect conceptual change (objective 4). During practical workshops a number of strategies to bring about conceptual change were implemented. Cognitive conflict, activities to produce cognitive conflict, discussions about conceptual change, interactive conceptual instruction, developing students' thinking skills, argumentation and reasoning, and student metacognition were some of the strategies used to lead students to more scientific knowledge construction especially on CRT.[10] The textbook study and the intervention of practical work to address misconceptions, both on-campus and through on-site chemistry workshops in rural areas, were used to make future recommendations for tertiary chemistry instruction.

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Chapter 2: Textbook analysis

This chapter contains the first paper, entitled:

A new proposed theoretical framework to standardize classification and terminology of inorganic chemical reaction types in general chemistry textbooks to reduce misconceptions.

To be submitted for publication to the Journal of Chemistry Education (ACS). References are done in ACS style.
Website for Author guidelines for the Journal of Chemical Education is:
http//pubs.acs.org/paragon plus/submission/jceda8/jceda8_authguide.pdf

2.1 Motivation

The poor performance of our students in chemical reaction types was the motivation for this study on the topic of CRT. The shallow understanding and misunderstanding of the terminology of CRT compelled us to research the terminology and the origin of the different words used. A desire to simplify and clarify the concepts and the classifications led to the proposed theoretical framework model. The complexity of CRT for the novice student emphasized the advanced skills and concepts the novice student has to master to become an expert in CRT. Therefore, part of the incentive to do this research was to break down the skills and concepts into more manageable pieces and connect these in a logical, consistent classification system. Consequently, a first line of action was to look at the textbooks for clear classification systems and terminology. As a solution to the lack of distinct classification systems the theoretical framework model was proposed for greater clarity to promote student learning. We, thus, proposed our new theoretical framework model as a new system for the classification of CRT.

Outline of paper 1

- Abstract
- Introduction
- Methodology
  - *Theoretical framework*
  - *Data analysis*
- Results and discussions
  - *Classification of listed CRT based on the TFM (analysis 1)*
  - *Classification of content and explained CRT based on the TFM (analysis 2)*

2.2 Paper 1

A new proposed theoretical framework to standardize classification and terminology of inorganic chemical reaction types in general chemistry textbooks to reduce misconceptions.

Maria H. du Toit

Abstract

This study was initiated due to a desire to analyze the reasons for the poor performance of students in chemical reaction types (CRT). Moreover, students' understanding of CRT is exacerbated by differences in the conceptualization and terminology of CRT in general chemistry textbooks. For example, words such as double displacement and neutralization, are some of the concepts students find inconsistent and use incorrectly. To determine the cause of the misconceptions, 102 general chemistry textbooks were studied. The great variety of CRT offered in textbooks, leads to the new proposed theoretical framework. Listed CRT in textbooks were coded according to the proposed theoretical framework model (TFM) and then the TFM was incorporated in the coding diagrams. The initial analysis indicated that none of the specifically listed CRT completely matched the TFM, but after a comprehensive chapter analysis there were six perfect matches and 24 near matches to the TFM. In the light of the ambiguous and confusing number of CRT and CRT terminologies, this study proposes that the TFM should be used as a standardized classification system for CRT. The results also indicated the success of the proposed TFM. Therefore, the implementation of the new TFM will help towards a more straightforward and explicit understanding of a complex chemistry concept.

KEYWORDS: first-year undergraduate, inorganic chemistry, general chemistry, terminology; classification; chemical reaction types; aqueous solution chemistry, misconceptions, textbooks.

Introduction

Chemistry is a complex and difficult subject.[1-4] Moreover, to exacerbate this assertion many students are confused due to misconceptions.[5-8] Misconceptions occur not only due to teaching problems but importantly, also because of a lack of standardization of terminology and classifications especially in textbooks.[9-11] Textbooks are a major source of information for undergraduate students and therefore it is imperative that the authors of these books use standardized classifications and terminology. This study will specifically focus on misconceptions of CRT as induced by general chemistry textbooks. First year students perform very poorly in chemical reaction types.[12] Chemical reaction types (CRT) are especially important because an understanding of them may largely affect our proficiency in 'talking' science. The general public and particularly chemistry students may have little understanding of events like acid rain, heart burn, batteries, rust or the production of salts like calcium carbonate if they cannot distinguish between chemical reaction types. The published literature, examination results and questionnaires indicated that students have major problems with identifying and explaining chemical reaction types.[6, 11-14] In addition, chemistry textbook writers through the years have made various comments about the difficulty that students have with chemical reaction types.[15-16]. According to textbook writers "one of the most difficult tasks for someone inexperienced in chemistry is to predict what reaction might occur when two solutions are mixed".[17]

Very little research has been conducted on chemical reaction types and their classification. The research has focused mostly on misconceptions about chemical reaction types and the writing of chemical equations.[5-6, 14] Chemical reaction types and the writing of balanced chemical equations are part of the 'language' of science and forms the basis of understanding of chemistry—which is necessary to achieve a clear and deep understanding of the concept. For a language to be a means of communication, standard classification and terminology must be defined or be available so that two parties understand each other. Communication at best is difficult as seen by this statement of Cady[18]:

> It is a very difficult matter to convey thought from one person to another by means of words, and anything like accuracy can only be attained when the words have as nearly as possible the same meaning to each. For this reason it is necessary to discuss at some length the significance, in connection with chemistry, of some of the terms used. Cady, p.1.

The use of chemistry terminology must be clearly defined to ensure that the users understand exactly the correct intended concept. According to Brady[19] and Brady and Humiston[20]: "chemistry is a difficult subject because of difficulty of conceptual communication between instructor, the textbook and the student." In another textbook Brady and Holum[21] stated that a "good reason why students need textbooks is to get the complete version and not only the abbreviated version of lectures". Standard terminology defines the concepts so that everyone has the same knowledge or meaning and can communicate effectively to facilitate understanding. Understanding is hindered when the classification systems do not correspond from textbook to textbook and the terminology is ambiguous or unclear. Uniform and clearly defined classification systems enhance concept formation between textbooks for knowledge dissemination. Specifically in terms of CRT, we see a lack of standardized classification.

A major academic medium of knowledge is textbooks.[11] The first line of contact between learning material and users of learning material in tertiary chemistry education is the general chemistry textbooks. These textbooks are chosen around the world, based on the lecturers' own preference. Therefore, if the core principles are not similar, students will have different knowledge bases and consequently a different understanding (which could be a misconception) of a certain topic or concept. As early as 1789, Lavoisier stated the constructivist principle in the preface of his book by saying you have to go "from what is known to what is unknown" and that you must make no assumptions that are not based on experiments.[22] Furthermore, in 1946, Deming wrote that the purpose of his book was "to present chemistry as *a manner of thinking*, rather than as a collection of facts, however systematized, or as an array of unsupported assumptions, to be taken on faith".[23] Also that "to know what sorts of trouble students actually are having, and to modify instruction accordingly, have been the guiding principles in the preparation of this book".[23] He further cautions that "students who neglect to think clearly about this (ions and free elements), or who are not careful to indicate charges carried by ions, will soon cease to make progress".[23] Then he mentions a very important issue, which we experience as a common failure among students today, namely he encourages student to use more than one textbook or reliable source of chemistry information. "One of our chief purposes is to learn to read chemistry".[23] The average student does not, however, read textbooks[24] and use the shortest route via class notes to achieve exam results.

The development of the chemistry topics in textbooks influenced the development and description of CRT. The earliest textbooks mostly contained topics related to the chemistry of the elements.[22, 25-26] Lavoisier (1789)[22] in his effort to systematically organize existing chemistry knowledge described three parts in his book: *(1) The formation and decomposition of aëriform fluids, of the combustion of simple bodies, and the formation of acids; (2) The combinations of acids with salifiable bases, and the formation of neutral salts; (3) Description of the instruments and operations of chemistry*. Silliman (1847)[27] already moved in his book *First Principles in Chemistry* towards a four part book: *(1) Physics with matter, light, heat, and electricity as topics; (2) Chemical Philosophy with topics: elements and their laws of combination, crystallization and chemical effects of voltaic electricity; (3) Inorganic Chemistry with non-metallic elements and metallic elements as topics*; and *(4) Organic Chemistry*. A hundred years later, Linus Pauling (1957)[28] in his book *College Chemistry, an introductory textbook of general chemistry* included a table of contents in six parts: *(1) An introduction to* *modern chemistry, (2) Some aspects of chemical theory, (3) Some non-metallic elements and their compounds, (4) Water, solutions, and chemical equilibrium, (5) Metals, alloys and the compounds of metals, and (6) Organic chemistry, biochemistry and nuclear chemistry*. The change through the years has been from chemical reactions to the chemical phenomena represented by the chemical reactions. The chemical reactions were being classified according to the chemical phenomena that were represented by these reactions.

Today general chemistry textbooks usually cover the following topics: (1) basic concepts of chemistry; (2) atoms, molecules and ions; (3) chemical reactions; (4) stoichiometry; (5) energy and chemical reactions; (6) the structure of atoms; (7) periodic trends and electron configurations; (8) bonding and molecular structure; (9) orbital hybridization and molecular orbitals; (10) carbon and organic chemistry; (11) gases; (12) intermolecular forces and liquids; (13) solids; (14) solutions; (15) rates of chemical reactions; (16) chemical equilibrium; (17) acids and bases; (18) aspects of aqueous equilibrium; (19) entropy and free energy; (20) electron transfer reactions; (21) main group elements; (22) transition elements; (23) nuclear chemistry. These topics are based on research into the relevant 'big ideas' in the chemistry curriculum for first year college or university students.[29] These topics are mainly the topics of general chemistry textbooks of the last 50 years.[30-32] For this study the chapters on chemical reactions mainly in aqueous medium, were the most important. Secondly, the chapters on solutions, acids and bases, aspects of aqueous equilibrium and electron transfer reactions, were of secondary importance.

The first attempt at formalizing nomenclature was the memoir *Chymical Nomenclature, A Memoir, on the necessity of reforming and bringing to perfection the nomenclature of chymisty.* This memoir was presented by Lavoisier to the Royal Academy of Sciences in Paris on 18 April 1787. The memoir was compiled by Mr. Antoine-Laurent Lavoisier, Mr. Louis-Bernard Guyton de Morveau, Mr.Claude-Louis Bertholet, and Mr. Antoine-Francois de Fourcroy. "It is the result of a great number of consultations, in which we have been assisted by the learning and advice of some geometricians of the Academy, and of several chymists".[22] The four chemists proposed the memoir because there was virtually no rational system of chemical nomenclature at this time. The challenge, however, is to select the best terminology for the chemical phenomena and also the best terminology for the chemical reaction types from all the historical resources. All topics in chemistry should have standard terminology as a language to help with the understanding of chemistry across knowledge areas and across the international borders. The nomenclature and terminology used most frequently worldwide are those created and developed by the International Union of Pure and Applied Chemistry (IUPAC)—which is the international body that standardizes chemistry terminology and names. Moreover, IUPAC has a series of colour coded books to indicate international standards on terminology, symbols, nomenclature and measurements in the fields of analytical chemistry (orange)[33], biochemistry and microbiology (white)[34], clinical laboratory sciences (silver)[35], inorganic chemistry (red)[36], organic chemistry (blue)[37], physical chemistry (green)[38], polymer chemistry (purple)[39] and general chemical terminology (gold)[40]. The IUPAC *Gold Book*[40], contains the definitions of a large number of technical terms used in chemistry, but unfortunately not about CRT classification and CRT terminology.

Lavoisier[22] was also one of the first chemists to formalize chemistry knowledge into a new systematic order. He used concepts or reaction types such as decomposition, composition or combination, combustion, fermentation, and oxidation. Up until 2016, classifications of CRT ranged from two to sixteen types. For better understanding and communication, a more standardized classification and terminology for chemical reaction types is needed. The proposal is that for inter-curriculum and global knowledge dissemination, one standard and one method of classification is needed for the general understanding of chemistry, especially CRT, to prevail. Consequently, the main aim was to evaluate CRT classification inconsistencies in textbooks that can contribute to students' misconceptions. The specific objectives were to: (1) identify the number and description of chemical reaction types in the different textbooks; (2) structure a new theoretical framework and compose a TFM as a new standardized classification system; (3) evaluate the existing textbook classifications against the TFM; (4) determine whether there is a growth (progression) in the classification of CRT from random to more meaningful, standardized classification over the years; and finally, (5) to assess CRT terminology used in textbooks. Therefore, 102 general chemistry textbooks were investigated for CRT classification and their use of CRT terminology.

Methodology

Theoretical framework

In support of the proposal to develop a theoretical framework, Ebbing and Gammon[15] said that:

> Among the several million known substances, many millions of chemical reactions are possible. Beginning students are often bewildered by the possibilities. How can I know when two substances will react when they are mixed? How can I predict the products? Although it is not possible to give completely general answers to these questions, it is possible to make sense of chemical reactions. Ebbing *et al*., p.133.

Zumdahl[17] added that “one of the most difficult tasks for someone inexperienced in chemistry is to predict what reaction might occur when two solutions are mixed”. Moreover, “one of the ways we bring order to the study of chemistry is by classifying chemical reactions by type. By classifying reactions, we were able to see patterns in some reactions that permit us to anticipate what happens in other reactions.”[21] Birk[41] emphasized the necessity of rules to classify CRT with his statement that “we can use rules to predict the products of reactions” and “predicting reaction products can be simplified further by classifying chemical reaction types in general categories”. Furthermore, “chemical reactions are classified according to the nature of the change at micro-particle level”.[42] The change can be a phenomenon like electron or proton transfer, the behaviour of the atoms (atoms combined to form products; or atoms replacing each other in a compound), or compounds decomposing into elements or other smaller compounds (as seen in the chemical reaction equations). In the preface of the textbook of Oxtoby *et al*.[43] there is a quotation from Aristotle which reads:

> The search for truth is in one way hard and in another easy, for it is evident that no one can master it fully or miss it completely. But each adds a little to our knowledge of nature, and from all the facts assembled there arises a certain grandeur.

However, O’Connor[44] cautions that “simple definitions are convenient, but we must recognize their limitations relative to real systems”. “It should be emphasized that our system is not an attempt to transform nature so that it fits into small categories but rather an effort to give some order to our many observations of nature.”[45]

The most important thing to consider is that “the key to dealing with the chemistry of aqueous solutions is first to focus on the actual components of the solution before reaction and then figure out how those components will react with each other”.[17] In the case of precipitation reactions, it is best to look at all the soluble ions in the separate containers, before the soluble ionic substances are mixed in the solution. Acid-base reactions can also be approached in the same way by studying the substances involved in the reaction.[17] Another important aspect to keep in mind is the observation by Whitten *et al*.[45] that “we will see that many reactions, especially oxidation-reduction reactions, fit into more than one category, and that some reactions do not fit neatly into any of them”. CRT cannot be forced into categories; the classification systems are just a way to order an overload of information to facilitate understanding. One more essential fact that must be remembered is that “an oxidation-reduction reaction consists of two processes that occur simultaneously”[46]. Oxidation cannot occur without reduction, just as a proton donor works together with a proton acceptor. Textbooks forget to explicitly state this and that can lead to entrenched misconceptions.

From all the textbook studies, there emerged three main classification systems: classification according to atom behavior (or particle rearrangement); classification according to chemical phenomenon (or chemical behavior) and classification according to the nature of reactants and products (gas formation, water formation, precipitation, etc.).[16, 47-48] In this study the classification is done according to the chemical phenomena and the behaviour of atoms. Classification done on the basis of chemical change (gas formation, colour change, temperature change, or precipitation) is more difficult and mixes chemical phenomena. This is clear in the case of gas forming reactions that can be redox or non-redox reactions. On the one hand, zinc and hydrochloric acid gives hydrogen gas as a product and is a redox reaction. On the other hand, sodium carbonate and hydrochloric acid gives sodium chloride, carbon dioxide gas and water as products and is a special acid-base reaction. Therefore, a new theoretical framework for chemical reaction types is needed to enable us to have an identical knowledge base for all users. As a result of all the different listed CRT by textbook authors, I consider the diagram in figure 1 as a new theoretical framework. It gives structure and order to all the CRT in textbooks. It clearly shows relationships among the reactions and whether the reactions are general or specific. Furthermore, this proposed new theoretical framework, is also a new classification system for chemical reaction types.

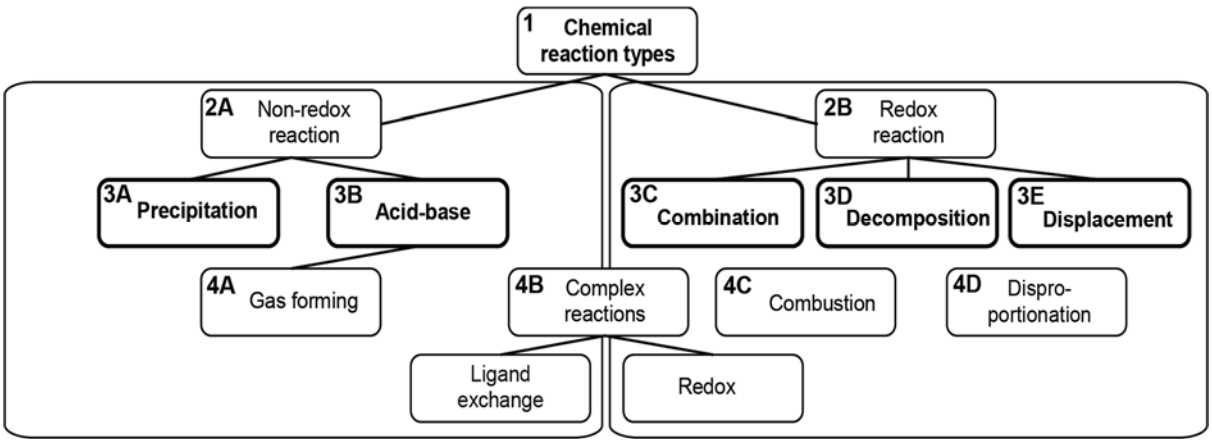

Figure 1. The new proposed four-level theoretical framework.

Level 1 and level 2

The topic, chemical reaction types (on level 1), is divided into two reaction types (level 2), redox and non-redox reactions (2A and 2B). The chemical phenomenon, as criterion for the classification, is electron transfer (at particulate level) or no electron transfer. Redox and non-redox reactions can be decided from the change in oxidation numbers of atoms going from reactants to products in a chemical reaction. No change indicates non-redox reactions and a change indicates redox reactions.

Level 3, general chemical reactions

At level 3 there is the further division of non-redox into precipitation (3A) and acid-base reactions (3B) and the redox into combination (3C), decomposition (3D) and displacement reactions (3E). Precipitation reactions and acid-base reactions, both work on the principle of ion-exchange (AB + CD → AD + CB). The criterion for division on this level is the nature of the reactants and the products: in precipitation one of the products is an insoluble salt and in acid-base reactions the reactants are an acid reacting with a base to form a salt and water ($H^+ + OH^- \rightarrow H_2O$, also called proton transfer reactions). Proton transfer and the formation of insoluble salts are the chemical phenomena. Non-redox reactions are called a number of names in the literature, namely: metathesis reactions, exchange reactions, ion-exchange reactions, double displacement, double replacement and double decomposition reactions.[19, 23, 45, 49-51]

The chemical phenomenon, as criteria for classification in redox reactions, is always electron transfer at particulate level and macroscopic and symbolic observations of the physical reactions and the written chemical equations for the reactions. When looking at the physical reactions, two elements are added together to form a compound (combination); one compound is taken and separated into its elements or smaller compounds containing elements of the original compound (decomposition); and an element and a compound is mixed and the element will displace another element form the compound (displacement). These will be the observations at macroscopic level. Based on the chemical equations for these reactions the observations at symbolic level are self-evident. In all cases of chemical reaction types writing the net ionic equations will enhance the students' ability to indicate different CRT.[23, 45, 52-53]

Level 4, specific chemical reactions

At level 4 (the specific level) there are divisions that are related to the classifications in level 3. Gas forming reactions are a specific example of acid-base reactions. Complexations are the reactions of metals and can be ligand exchange (when the metal cation exchanges ligands) or redox reactions (when the metal changes in oxidation state). Combustion is the reaction with oxygen to produce combustion products (water and carbon dioxide in the case of organic fuels). Internal rearrangement or disproportionation is a self-redox reaction where a substance reacts with itself (two compounds) or in itself (one compound) in a redox reaction (example for one compound: $Hg_2Cl_2 \rightarrow Hg + HgCl_2$). The same chemical compound is simultaneously reduced and oxidized to form two different products. Disproportionation reactions can be related to decomposition reactions.[54]

This new proposed theoretical framework is the empirical framework, based on general chemistry principles, that will be used to code the different CRT from the 102 textbooks studied. The coding helped us to identify patterns and trends in the classification of CRT. However, the TFM represents general CRT and therefore the special CRT in level 4 are not part of the main classification system (Results and Discussions, fig. 2, Level 4 in the TFM are represented by uncoloured and empty blocks).

Data analysis

The theoretical frame work was devised to represent the idealized best classification of the chemical reaction types through perusal of the literature. In the research process the 102 textbooks were coded into textbook groups based on the similarity of their chemical reaction types listed. The textbook groups were compared with the newly developed, proposed theoretical framework model (TFM) by drawing visual diagrams to detect patterns. Moreover, the change in the number of CRT in textbook groups over the years in which the different textbooks were published, was investigated. The most utilized and the least utilized classifications of chemical reaction types were considered and it was observed how these systems differed or corresponded to the proposed TFM. The 102 general chemistry textbooks studied spanned the period from 1661 to 2017. Books of each century were studied with special reference to the textbooks of the last 12 years (2005 to 2017) since the latter will have the biggest influence on present day lecturers, teachers and students. The books were selected based on their availability from different sources. Textbooks of some of the founding fathers of chemistry like Lavoisier, Boyle, Arrhenius, Mendeleev, and Dalton (representing each century) were included in the study.

The chapters that covered chemical reaction types, chemical equations, acids and bases, precipitation, oxidation-reduction and electrochemistry were reviewed. The idea was to follow the terminology from the earliest times of structured chemistry to the present day. Books with a dedicated chapter or section on chemical reaction types were separated from the rest of the books and studied in more detail. Furthermore, the proposed new theoretical framework was used to code the textbook results. The coding was done according to the number of CRT the authors listed in their classifications. For example, textbook group 1 are all the textbooks with no mention of chemical reaction types. Textbook group 2 are textbooks with two chemical reaction types (non-redox and redox reactions on level 2 as TG2 and

2A2B). All the coded textbook groups are indicated in table 1 (Results and Discussions) where they will be described in more detail. The proposed theoretical framework and statements made about chemical reaction types (CRT) were verified by comparing the framework to the textbooks studied.

Two separate analyses were made. The first analysis of the CRT was made strictly according to the CRT the authors listed in the textbooks. The second analysis was made according to the content and explanations given in the chapters on chemical reactions mainly in aqueous medium. The second analysis showed greater consensus of the CRT than the first analysis.

This study assumed that the 102 general chemistry textbooks are a good reflection of CRT classifications used through the years. However, the following could be seen as limitations, namely: the selection process of the available textbooks (a convenient sample); the time frame of textbooks over the years as not all the decades are represented by the same number of textbooks studied; the inclusion of the old masters can either enhance the study or detract from the study, depending on the focus of the reader; the emphasis on the last 12 years, because of the sampling and the uneven representations of books from all countries or continents; and of some of the authors there were more than one edition of their textbooks included. Still, the total number of textbooks should give a good indication of the validity of the proposed TFM. The proposed classification system were also rated and validated by chemistry researchers from South Africa and Norway.

RESULTS AND DISCUSSIONS

Classification of listed CRT based on the TFM (analysis 1)

The textbooks coded in textbook groups, with similar chemical reaction types, were visually represented in diagrams to identify patterns and to determine correspondence with the theoretical framework model (TFM) (table 1 and fig. 2). The change, in CRT over the years, was studied to look for progression towards standardized CRT classification and the textbook groups that corresponded the best to the proposed TFM were identified. Table 1 contains 106 entries made from 102 textbooks coded into textbook groups. Four textbooks proposed two different classifications and those four books were entered twice to indicate two different textbook groups.[20, 48, 55-56]

The 102 textbooks were grouped into 17 textbook groups, representing zero to 16 different CRT. The CRT from each textbook group were coded according to the 4 levels of the theoretical framework. Visual diagrams of the different textbook groups were drawn (see figure 2) to make it easier to identify patterns and to make comparisons with the proposed theoretical framework, presented by the theoretical framework model (TFM, in figure 2), more apparent. Most textbooks (35 of 102, 34%) use the classification 2B3A3B for three CRT. The rest of the textbooks have very different views: TG6 is 8% (8 of 102) and classify as 2A3C3D3E, TG7 is 5 % (5 of 102) and classify as 2B3A3B plus complexation and TG8 is 8% (8 of 102) and is coded as 2B3A3B plus gas forming reactions.

Table1. Chemical reaction types from 102 books divided into textbook groups, and coded according to the new theoretical framework.

Textbook groups (TG)	CRT	Number of books	Number of CRT
1	***none***	34	0
2	**2A2B**	2	2
3	**2B3B**	3	2
4	**2B3A3B**	35	3
5	**2B3A3B4C**	1	4
6	**2A3C3D3E**	8	4
7	**2B3A3B4B**	5	4
8	**2B3A3B4A**	8	4
9	**2A3C3D3E** and **4D**	1	5
10	**2A3C3D3E** and **2B**	1	5
11	**2A3C3D3E** and **3B**	1	5
12	**2A3C3D3E** and **4C**	2	5
13	**2B 3A3B4A4B**	1	5
14	**2A2B3C3D3E** and ionization	1	6
15	**2B3A3B3C3E4B4D**	1	7
16	**2A2B3B4C** and nitration, halogenation, sulfonation, diazotization	1	8
17	**2A3C3D3E** and organic chemistry reactions (*addition; substitution; insertion; isomerization; polymerization; oligomerization*) and **2B3A3B4B** and hydrolysis and solvation	1	16

We considered it to be simpler to have two classifications, redox reactions or non-redox reactions. These two classifications can then be further divided into the five chemical reaction types of level 3 according to the proposed theoretical framework: precipitation and acid-base reactions as non-redox reactions and combination, decomposition and displacement reactions as redox reactions (theoretical framework model (TFM) in figure 2). Level 4 will represent the special reaction types associated with reaction types of level 3. The coded textbook results, based on the framework in figure 1, are visually represented in figure 2.

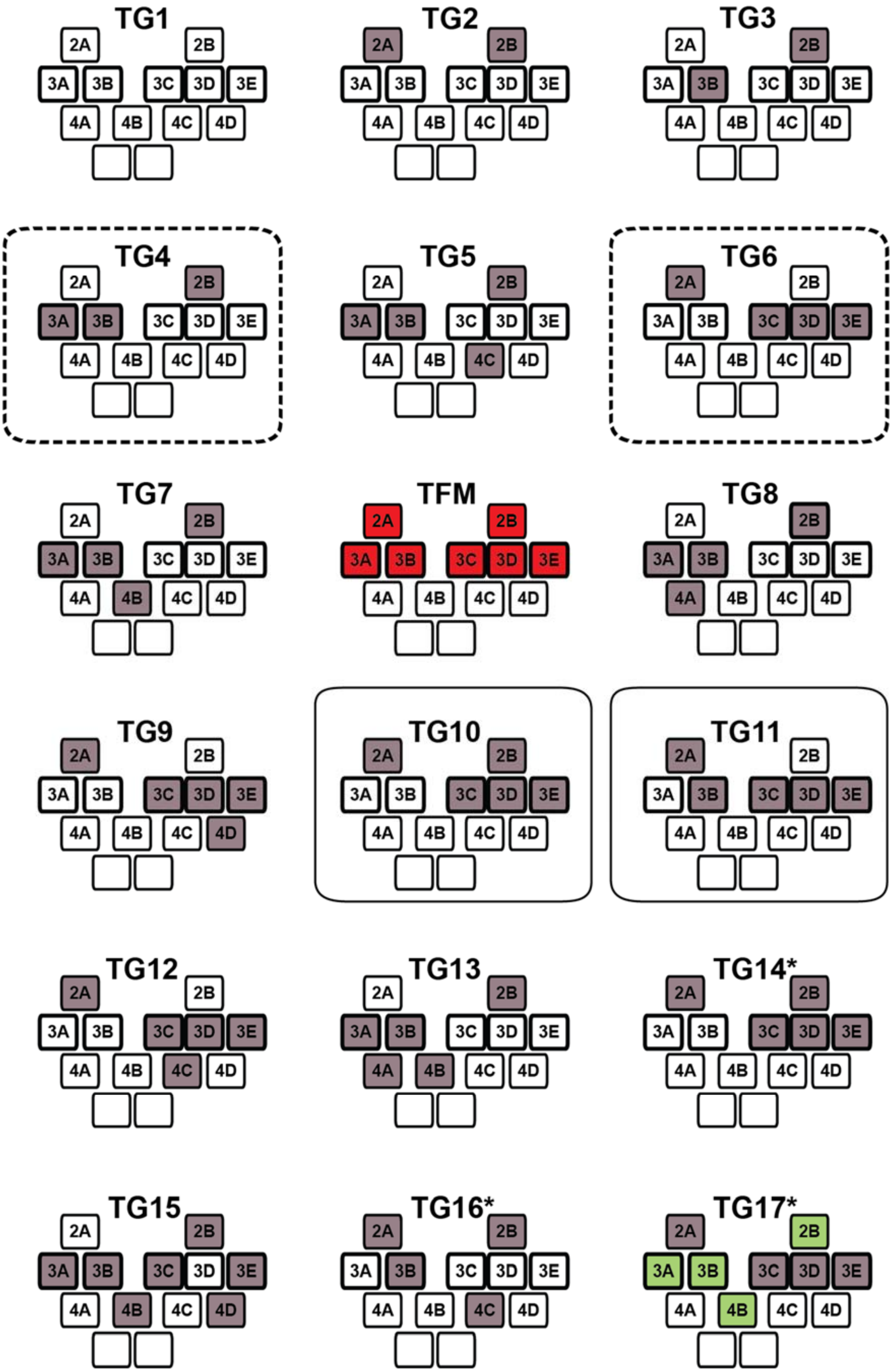

Figure 2. Visual representation of table 1 to see the CRT classification patterns.

Figure 2. Visual representation of table 1 to see the CRT classification patterns. The TFM is shown in the centre with reaction types indicated in red. The shading of the squares in the textbook groups (TG) indicate the CRT in that TG. The dotted lines around TG4 and TG6 indicate that together they make TFM. The TG indicated by an asterisk are outliers that need little consideration. Open empty blocks in all the TG represent a subset of 4B (complexation) not part of the main classification, but included in some textbooks. TG16* indicates the four black CRT plus four more CRT not indicated; TG17* indicates four black CRT which is part of the 10 general CRT and four green CRT which is part of the 6 special CRT (the general and special are terminology used by that author). The rest of the TG17* CRT is not indicated.

The theoretical framework model (TFM) is the representation of the proposed theoretical framework: non-redox reactions and redox reactions both extended to level 3 (2A2B3A3B3C3D3E). By studying the visual representations, we observed that the TFM is equal to TG4 plus TG6. The TFM is also very close to TG10 and TG11. None of the listed CRT classifications of the textbook groups is exactly the same as the TFM, the proposed model. Moreover, figure 3 highlights the number of textbooks per textbook group, further illustrating the varied nature of the classifications across the textbooks.

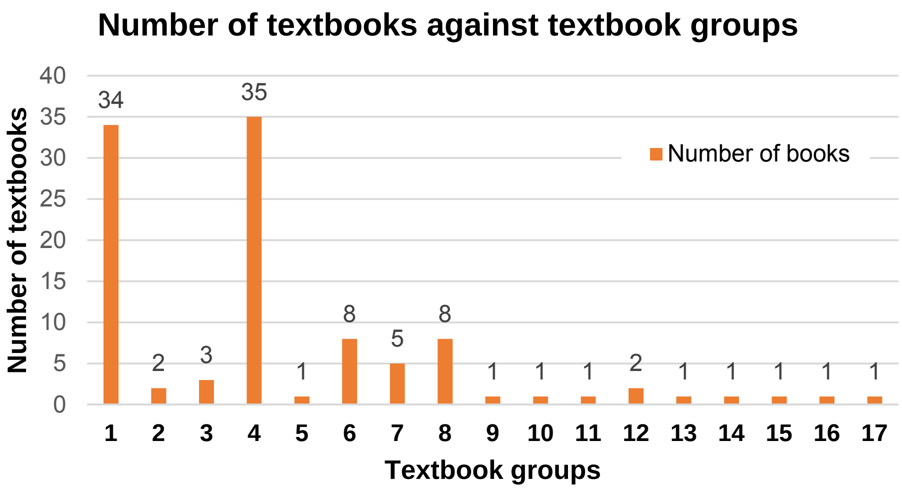

Figure 3. Number of textbooks per textbook group.

In figure 3 it is easy to see that TG4 is the most widely used CRT classification (35 of 102, 34 %) in the selection of available textbooks that were used in this study. TG1, which represents textbooks without CRT, is found in 34 textbooks. Some of the older textbooks or textbooks with a slightly different emphasis belong to TG1 with no specifically indicated chemical reaction types. In combination, using the coded results of table 1, the visual representations of the textbook groups in figure 2 and the graph in figure 3, the different CRT classifications will now be discussed.

NO CRT [TG1]

In 34 of the textbooks (33%) there is no special mention of chemical reaction types made in any chapter.[18, 22, 25-27, 49, 57-84]

TWO CRT [TG2 and TG3] (also see Appendix A of analysis 2)

Five of the textbooks indicated only two chemical reaction types.[20, 44, 55-56, 85] O'Connor[44] and Tillery *et al*.[56] name the two types metathetical reactions (non-redox) and oxidation-reduction reactions (redox) (TG2). On the other hand, Jones *et al*.[55], Brady and Humiston[20], and Slabaugh and Parsons[85] talk about acid-base and oxidation-reduction as the two chemical reaction types (TG3). Therefore, the classifications are seen as redox and non-redox reactions or in the case of Jones *et al*.[55], Brady and Humiston[20], and Slabaugh and Parsons[85] as proton transfer and electron transfer reactions. The TG3 classification ignores or omits precipitation as a reaction type.

THREE CRT [TG4] (also see Appendices B and C of analysis 2)

Thirty five textbooks (34%) indicate three chemical reaction types: precipitation, acid-base and redox reactions (TG4).[15, 17, 19-20, 28, 30, 43, 46, 51, 53-55, 86-108] Out of the 68 textbooks that supply a special chapter on chemical reaction types mainly in aqueous solutions 35 (51%) books give 3 CRT. This 51% indicates the general preference for 3 CRT.

FOUR CRT [TG5] (also see Appendix D of analysis 2)

One textbook indicates four CRT comprising of the three CRT in TG4 with the redox reaction, combustion as the fourth reaction type (TG5).[109] The criteria for the first three reaction types can be seen as chemical phenomena (formation of a solid phase precipitate, proton transfer and electron transfer—explained at sub-microscopic level) whereas the fourth chemical reaction type is also a redox reaction and classified as the reaction with oxygen (explained on the symbolic level). The TFM considers combustion is a specific chemical reaction type (level 4) rather than a main chemical reaction type (level 2 or 3).

FOUR CRT [TG6] (also see Appendices D and E of analysis 2)

Eight textbooks give four CRT which is an extension of the redox reactions of the two CRT from TG2 called TG6.[41, 48, 52, 56, 110-113] Only now metathetical reactions are called exchange reactions or double–displacement reactions and oxidation-reduction reactions are extended to direct synthesis, decomposition, and single-displacement.[41] Thus exchange reactions (2A) are kept as a group and redox reactions (2B) are extended as in level 3.

FOUR CRT [TG7] (also see Appendix D of analysis 2)

Five textbooks give the three general CRT as in TG4 (precipitation, acid-base and redox) and add complexation as the fourth chemical reaction type called TG7.[114-118] Complexation is a viable chemical reaction type depending on the difficulty level of the textbook. Complexation is a specific type of chemical reaction (level 4), the reaction of Lewis acids and bases. Complexation reactions can be redox reactions or non-redox reactions (ligand exchange), which further complicates its classification. For example:

$[Cu(H_2O)_6]^{2+} + 4NH_3 \leftrightarrows [Cu(NH_3)_4(H_2O)_2]^{2+} + 4H_2O$ (ligand exchange) and

$[Ru(H_2O)_6]^{2+} + [Ru(H_2O^{18})_6]^{3+} \leftrightarrows [Ru(H_2O)_6]^{3+} + [Ru(H_2O^{18})_6]^{2+}$ (ligand redox reaction)

FOUR CRT [TG8] (also see Appendices D and E of analysis 2)

The final group of four chemical reaction types is given by eight textbooks (TG8).[21, 31, 47-48, 119-122] The three general CRT (precipitation, acid-base and redox) and gas forming reactions are given as the four CRT. Gas forming reactions are also acid-base reactions or redox reactions and this ambiguous classification criterion indicates that gas forming reactions should not be seen as a different chemical reaction type. If the criteria for classification of chemical reaction types are chosen according to the products that form in chemical reactions gas forming, precipitation and acid-base reactions are definitely chosen reaction types. The products of redox reactions are then part of those reactions. A number of textbooks see gas forming reactions not as a main CRT, but as a specific type of acid-base reaction.[30, 51, 87-88, 103-104, 111]

FIVE CRT [TG9 to TG13] (also see Appendix F of analysis 2)

Six textbooks indicate five CRT. Five textbooks have exchange reactions (2A) (or double decomposition reactions or metathesis, double displacement or double replacement) and the extended redox reactions (3C, 3D, 3E) plus either internal rearrangement (4D) (TG9)[23], or other redox reactions (2B) (TG10)[45], or neutralization (3B) (TG11)[123], or combustion (4C) (TG12)[124-125] as the five chemical reaction types. Deming[23] sees internal rearrangement (ABC → ACB or triangle A-B-C) as a fifth reaction type. Whitten *et al*.[45] sees other "oxidation-reduction" reactions as the fifth type instead of internal rearrangement (or disproportionation). Corwin[123] sees neutralization reactions as a fifth reaction type. Timberlake[124-125] sees combustion reactions as the fifth reaction type. Hardwick[126] has a completely different set of 5 CRT (acid-base, precipitation, redox, gas forming and complexation) (TG13).

Neutralization reactions are acid-base reactions and thus part of exchange reactions (or double-replacement reactions). Internal rearrangement reactions are specific redox reactions and a special case of a decomposition reaction (level 4). The redox reactions of Whitten *et al*.[45] are considered to cover the specific redox reactions of level 4. Timberlake's[124-125] combustion reactions are also a specific redox reaction 4C of level 4. The further problem with neutralization is the question whether it only represents the balanced molar reaction between strong acids and strong bases or whether it represents all acid-base reactions. All the listed CRT—of textbooks with 5 CRT—represent different sets of CRT.

SIX CRT [TG14] (also see Appendix G of analysis 2)

Deming[127] (TG14) indicates six chemical reaction types in his textbook. Direct union, decomposition, displacement, other cases of oxidation and reduction, double decomposition and ionization are seen as the six types. Deming[127] has all the reactions in level 2 (non-redox and redox) and level 3 (precipitation; acid-base; combination, decomposition; single displacement) covered. Other redox reactions presumably refer to 4C4D that indicate specific redox reactions. Ionization is debatable as a chemical reaction type.

SEVEN CRT [TG15] (also see Appendix G of analysis 2)

Eastman[42] indicates seven chemical reaction types in his textbook (TG15). Oxidation-reduction (redox) (2B), proton transfer reactions (acid-base) (3B), Lewis acids (complexation) (4B), ion-combination reactions (precipitation) (3A), displacement or substitution (3E), addition reaction or synthesis (3C), and reorganization reactions (isomerization) (4D) are the seven types of reactions. If you have redox reaction (2B) you do not need to include the extended redox reactions (3C and 3E) or else you need to mention (3D) decomposition as well. These seven CRT are a confusing choice of CRT without logical, supporting arguments.

EIGHT CRT [TG16] (also see Appendix G of analysis 2)

Pyke[128] uses eight chemical reaction types: combustion, oxidation-reduction, neutralization, double decomposition, nitration, halogenation, sulfonation, and diazotisation (TG16). "Double decomposition (2A) takes place when two compounds react in such a way as to be converted into two others by "changing partners, as it were."[128] Thus, the neutralization, is according to definition, then double decomposition. Combustion, nitration, halogenation and diazotisation are oxidation-reduction reactions. This classification then diminishes or decreases the real number of chemical reaction types.

SIXTEEN CRT [TG17] (also see Appendix G of analysis 2)

1. Nelson[50] (TG17) uses ten general chemical reaction types: combination, decomposition, single displacement, double decomposition, addition, substitution, insertion, isomerization, polymerization, oligomerization and six special CRT precipitation, neutralization, hydrolysis, redox reaction, solvation, complexation. The first three general CRT reactions are extended redox reactions (3C, 3D, 3E) and double decomposition is non-redox reactions (2A). Addition, substitution, insertion, isomerization, polymerization, and oligomerization are organic chemistry reactions and are not necessarily reactions in aqueous medium. We are of the opinion that organic chemistry reactions and inorganic chemistry reactions mainly in aqueous medium should not be discussed simultaneously in class. For example, the terminology can cause confusion as the additions are different mechanisms and the same is true for the substitutions. The six special CRT: precipitation (3A), neutralization (3B), redox reaction (2B), complexation (4B), hydrolysis, and solvation are also reactions over several levels (of the proposed framework). Hydrolysis means the chemical breakdown of a compound due to the reaction with water (a chemical reaction) and solvation means the molecules of the solvent surrounds the molecules or ions of the solute (not a chemical reaction). Hydrolysis can be an acid-base reaction as in salt hydrolysis or an organic chemistry reaction, for example, for esters or halo-alkanes. Hydrolysis would thus be another special reaction type in level 4.

Therefore, one of the nearest matches of the selected textbooks to the proposed TFM is the textbook of Chang and Goldsby[91] (Figure 4).

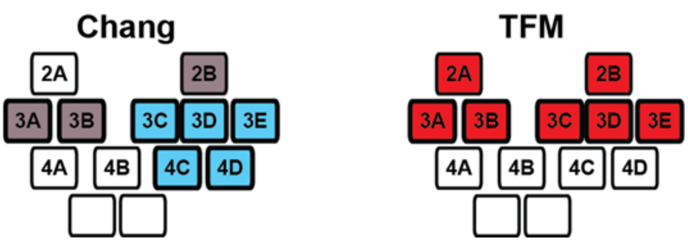

Figure 4. Comparison between the textbook of Chang and Goldsby[91] and TFM. The empty cubes represent extra, special reaction types which are not important for the main classification.

The listed CRT in their textbook are shown in TG4, but they also give redox reaction types: combination, decomposition, combustion, displacement and disproportionation (3C3D3E4C4D; blue blocks) as an extension of redox reactions. Thus, their classification corresponds well with TFM as general chemical reaction types, but they also give combustion and disproportionation as extra, special reaction types (figure 4). The extra, special reaction types are not considered as important for the main CRT classification.

CRT growth and development in textbooks

To summarize, the number of textbook groups (TG1 to TG17) and thus the different classifications of CRT are confusing. Most textbooks have their own classification. Chemistry is already a complex subject and such unnecessary confusion makes understanding difficult and prevents the sharing of knowledge between textbooks and curricula. In figure 5 the variation is visually presented by a graph illustrating the year of publication of the textbook against the coded textbook groups, with the aim of looking for consistency that will show preference and progression towards a specific CRT classification. The first 13 textbooks (1661-1924) were not included on the graph in figure 5 (their value was TG1 consistently) allowing for greater visual clarity. This graph clearly shows that there is no progression towards any uniform classification through the years. Pauling[28] was the first textbook with three CRT (TG4), but through the years there were numerous variations in CRT. The last 12 years showed an increase in preference for TG4 (20 of 39, 51 %), but the variance between CRT is still too great to ensure clarity of understanding. Consensus is needed to ensure progression to better understanding and concept formation.

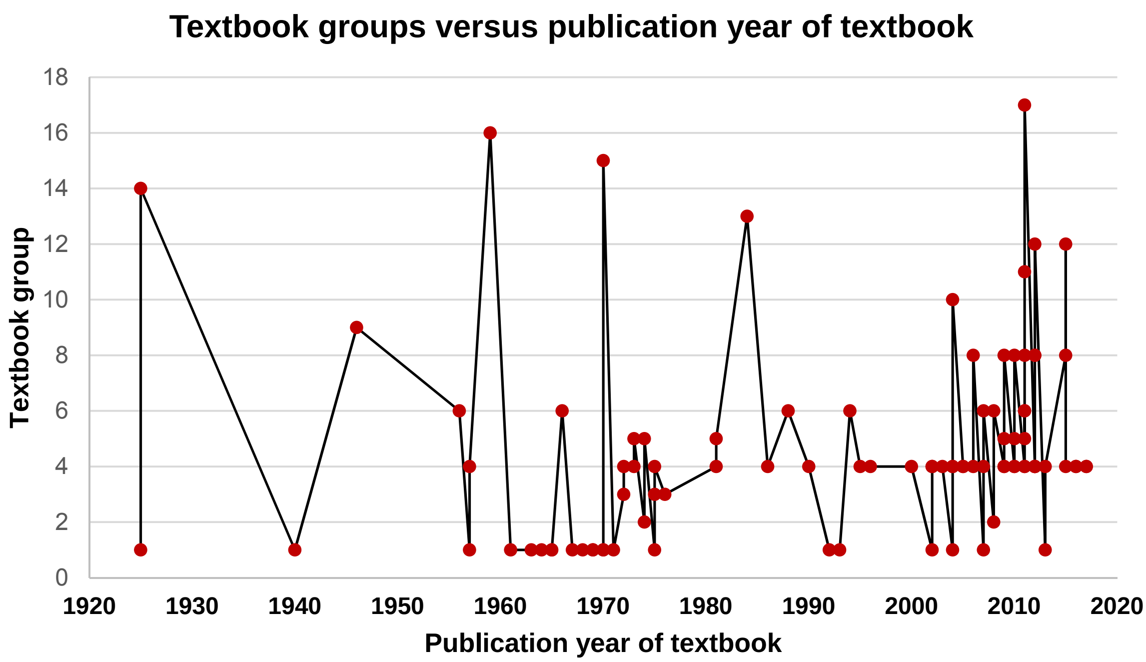

Figure 5. The listed CRT changes through the years (as given by the textbooks).

The answers of the following questions emanated from the results of the textbook study.

- *What is the most utilized CRT classification and why?*

According to the graph (figure 3) the most utilized CRT classifications are TG1 and TG4. In TG1 the textbooks do not discuss CRT and concentrate on other chemistry topics, some without even mentioning any chemical reaction types. TG4 (**2B3A3B**) is then evidently the most utilized classification of CRT. The first textbook that started with this classification is Pauling in 1957 and then other textbooks followed.[15, 17, 19-20, 28, 30, 43, 46, 51, 53-55, 86-108] Pauling does not have a dedicated chapter for chemical reaction types, but he talks decisively about oxidation-reduction reactions (chapter 12), acid-base reactions (chapter 20) and precipitation reactions (chapter 21).

- *How does the most utilized CRT classification differ from the theoretical framework model (TFM) and why is a change towards TFM proposed?*

TG4 is the most utilized CRT, it represents three chemical reaction types based on three chemical phenomena. This is a very sound classification, although precipitation and acid-base reactions are already the extensions of non-redox reactions (on level 3) whereas the classification redox reaction is the un-extended classification on level 2 according to the proposed theoretical framework. Two CRT, namely: redox and non-redox, which are subsequently extended for redox to combination, decomposition and single displacement and for non-redox, to precipitation and acid-base reactions. These yield FIVE reaction types which represent all the main CRT that occur mainly in aqueous solutions. The most logical grouping would be the proposed TFM (red) that is a combination of TG4 and TG6. The specific CRT of level 4 are all extensions of level 3 and not important enough or as widely used as the reactions of level 3. For each of those CRT there is an argument to be made, but they are all special cases of level 3 and should be seen as applications of level 3.

- *How do the rest of the textbook groups differ from each other and from the TFM?*

TG2 is a good choice because it is the very first division between non-redox and redox reactions.[44, 56] TG3, however, makes less sense because only electron transfer and proton transfer are considered. Precipitation as CRT is ignored in three textbooks.[20, 55, 85] TG4 is the most utilized with non-redox reactions extended but redox reactions not extended.[15, 17, 19-20, 28, 30, 43, 46, 51, 53-55, 86-108] TG5 does not extend the redox reactions to level 3, but includes combustion (4C) as a reaction type. Combustion is a special type of redox reaction and not a general type as indicated by level 3 reactions.[109] TG6 extends redox reactions, but not non-redox reactions.[41, 48, 52, 56, 110-113] TG7 is TG4 with complexation (4B) as extra CRT.

Complexation as special CRT depends on the difficulty level of the textbook and on the amount of content devoted to complexation or Lewis acids and bases.[114-118] TG8 is similar to TG4 except that gas forming reactions is also seen as a chemical reaction type. Gas forming (4A) is a special type of acid-base reaction and should not be seen as a separate chemical reaction type from acid-base.[21, 31, 47-48, 119-122] TG9[23] is the same as TG6 plus disproportionation (4D)[23] and TG12[124-125] is similar to TG6 plus combustion (4C)[124-125]. Disproportionation and combustion are both specific redox reactions. TG10 and TG11 are the closest to the TFM. However, TG10 is not extended for non-redox reactions[45] and TG11 left out precipitation as an extension of non-redox reactions and did not include level 2 of redox reactions.[123] TG13 and TG7 is similar, except that TG13 has gas forming also as a separate chemical reaction type.[126] TG14 is TG10 plus extra CRT not indicated on figure 2.[127] TG15, 16 and 17 as outliers as they are too far removed from the standard CRT to be important.

- *As a case study, what is the CRT model used at our home university (North-West University (NWU) in South Africa) that appears in the prescribed textbook for the first year general chemistry course (CHEM111)?*

At NWU, the textbook *Chemistry and Chemical Reactivity*[31] is used. This book proposes four CRT (**2B3A3B4A)** as indicated in TG8. TG8 has gas forming reactions as a fourth chemical reaction type which is a special case of acids and bases (3B). Gas forming reaction is a confusing reaction type (as stated previously) because there are many reactions (of different types) with gases as products. Thus, although this textbook is used, gas forming reaction is not considered as a main reaction type. Moreover, there are many different general chemistry textbooks in use in the various South African universities (not taking into account the different school textbooks). Therefore, the confusion in CRT and the misconceptions as a result of this confusion, in South Africa alone, are significant. These problems with misconceptions are also true for the rest of the world as highlighted by the current study. Therefore, as a recommendation to minimize learning difficulties, we would like to propose the use of the new theoretical framework and the TFM as classification for CRT in future. TG4 plus TG6 would be the ideal. TG10 and TG11 can also be accommodated in this TFM classification. At the very least a standardized classification system is proposed that can be put forward as benchmark for CRT mainly in aqueous medium for inorganic chemistry at first year level. For a number of textbooks their current CRT classification can easily be adapted to the proposed TFM.

Classification of content and explained CRT based on the TFM (analysis 2)

The comprehensive content analysis of CRT chapters are given in appendices A to G. All the reaction types are reviewed again with this comprehensive analysis.

TG4

After coding the TG4, the next step was a complete analysis of the CRT chapter contents. The complete contents of the chapters on CRT, the explanations, the supporting arguments and the chemistry concepts that formed the basis of the listed CRT were studied. The textbooks of TG4 gave three CRT, but if their supported arguments for reactions mainly in aqueous medium are investigated, they come nearer to or are exactly the same as the TFM. The textbooks by Ebbing or Ebbing and Gammon are a case in point (see fig.6).[15, 30, 92-93]

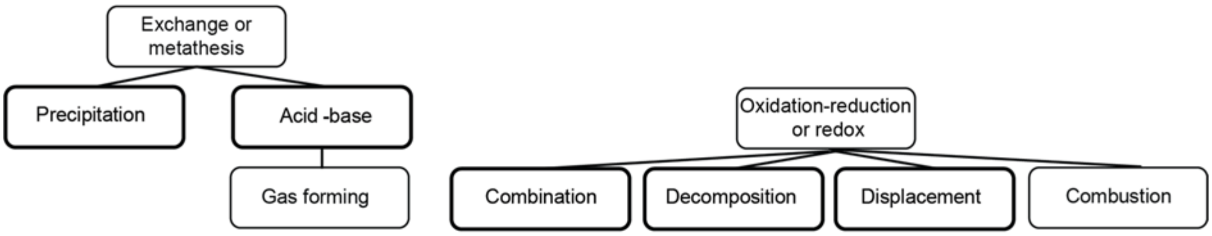

Figure 6. Chemical reaction types mainly in aqueous medium as described by the textbooks from Ebbing and Ebbing & Gammon. The authors consider precipitation, acid-base and redox reactions as the three CRT and on one level. If the levels are adjusted to precipitation, acid-base, combination, decomposition and displacement (five CRT) in one level (combustion excluded), the representation in figure 6 corresponds well with TFM.

According to the Ebbing textbooks, the listed CRT are: precipitation, acid-base and oxidation-reduction reactions.[15, 30, 92-93] Assessing the complete contents of the chapter, the only difference between the Ebbing textbooks and the TFM is that redox should be level 2, combination, decomposition and displacement should be level 3 and combustion reactions should move one level down to level 4. Furthermore, the Brown, *et al*. textbooks[86-89] correspond exactly with the Ebbing textbooks.[15, 30, 92-93] Silberberg[51, 53] and Burdge[54] are exactly the same as the TFM and can be used as support for the proposed theoretical framework. Silberberg is of the opinion that combustion reactions do not fit into the classification (similar to TFM). [51, 53] (Thus in figure 6 combustion must be removed.) Similarly, Burdge[54] considers disproportionation to be an example of decomposition reactions and thus also not to be included in the final CRT. Equally, Chang[90] has the same classification for CRT as the Ebbing textbooks[15, 30, 92-93], but in the place of combustion, the

Chang textbook[90] has disproportionation. The Chang and Goldsby textbook[91] has the same classification as the Ebbing textbooks[15, 30, 92-93] with disproportionation added (figure 4). Chang and Goldsby[91] make no mention of non-redox reactions (metathesis, or exchange) as classification elements (on level 2). Surprisingly, Pauling[28] made this classification of three CRT already in 1957. His chosen CRT are TG4 with precipitation, acid-base and oxidation-reduction with oxidation-reduction extended to combination, decomposition, substitution and other oxidation-reduction reactions. Substitution and displacement is the same and other oxidation-reduction reactions can include combustion and disproportionation. Despite these extensions of the listed CRT, McMurray,[99-101] Masterton,[98] Gilbert,[94] Jones,[55] and Mackay[96-97] stay strictly with the three listed CRT. In another case, Brady and Humiston[20] and Brady[19] correspond with TFM without extending the redox reactions to level 3. The Zumdahl textbooks[17, 106-108] and Zumdahl and DeCoste[104-105] show the same classification as Brady,[19] but without the gas forming reactions. In addition, Gilbert[95] has three CRT with combination and combustion as redox extensions. Hill and Petrucci[46] is similar to Gilbert,[95] but with disproportionation as redox extension. Oxtoby[43, 102] is also the same, but with combustion and disproportionation as redox extensions. Petrucci *et al*.[103] also chose three CRT, but with gas forming reaction as an acid-base reaction and disproportionation as a redox extension.

The inference that can be made from all these classifications and classification extensions is that the proposed theoretical framework is a good representation of textbook classifications of inorganic mainly aqueous reactions through the years. The three CRT were the preferred classification and with this three CRT-classification and its supported extensions there is a solid argument for the implementation of the TFM. TG2 with two CRT, non-redox and redox reaction, of O'Connor[44] and Tillery[56] support level 2 of the proposed theoretical framework. O'Connor[44] calls the non-redox reactions metathetical reactions and extends these reactions to proton exchange (acid-base) and ion-exchange (precipitation) reactions. The TG3 also with two CRT of Jones *et al*.[55]; Brady and Humiston[20] and Slabaugh and Parsons[85] ignores precipitation and only discuss proton transfer (acid-base) and electron transfer (oxidation-reduction). Thus TG3 is only partially helpful towards the argument in favour of the TFM. Similarly, the TG5 of Spiers and Stebbens[109] also only partially supports the new framework. Spiers and Stebbens[109] offer four CRT, the three of TG4 plus combustion. Their mention of combustion lends weight to the inclusion of combustion as a reaction type in level 4.

Undeniably, the TG6 is an important group for the argument in favour of TFM. The four listed CRT consist of unextended double displacement and extended redox reactions as combination, decomposition and (single) displacement. Although, Timm[113] and Cracolice and Peters[110] keep strictly to the four listed reaction types, Tro[48] and Greenstone *et al*.[52] extend the double displacement to precipitation and acid-base with gas formation as a special acid-base reactions. Regrettably, they do not take the extended redox reactions (combination, decomposition, single displacement at level 3) back to redox reactions in level 2. Still, they both give good support to the argument in favour of the TFM. Sherman *et al*.[112], Moore *et al*.[111] and Tillery *et al*.[56] are exactly the TFM. Sherman *et al*.[112] takes the extended reactions combination, decomposition and single displacement back under redox reactions (level 2) and extends double displacement (non-redox at level 2) to precipitation and acid-base reactions (level3). Furthermore, Moore *et al*.[111] is exactly the same as Sherman *et al*.[112], with the further addition of gas forming reactions as acid-base reactions (level 4). Equally, Tillery *et al*.[56] with his two CRT (non-redox and redox reactions), his four CRT (ion-exchange, combustion, decomposition, replacement) and his extension of ion-exchange into solid forms (precipitation), gas forms (gas forming reactions as part of acid-base) and water forms (acid-base) corresponds perfectly with the TFM. He states clearly that combustion, decomposition and replacement are subclasses of redox reactions. In addition, Birk's[41] scheme for CRT completely supports the proposed TFM except for his addition of hydrolysis as reaction type.

The five textbooks of TG7 have three listed CRT plus complexation and give credence to the inclusion of complexation in level 4 of the proposed theoretical framework. Moreover, Cruywagen *et al*.[116]; Day and Johnson[117]; Mahaffy *et al*.[118]; Atkins and Jones[114] and Burrows *et al*.[115] attached importance to complexation as reaction type. Despite the fact that the eight TG8 textbooks have gas forming reactions as an extension of metathesis or double displacement reactions (level 3), instead of as a special case of acid-base reactions (level 4), they also correlate well with the TFM. Only Tro[47] sees gas forming reactions as acid-base reactions. Yet, Brady and Holum[21]; Brady and Jespersen[119] and Kotz *et al*.[31, 120-122] see precipitation, acid-base and gas forming (level 3) as extensions of double displacement reactions. Some of the redox reactions of TG8 are slightly extended to single replacement and / or combustion. Except for the gas forming reactions at level 3 instead of level 4, these textbooks can also be used to strengthen the argument for the TFM. Only Tro[47-48] gives no level 2 support as non-redox and redox reactions. Of the five CRT textbooks, Deming's[23] internal rearrangement is on level 3 and not on level 4, in Whitten *et al*.[45] the other oxidation-reduction reaction may represent disproportionation and should also be on level 4; Timberlake's[124-125] combustion should be on level 4 and Corwin's[123] neutralization is like a double entry next to double displacement. In addition, Hardwick[126]; Deming[127]; Eastman[42]; Pyke[128] and Nelson[50] move too far away from the TFM with from five to sixteen CRT.

With six perfect textbook matches for the theoretical framework model (TFM, fig.2) and the proposed new theoretical framework (fig.1) and 24 nearly exact textbook matches, we maintain that the TFM may offer a more uniform and standardized way to look at chemical reaction types in future.

Assessment of terminology

The use of terminology is also not standardized and many ambiguous terms are used synonymously causing additional confusion. However about some terms there is no uncertainty as only one word is used for the specific concept, such as decomposition, combustion, precipitation and hydrolysis. On the other hand, in the case of words such as synthesis, single displacement, double displacement, internal rearrangement, acid-base reactions and redox reactions there are more than one word used for the same concept. These multiple words for the same concept may lead to misconceptions and concept confusion. The different types of terminologies used in the textbooks are indicated on Table 2. The bold terminology of column 1 (reaction types) are the terminology proposed for standardization by IUPAC if possible.

Table 2. List of the different terminologies used for the various specific chemical terms associated with CRT.

Reaction type	**Alternative terminologies**
Combination[18, 22, 26-28, 42, 45, 52-53, 56, 61, 66-68, 75, 79, 92, 112, 128] (71 entries)	synthesis[42, 56-57, 63, 70], formation[22, 57], direct union[23, 127], addition reaction[42, 50], direct synthesis[41, 57]
Decomposition[15, 22, 26-28, 52, 60, 67, 75, 89, 112, 123, 127] (79 entries)	
(Single) Displacement[23, 26, 41-42, 52, 57, 60, 64, 76-77, 79, 82, 127] (83 entries)	single replacement[30, 52, 112, 119, 123-124], transfer[23, 50], substitution[26, 28, 42, 50, 61, 75]
Non-redox reactions[30]	double displacement[31, 44-45, 48, 52-53, 57, 108, 121], double replacement[19, 21, 31, 52, 112, 121, 124, 127], double decomposition[50, 52, 57, 75, 82, 127-128], metathesis[15, 19-21, 30-31, 45, 51, 53-54, 87-88, 92-93, 111, 119, 121] (metathetical reactions[44]), coordination reaction[103, 115], exchange reaction[30-31, 44, 49, 87-89, 92-93, 111, 121], ion-exchange reaction[44, 51, 53, 56-57, 94, 101], ion-combination reaction[42]
Disproportionation[43, 45-46, 54, 90, 103]	isomerization[42, 50], reorganization reaction[42], self-redox reaction[45-46, 90, 103], internal rearrangement[23].
Combustion[18, 22-23, 26-27, 43, 45-46, 51, 57, 61, 66, 76, 80, 90, 92, 103, 109, 128] (52 entries)	
Precipitation reaction (175 entries)	
Acid-base reaction (163 entries)	Neutralization (121 entries), proton transfer reaction (27 entries)
Gas forming reactions[19, 30-31, 48, 51, 87-]	special acid-base reaction[86-89]

88, 99, 103-104, 111, 119, 126	
Hydrolysis[41, 44, 50, 52, 62-63, 76, 78-80, 82, 95]	
Redox Reaction (214 entries)	oxidation-reduction reaction (89 entries), electron transfer reaction (40 entries)
Oxidation (455 entries)	
Reduction (282 entries)	
Nitration[128]	
Halogenation[128]	
Sulfonation[128]	
Diazotisation[128]	

If we first consider combination, all the listed alternative terminologies for combination reactions are viable (Table 2). Combination indicates that you combine two or more substances to form a new substance. Therefore, firstly, synthesis indicates that a new product is made from two or more reactants. Secondly, formation means reactants give rise to a new product. Thirdly, direct union and direct synthesis implies the simplest forms of union and synthesis. However, direct union and direct synthesis as terminologies can be ignored due to less common use and for clarity. Finally, addition reactions specify that an entity is added to an existing substance. Addition is more suitable for organic chemistry where there is a big molecule and an entity is added to that molecule. Hence, synthesis, formation and combinations are the more appropriate options for indicating this type of redox reaction with combination the most widely used and therefore we consider it as the most suitable term with the clearest description.

Consequently, when considering terminology, the decision should be which word is the most useful. According to Joel Hildebrand[70] “don’t ask which is “right” and which is “wrong”. The only question that should be asked is which is most useful.” If there is standardization on the most useful word for a single concept, much confusion can be eliminated and clear communication can be established. The same is true for the other terminologies of CRT. Terminologies like double displacement, metathesis, double replacement, double decomposition and ion-exchange reactions are listed in textbooks as CRT but these terminologies are not true chemical reaction types. These descriptions are models for explanation but not of physical reality. No two ions are displacing other ions in compounds. There are two soluble ionic substances and at least four types of ions in the solution. Only two types of ions react with each other to form either an insoluble compound or water or a gas. The rest of the ions remain in aqueous solution. No ions displace any other ions.

Non-redox reactions is a better classification and terminology because it can be determined in terms of chemical phenomena (electron transfer or no electron transfer). Neutralization is another confusing concept. Does neutralization only occur between a strong acid and a strong base to give a neutral salt solution or is it indiscriminately used for any acid-base reaction regardless of the pH of the resulting salt solution? The same ambiguity surrounds replacement or displacement. Replacement according to the dictionary means: spare, extra, auxiliary, additional, substitute, stand-in, proxy etc. Displacement according to the dictionary means: movement, dislodgement, supplanting, translation, shift, dislocation etc. Again it is a case of not what is right or wrong, but what "is the most useful word" and one word for one concept will give greater clarity of understanding. IUPAC should indicate the most appropriate word for the concept. Transfer and substitution are less common words for the concept of displacement and should thus be disregarded. Displacement is according to textbook writers the preferred word and used twice as often as replacement.[77, 91] Terminologies that were not included in the table are old terminology that disappeared from use in later textbooks such as calcination (making a calx or a salt); oxydable (making an oxide), acidifiable (making an acid), lixiviation and salifiable (making a salt).[22, 75]

CONCLUSION

This research represents the first attempt to standardize and clarify CRT classification and terminology. The aim was to examine 102 general chemistry textbooks to determine their CRT classification and to see if standard benchmarks exist or are being approached over the course of time. Thus, the task was to identify the number and descriptions of CRT and to assess the terminology of chemical reactions. The study of 102 general chemistry textbooks revealed the lack of uniform criteria for identifying CRT. The subsequent confusing terminology surrounding the principles of CRT further clouds the issue. Some textbooks presuppose knowledge that is not clearly explained or stated.[68] Other textbooks have extreme differences in the number of CRT stated[50, 90], others give no criteria, and on the other extreme very different criteria according to which CRT are classified[41, 51, 111, 118]. Of the 102 general chemistry textbooks studied, 33 % advocated three CRT and 21 % advocated four CRT. The choice of three of the CRT were uniformly the same types, but the promotors of the four CRT came from four different classifications of CRT. The range of CRT is too wide and too confusing to lead to clear and easy understanding of inorganic mainly aqueous CRT and related chemistry concepts. This wide range of CRT can be the cause of misconceptions and incorrect concept formation for students.

Moreover, another objective was to determine whether there is a growth or progression in the knowledge over the years. The graph in figure 5 indicated that over the years no consensus was reached pertaining to classification of CRT. This finding underlines the urgent need for standardization with regards to classification of CRT. No existing benchmark system for CRT was found. Different authors followed different classifications, some authors supported their classifications with criteria and most authors just stated their listed CRT without classification criteria. The lack of a benchmark system was the incentive for the proposal of a new theoretical framework for CRT (fig. 1). This new TFM incorporated all CRT relevant to reactions in water medium that occur in textbooks and organized them in a logical tree-like classification system. The proposed TFM as classification system was well supported by the second content analysis of the CRT chapters from the textbooks. The declared, listed CRT from the textbooks plus their supporting arguments and comprehensive information in the contents of the CRT chapters, gave exact matches for the TFM.

Furthermore, the confusion and ambiguousness of the CRT terminology can be observed from table 2 results. If the terminology can be standardized, it would go a long way towards clarification and simplification of a complex concept in chemistry. IUPAC's mission is to set standards of measurement, symbols and terminology, but they should also consider the stating of uniform criteria for inorganic chemistry chemical reaction types mainly in aqueous solution and standardization of the terminology used in the classification for CRT. We suggest that IUPAC should investigate the terminology of CRT with the aim of greater clarity and less ambiguity. Textbook writers and IUPAC should adhere to one universal classification system for CRT to make it easier for students to grasp the principles of reactions mainly in aqueous solutions. Science or chemistry is all about communication. Never presuppose knowledge from one level of understanding to the next level of understanding. Clarify the terminology and concepts clearly at each level before using and applying the concepts. Choose significant and meaningful CRT and describe them well, then the concept becomes easier to use and widely applicable for students.

Students find it difficult to correctly identify CRT, and deeper understanding and advanced skills are necessary for them to successfully complete the task.[16] Zumdahl[108] stated that "doing chemistry requires both understanding ideas and remembering key information." Standardizing classification systems of CRT and standardizing terminology, should decrease the working memory overload[4] that students experience (especially novice students) and help them towards better concept formation. In the light of the widely different classifications, a new clarified classification system was proposed to help eliminate the possible misconceptions that may hinder the clear understanding of CRT in mainly aqueous solutions in chemistry. The results of this study indicated the confusion that exists with the terminology and classification of CRT in textbooks. For inter-curriculum and global knowledge dissemination one standard and one method of classification is needed for general understanding of chemistry, especially CRT, to prevail. The proposed TFM incorporated classification systems of different textbooks into a concise, but elaborated classification system that contain the main elements of general chemical reaction types mainly in aqueous solutions. The TFM should in its simplicity, enhance understanding and minimize misinterpretation.

Implications for science teaching and learning

Deeper understanding and advanced skills are necessary for the comprehension of CRT, thus, deeper understanding and advanced skills must be taught to achieve success. The different essential skills and knowledge systems underlying the CRT concepts must be identified and taught individually. There should be a concerted effort by educators to ensure that students first master the underlying supporting skills and concepts necessary for understanding CRT before teaching them to integrate and utilize this knowledge and skills to identify CRT. Thus, oxidation numbers; names and formulas; the meaning of names and formulas; the identification of acids, bases, salts, gases, and complexes; writing chemical equations; balancing chemical equations; completing chemical equations and writing ionic equations and net ionic equations should be mastered separately, before identifying CRT is attempted. The progression of these concepts are well designed in both school curriculums and tertiary curriculums, but is often taught without the “bigger picture” in mind. The essential requirement is to focus on the ultimate goal, and teach or facilitate towards the ultimate goal. Thus, standard benchmarks will facilitate proficiency in CRT identification and use. Furthermore, we appeal to lecturers and teachers to teach the variety of skills and concepts necessary for deeper understanding of CRT in such a way that students can identify and use CRT confidently.

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2.3 Supplementary information for analysis 2

The results of the second comprehensive textbook CRT chapter analysis (analysis 2). These appendices are in most cases the textbooks' listed CRT (analysis 1) plus the textbooks' comprehensive content analysis (analysis 2).

Appendix A: 2 CRT

TG2 [1]

A = Non-redox
B = Redox

TG2 [2]

A = Metathetical
- o Proton exchange (acid-base)
- o Ion-exchange
  - Acid base
  - Precipitation
  - Ion-exchange with polymer

B = Oxidation-reduction

TG3 [3]

A = Proton transfer
B = Electron transfer

TG3 [4-5]

A = Acid-base
B = Oxidation-reduction

Appendix B: 3 CRT

A	B	C

TG4 [6]

A = Precipitation
B = Acid-base
C = Oxidation-reduction
- Combination
- Decomposition
- Substitution
- Other oxidation-reduction reactions

TG4 [3]

A = Precipitation
B = Proton transfer
C = Electron transfer

TG4 [7-8]

A = Solubility
- Hydrolysis

B = Acid-base
C = Oxidation-reduction

TG4 [9-12]

A = Precipitation
- Ion-interchange (or double displacement reaction)

B = Acid-base
C = Oxidation-reduction
- Photosynthesis
- Combustion

TG4 [13-15]

A = Precipitation
B = Acid-base
C = Redox

TG4 [16-17]

A = Precipitation
B = Acid-base
C = Oxidation-reduction
- Combustion
- Disproportionation

TG4 [18]

A = Precipitation
B = Acid-base
C = Oxidation-reduction
- Disproportionation

TG4 [19]

A = Precipitation (double-displacement, metathesis, ion-exchange)
B = Acid-base (neutralization reactions)
- Gas forming

C = Oxidation-reduction
- Combination
- Decomposition
- Displacement

(Note: Thermal decomposition and electrolytic decomposition also mentioned. Combustion reactions do not fit into this classification)

TG4 [20-22]

A = Precipitation *(think in terms of ion interchange)*
B = Acid-base *(neutralization)*
C = Oxidation-reduction

TG4 [23]

A = Precipitation
B = Acid-base
- Ion-exchange

C = Oxidation-reduction

TG4 [24-25]

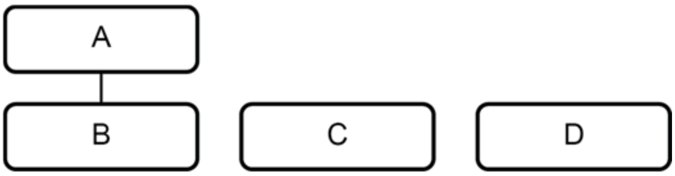
A = Precipitation
B = Acid-base
C = Oxidation-reduction
- Combination
- Decomposition
- Displacement
- Disproportionation

TG4 [26]

A = Precipitation
B = Acid-base
- Gas forming

C = Oxidation-reduction
- Disproportionation

Appendix C: 3 CRT (other)



TG4 [4]

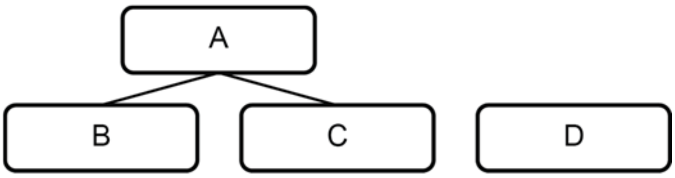
A = Metathesis
B = Precipitation
C = Acid-base
- o Gas forming

D = Oxidation-reduction

TG4 [27]

A = Ion-exchange
B = Precipitation
C = Acid-base
D = Oxidation-reduction
- o Combination
- o Combustion

(Hydrolysis also mentioned)



TG4 [28]

A = Metathesis
B = Precipitation
C = Acid-base
D = Oxidation-reduction
- o Combination
- o Decomposition
  - Disproportionation *(is an example of decomposition reactions)*
- o Combustion

TG4 [29-32]

A = Metathesis (or exchange reactions)
B = Precipitation
C = Acid-base
- o Gas forming

D = Oxidation-reduction
- o Combustion (2006, 2009, 2012, 2015)
- o Displacement (2006, 2009, 2012, 2015)
- o Combination (2012, 2015)
- o Decomposition (2012, 2015)

TG4 [33-36]

A = Exchange
B = Precipitation
C = Acid-base
- o Gas forming

D = Oxidation-reduction
- o Combination
- o Decomposition
- o Displacement
- o Combustion

TG4 [37]

A = Metathesis (or double replacement)
B = Precipitation
C = Acid-base
- o Gas forming

D = Redox

Appendix D: 4 CRT

TG4 [38]

- A = Thermal decomposition
- B = Precipitation (or double displacement, or metathesis, or ion-exchange)
- C = Acid-base
  - o Gas forming
- D = Oxidation-reduction
  - o Combination
  - o Decomposition
  - o Displacement

TG5 [39]

- A = Precipitation
- B = Acid-base
- C = Electron transfer
- D = Combustion

TG6 [40-41]

- A = Double replacement
- B = Combination
- C = Decomposition
- D = Single replacement

TG6 [42]

- A = Double replacement (or double displacement, or double decomposition)
  - o Neutralization (or proton transfer, or water is formed)
  - o Gas forming (gas is formed)
  - o Insoluble product (insoluble product is formed)
- B = Composition (or combination, or synthesis)
- C = Decomposition
- D = Single replacement (or simple replacement or displacement)

TG6 [1]

- A = Ion-exchange (or non-redox reactions)
  - o Solid forms
  - o Gas forms
  - o Water forms
- B = Combination (or synthesis)
- C = Decomposition
- D = Replacement

(B, C, D are subclasses of redox reactions)

TG6 [43]

- A = Double displacement
  - o Precipitation
  - o Acid-base
  - o Gas forming
- B = Synthesis
- C = Decomposition
- D = Single displacement

(B, C, D are subclasses of redox reactions)

TG7 [44-47]

- A = Precipitation
- B = Acid-base
- C = Complexation (reactions between Lewis acids and bases)
- D = Oxidation-reduction

TG7 [48]

- A = Precipitation
- B = Acid-base
- C = Complex
- D = Oxidation-reduction
    - Combustion
    - Corrosion
    - Photosynthesis
    - Metabolism of food
    - Extraction of metals

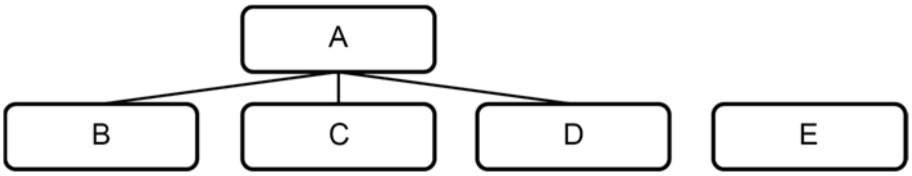
TG8 [49]

- A = Precipitation
- B = Acid-base
- C = Gas forming (gas-evolution reactions are also acid-base reactions)
- D = Oxidation-reduction

TG8 [43]

- A = Precipitation
- B = Acid-base
- C = Gas forming
- D = Oxidation-reduction
    - Combustion

Appendix E: 4 CRT (other)



TG8 [50]

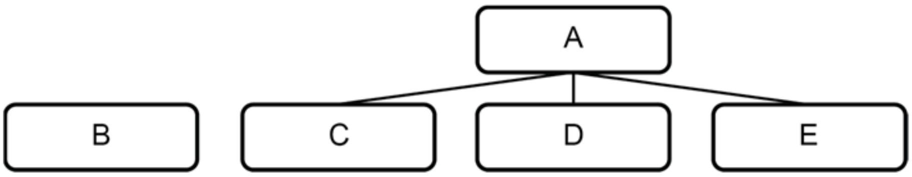
A = Metathesis
B = Precipitation
C = Acid-base
D = Gas forming
E = Oxidation-reduction
- Single replacement

TG8 [51-54]

A = Metathesis (or exchange, or double displacement, or double replacement)
B = Precipitation
C = Acid-base
D = Gas forming
E = Oxidation-reduction

TG8 [55]

A = Double replacement (or metathesis)
B = Precipitation
C = Acid-base
D = Gas forming
E = Oxidation-reduction
- Single replacement
- Combustion



TG6 [56]

A = Redox
B = Double replacement
- Precipitation
- Acid-base

C = Combustion
D = Decomposition
E = Single replacement

TG6 [57]

A = Redox

B = Double displacement (or non-redox)

- Precipitation
- Gas forming
- Acid-base
- Hydrolysis

C = Direct synthesis

D = Decomposition

E = Single displacement

TG6 [58]

A = Oxidation-reduction

B = Exchange reaction (or metathesis, double displacement)

- Insoluble product (precipitation)
- Acid-base (water as product)
- Gas forming

C = Combination

D = Decomposition

E = Displacement

Appendix F: 5 CRT

A	B	C	D	E

TG9 [59]

A = Exchange
B = Direct union (combining)
C = Decomposition
D = Internal rearrangement
E = Transfer or displacement

TG10 [60]

A = Metathesis (or double displacement)
- o Precipitation
- o Acid-base

B = Oxidation-reduction (may be disproportionation)
C = Combination
D = Decomposition
E = Displacement

TG11 [61]

A = Double replacement
B = Neutralization
C = Combination
D = Decomposition
E = Single replacement

TG12 [62-63]

A = Double replacement
B = Combination
C = Decomposition
D = Single replacement
E = Combustion

(Classification according to symbolic representation only.)

TG13 [64]

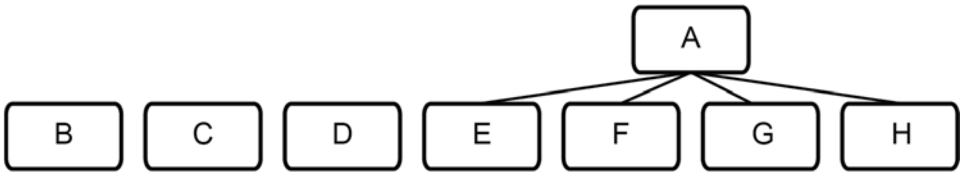
A = Precipitation
B = Acid-base
C = Gas forming
D = Complex
E = Oxidation-reduction

Appendix G: 6 and more CRT

TG14 [65]

A = Double decomposition
B = Ionization
C = Other redox reactions
D = Direct union
E = Decomposition
F = Displacement

(Double decomposition is not equal to double replacement.)

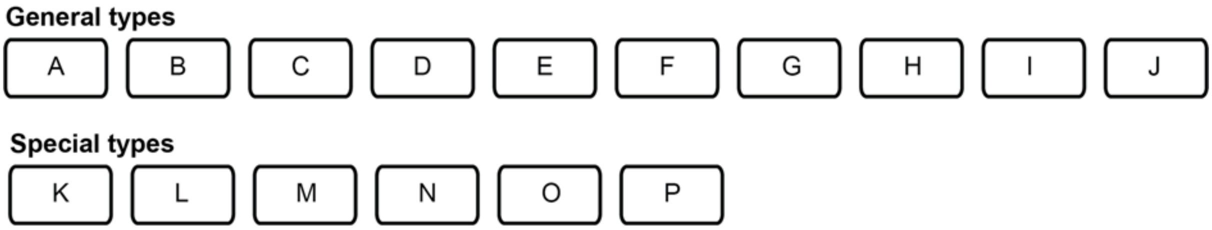


TG15 [66]

A = Oxidation-reduction
B = Ion-combination
C = Acid-base
D = Lewis acids and bases (Complexation)
E = Synthesis
F = Decomposition
G = Displacement (or substitution, or single displacement)
H = Reorganization (or isomerization)

TG16 [67]

A = Double decomposition
B = Neutralization
C = Oxidation-reduction
D = Combustion
E = Nitration
F = Halogenation
G = Sulfonation
H = Diazotisation



TG17 [68]

A = Double decomposition
B = Combination
C = Decomposition
D = (Single) displacement
E = Addition
F = Substitution
G = Insertion
H = Isomerization
I = Polymerization
J = Oligomerization

K = Precipitation
L = Neutralization
M = Hydrolysis
N = Redox
O = Solvation
P = Complexation

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Chapter 3: Misconception intervention

This chapter contains the second paper, entitled:

Chemistry for the masses: the value of small scale chemistry to address misconceptions (in especially chemical reaction types) and re-establish practical work in diverse communities

Submitted for publication to the Conference Proceedings of ACRICE (African Conference for Research in Chemistry Education) to be published as a peer reviewed Springer publication. References done in APA style. (Date of submission: 5 July 2016)

3.1 Motivation

This paper reports on misconceptions of chemical concepts that were identified through literature, questionnaires and examination results, especially for chemical reaction types (CRT) (du Toit & Read, 2012; Horton, 2007). Conceptual change strategies were studied and practical workshops were conducted where teachers were confronted with specific misconceptions and asked to achieve conceptual change in order to attain deeper understanding and lasting scientific knowledge. Teachers meet with students' incomplete knowledge on a regular basis and should be taught skills to effect conceptual change. Practical workshops, with individual hands-on structured and open experiments aimed to correct misconceptions or help to complete incomplete conceptions, are a good instructional strategy. Therefore, workshops were used as interventions to address misconceptions and to achieve conceptual change. The motivation for this study was to evaluate the applicability of the small scale chemistry (SSC) kit (MYLAB) to eliminate misconceptions. The kit can be used to implement most of the conceptual change instructional strategies. This paper is reported as part of a larger, on-going research study of interventions to address CRT misconceptions.

Outline of paper 2

- Abstract
- Introduction
- Contextual background of the study
- Materials
- Methodology of specific workshops on CRT misconceptions
    - Formal workshops
    - Informal workshops
- Results
    - Results of formal workshops
    - Results of informal workshops

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3.2 Paper 2

Chemistry for the masses: the value of small scale chemistry to address misconceptions (especially in chemical reaction types) and re-establish practical work in diverse communities.

Maria H. du Toit

Abstract

Chemistry is one of the main subjects learners struggle with at school level. Moreover, many schools do little or no practical work to enhance learners' understanding of theoretical work. As a result of this lack of practical support, many learners struggle with misconceptions that hinder their progress and disadvantage them at subsequent higher levels. Furthermore, schools in rural settings have many resource barriers that seriously hinder effective teaching. Therefore, this poor performance of learners and students in chemistry combined with the resource constraints of many schools were the main driving force for the development of the MYLAB Small Scale Chemistry and Natural Science kits (Grade 4 to 12). The workshops aim to support the local teachers in presenting practical work with the aid of the kits. Participant teachers acquire hands-on experience with the kit relevant to their particular teaching grades, whilst having expert help available. Problem areas such as misconceptions are addressed and difficult theory is discussed. Participants fill in pre-workshop questionnaires and post-workshop evaluation forms. Consequently, the focus of this study is to show that the introduction of small scale chemistry kits, through onsite workshops, is valuable. The kits allow access to chemistry to all especially reaching remote schools, as well as improving chemistry subject knowledge and addressing chemical reaction type misconceptions by re-establishing practical work in schools. The MYLAB project has been running for 22 years, totalling 260 workshops for 1950 teachers from 1800 different schools, as well as a large number of learners. Feedback from participants include comments such as "very useful in helping a teacher relate the (practical) material with the content of the curriculum" and "if all science teachers could be exposed to this, science teaching would be greatly enhanced in our schools." In the workshops that specifically addressed misconceptions related to the principles of chemical reaction types, the results indicated that teachers themselves had misconceptions and that they need more training in conceptual change strategies.

Keywords: teachers, first-year undergraduate, inorganic chemistry, aqueous solution chemistry, chemical reaction types, misconceptions, small-scale chemistry kit, practical work, onsite workshops

Introduction

Why is chemistry so essential? Chemistry is a central science and is important in medicine, education, pharmaceuticals, engineering, forensics, materials, polymers, nutrition, physics and a number of other knowledge fields. However, according to research and experience, school learners (Arends *et al*., 2015; Beaton, 1996; Martin, Mullis, & Chrostowski, 2004; Martin, Mullis, Foy, & Stanco, 2012; Spaull, 2013) and first year students (Potgieter & Davidowitz, 2011) perform below par in chemistry. Learners, and in some cases educators, have inadequate knowledge of the fundamental principles which underpin the study of chemistry. Compounding the problem of chemistry education is a serious shortage of skilled teachers in mathematics and science in South-African schools (Arends *et al*., 2015; Beaton, 1996; Martin *et al*., 2004; Martin *et al*., 2012). The lack of skilled teachers undermines effective teaching. Ineffective teaching leads to the absence of "links" between existing knowledge and new knowledge and leaves memorization as only option (Marais & Mji, 2009). Incomplete understanding of concepts leads to lack of self-discipline in students to complete self-study and homework assignments. This circle of under-qualified teachers and inadequate school systems and school resources results in poorly prepared students, and this impacts negatively on motivation and career-drive of students (Marais & Mji, 2009).

Furthermore, the complexity of chemistry as subject also contributes towards the poor performance of students. The abstractness and the language of chemistry make it difficult for students to understand and master the subject. Consequently, the students experience chemistry as difficult and lose concentration and motivation to study the subject. Additionally, due to the challenging nature of the subject, students do not receive encouragement and help from parents to master chemistry (Nbina, 2012). Traditionally chemistry comprises theoretical as well as practical work. Moreover, practical work is an essential part of science education (Millar & Abrahams, 2009). In the words of Julia Buckingham, "Practical work is an integral part of science, it is not an add-on. It is something that encourages students to question, to explore – it excites them" (Adams, 2014). Nevertheless, despite the importance of practical work, most chemistry teaching has deteriorated into lectures and memorizations to address time-constraints and curriculum overload. Some of the main reasons listed why South African schools are not doing enough practical work are a lack of resources. Many schools have resource barriers (Marais & Mji, 2009) and lack laboratories, time and have large classroom size and assessment pressures (Heeralal, 2014). Moreover, South African school management have difficulty with the concept that Physical Sciences (the combination of physics and chemistry in the last three school years) need more financial investment than other subjects. In addition, personal experience and literature show that educators are discouraged from doing practical work because of time constrains, lack of self-confidence and motivation, lack of organization, fear of working with chemicals, anxiety about performing experiments, and insufficient understanding of relevant chemistry concepts (Kibirige, Rebecca, & Mavhunga, 2014). Compounding these problems is the remoteness of many rural schools, as is also the case in South Africa. Some schools do not even have adequate access roads. If practical work is to flourish and become the central activity of teaching chemistry, these issues have to be addressed.

The poor performance of learners and students in chemistry combined with the resource constraints of many schools were the main driving force for the development of the commercially available MYLAB Small Scale Chemistry and Natural Science kits (Grade 4 to 12) (www.mylab.co.za). My colleague and I, at the North-West University (Potchefstroom, RSA), developed the kit and compiled the worksheets. The value of small scale chemistry kits to increase students' understanding of chemistry concepts was researched in Ethiopia with positive results (Tesfamariam, Lykknes, & Kvittingen, 2014). Moreover, the international drive towards green and microscale chemistry substantiate the value of small scale chemistry (Tantayanon, 2005).

The MYLAB kits include all the apparatus the learners need, all the chemicals, adequate and challenging worksheets based on school curriculum outcomes, memorandums for worksheets and preparation material (in the DVDs). Neither laboratories, nor electricity or running water are necessary. These small scale chemistry kits are an easy and cost-effective way to reach large numbers of schools and pupils in rural areas (Du Toit, 2012a) and provides a solution for easy transfer of knowledge and practical skills. The main advantages of using the kits include easy storage, ease of use, less expensive to maintain than standard laboratory equipment if there are breakages, and the use of small amounts of chemicals. Furthermore, experiments can be done easily, seen clearly, performed in a shorter time and are safer. Also, the wide range of experiments that can be performed makes it especially valuable. Short, quick, easy experiments with small scale chemistry kits can be used in ordinary class rooms to highlight, discover, test and investigate chemistry concepts. Thus, the independence of the chemistry kits of classroom facilities, electricity, and running water, make them imminently suitable for diverse communities and under-resourced schools. Moreover, onsite training workshops are presented for schools purchasing these kits. In the workshops to introduce small scale chemistry workshops we try to address the main concerns which educators experience, for example the lack of: self-confidence, background knowledge, sufficient theoretical knowledge, practical skills, and knowledge about chemicals and safety data (Du Toit, 2006, 2014, 2015, 2016).

However, when practical work is done, there is a need to at the same time address trouble-shooting (what to do if an experiment does not work or give the desired results) and misconceptions (wrong chemistry concepts held by educators or learners). Misconceptions are notoriously resistant to conceptual change; therefore educators (and learners) need to be confronted with the correct concept through their own investigation (Hewson, 1992; Taber, 2002). On the whole, to bring about conceptual change there are various strategies (Hewson, 1992; Kyle & Shymansky, 1989; Riordan, 2012) that can be followed. For example, a simple four step approach (Bybee, Carlson-Powell, & Trowbridge, 2008) also applied in this study are:

(1) first the action then the words,

(2) talk through the new concept,

(3) teach the concept to someone else,

(4) don't let the concept die.

To apply the action step in chemistry teaching practical work is of vital importance. There are many topics the students do not fully understand and the school system does not provide enough time for practice and reinforcement of concepts (Ali, 2012; Nbina, 2012). However, one of the solutions are small scale chemistry experiments which are especially useful in addressing the first step of teaching for conceptual change: first the action then the words. Implementing small scale chemistry makes it easy to confront students with the correct scientific concept (Niaz, 1995). With the small scale chemistry kits the students can discover the concepts themselves, which is a precursor to better and deeper understanding involving more than one of their senses. Physical confrontation and one's own explanations of chemical phenomena contributes to active learning with improved long term effects.

The focus of this study is to show that small scale chemistry kits, through onsite workshops, are valuable to allow access to chemistry to all (especially reaching remote schools), and improving chemistry subject knowledge (especially on chemical reaction types) by re-establishing practical work in schools (especially to accomplish conceptual change). Through evaluating 22 years of onsite workshops I specifically want to illustrate (1) the effectiveness of MYLAB sets as a replacement for an entire laboratory; (2) how small scale chemistry experiments can be used to address and improve misconceptions in chemical reaction types; and (3) the value of onsite workshops to train chemistry teachers and reach remote communities.

Contextual background of study

The effectiveness of MYLAB as mini-laboratories have been indicated by the workshops held all over the country. To re-establish practical work and address misconceptions in chemistry numerous workshops had been held over South Africa as part of the MYLAB project. The MYLAB project has been running for 22 years, totalling 260 workshops for 1950 teachers from 1800 different schools across the country (see Figure 1 and Appendix A), as well as a large number of learners.

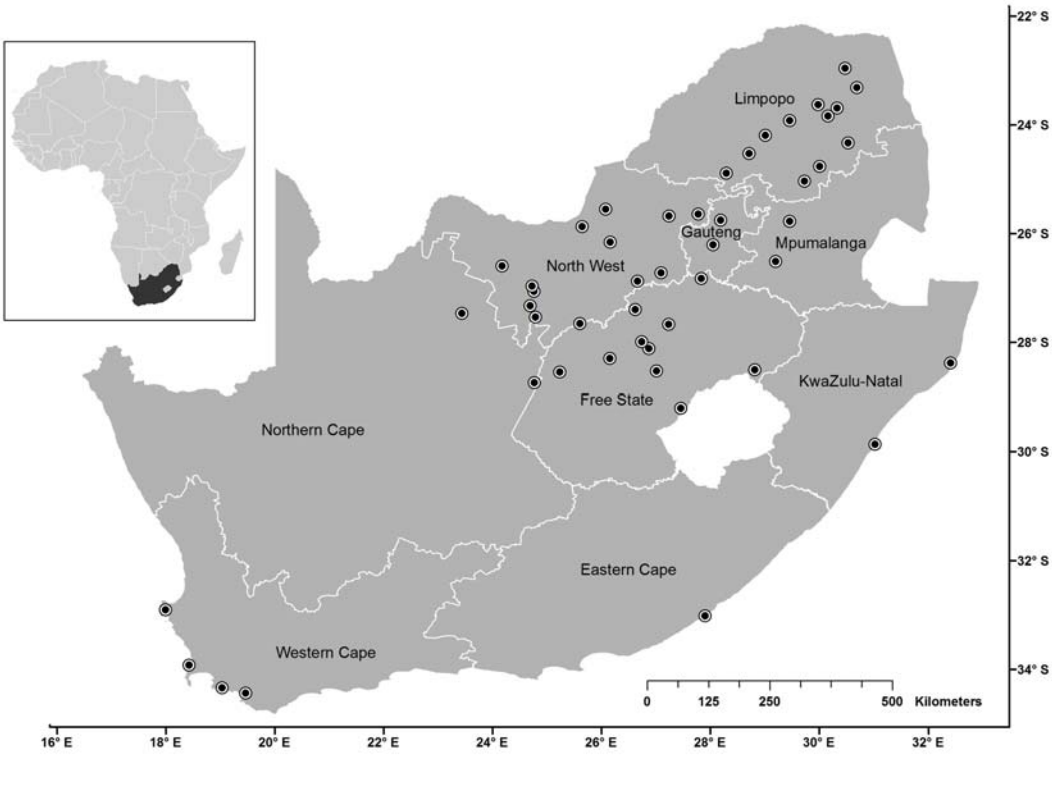


Figure 1: Map of South Africa indicating the location of the towns and villages in which workshops where presented. The inset map indicates the position of South Africa within the African continent. Appendix A gives the names and the positions of the towns.

The value of onsite workshops were demonstrated by the individual attention and support teachers received during the workshops. Approximately 260 onsite workshops were held to re-establish practical work in diverse communities and especially rural communities in South Africa (Du Toit, 2006, 2014, 2015, 2016). Workshops were also held on the North West

University campus for pre-service and in-service teachers (Du Toit, 2012b). Venues for workshops included science centres, schools and community halls. Due to financial constraints, workshops were done on demand. A provincial education department, a school or a financial institution requested a workshop or workshops. For the same reason follow-up workshops were not always possible.

The participant samples consisted mostly of the science teachers and/or subject advisors of the school or schools in the region. The maximum number of teachers in a workshop group was 25 (although larger numbers have been accommodated) to be able to give high quality individual attention to each participant. The workshop presenter was supported by one to three workshop facilitators. In workshops teachers were usually expected to do individual work, because in their classrooms they are on their own. When groups were larger than 25, the teachers were allowed to work in groups to solve the experimental problems. The aim of this arrangement was to give attention to as many teachers as quickly as possible to prevent individual frustration when problems arose during training.

The workshops followed a set program and four to six experiments were done daily according to the South African school curriculum to support the teachers in their teaching endeavours. Some workshops were done **formally** where teachers wrote tests, completed experimental worksheets and formal evaluation assessments (Du Toit, 2006; Tholo *et al*., 2006) and other workshops were **informal** with no formal assessment (Du Toit, 2014, 2015, 2016). Formal workshops further required that teachers had to prepare study material for a specific workshop in advance. On the other hand, in informal workshops teachers of different grade groups (such as grades 10 to 12 or grades 8 to 9 or grades 4 to 7) were teamed together and concentrated attention was given to difficult concepts and practical experiments for each specific grade group. No formal written work was done and no marks were attached to feedback. However, teachers received written hand-outs and made personal notes. The atmosphere in informal workshops was relaxed and discussion was encouraged.

Formal and **informal** workshops play an important role in teaching chemistry for the masses. **Formal** workshop programs are used when there is ample time and the presenter and participants can work towards deeper understanding and a more critical evaluation of what they are doing be it experimental investigation or proving or disproving misconceptions. **Informal** workshops are used when there is time constraints and the presenter and participants do what they can in the time available. Teachers gave their informed consent for the anonymous use of their workshop reports and scores in the research on Chemistry Education.

Materials

The teaching materials used are the MYLAB small-scale chemistry (SSC) kits as shown in figure 2. The toolbox of the kit is 42 cm x 20 cm x 23 cm and contains the complete SSC laboratory. The apparatus is built around the 5 ml glass test tube. The support material consists of worksheet manuals for learners and for teachers and one DVD per grade. The top tray contains all the chemicals needed for grades 10 to 12 chemistry. The middle tray contains the bigger apparatus pieces such as the back plate, baseplate and test tubes (see figure 2). The bottom tray contains the smaller apparatus pieces like the stoppers, spatula, test tube brush and electrodes.

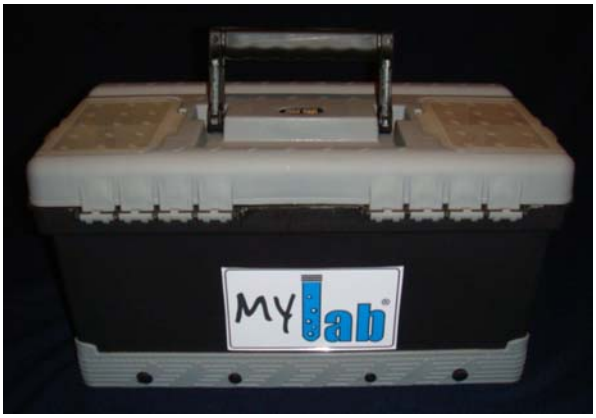
MYLAB kit	Top tray
	
Middle tray	Bottom tray
	
Extra: Worksheet manuals and DVDs	Apparatus setup

Figure 2: The MYLAB kit showing some of the components and setup.

The MYLAB kits are designed so that students can learn through self-experimentation. These kits address the problem of under achievement in chemistry and natural science by making practical work easy, cost-effective, safe, and quick. The kits are portable and versatile. The MYLAB kits are tailor made for hands on teaching of natural science and chemistry at school level in South Africa. MYLAB kits are complete and no laboratory is needed. MYLAB kits provide an inexpensive solution to the problem of inadequate apparatus at school. What makes the MYLAB kits unique is that it is a compromise between the conventional and micro-scale apparatus. The MYLAB kit is a Small Scale Laboratory with apparatus of durable materials. According to green chemistry principles, small amounts of chemicals are used. All chemistry experiments from grade 10 to 12 can be performed with the MYLAB kits. All natural science experiments from grade 4 to 9 can be performed with the MYLAB kits. The apparatus is supported by worksheets and DVDs.

Methodology of specific workshops on CRT misconceptions

Various misconceptions about chemical reaction types are well documented (Barke *et al*., 2009; Horton, 2007; Taber, 2002), however not all misconceptions are relevant in the specific classroom situation. Students' specific misconceptions arise due to their understanding, background knowledge and the way they were taught chemical reaction types (CRT). These misconceptions can arise in class, during practical work or in workshops while CRT are addressed or explained. Therefore, teachers have to keep the strategy for conceptual change in mind and address the misconceptions accordingly (Bybee *et al*., 2008). There are a large number of conceptual change strategies available in literature all with the same aim in mind (Hewson, 1992; Kyle & Shymansky, 1989; Riordan, 2012). Any one of these strategies can be used. According to Hewson (1992) the ultimate goal is to teach students two things: (i) to "form the habit of challenging your concept with other concepts and (ii) to develop appropriate strategies for having alternative conceptions compete with one another for acceptance.” General chemistry misconceptions, especially on chemical reaction types, obtained from literature are shown in table 1.

Formal workshops

In formal workshops written reports were required. Students (in-service and pre-service teachers) received specific examples of documented misconceptions such as the examples on table 1 and table 2. They had to complete and submit a report with their results and conclusions. They had to make use of conceptual change models to address misconceptions.

Table 1: Misconceptions in chemical reaction types (subset from Horton, 2007).

	Misconceptions
1	"Chemical reactions are caused by mixing of substances"
2	"Chemical reactions are reactions which produce irreversible change”
3	"The original substance vanishes "completely and forever" in a chemical reaction."
4	"Chemical reactions between gases are simply mixing".
5	"Physical changes are reversible while chemical changes are not".
6	"Precipitation reaction results in change in mass”.
7	"Mass increases because a solid weighs more than a liquid"
8	"Mass is lost in combustion".
9	"Testing for acids can only be done by trying to eat something away”.
10	"When Mg is placed in aqueous HCl, the acid is the driving force, because it (the acid) is very strong."
11	"Mixing an acid with a base (without regard to quantities) neutralizes the base resulting in a neutral solution."
12	"In neutralization all the H and OH ions are cancelled."
13	"If a reaction doesn't involve oxygen it is not oxidation."
14	"Reduction is the removal of oxygen in a reaction."
15	"Electrons can flow through aqueous solutions without assistance from the ions."

Listed in table 2 are CRT examples that we used to demonstrate to teachers how conceptual change strategies, in to address misconceptions, can be taught.

Table 2: Three documented misconceptions and examples of experiments, which we devised, and which can be used to address misconceptions and bring about conceptual change.

Misconception 1	"Chemical reactions are caused by mixing of substances" (Horton, 2007)
Origin	The use of language and macroscopic observation may be the possible origins of this misconception, e.g. Na and water or an acid and a base are "mixed together" according to learners. Stoichiometry, the law of definite proportions and reaction conditions are completely ignored. The difference between mixtures and chemical reactions are not properly defined and explained.
Correct concept	"Chemical reactions are caused by mixing of substances" can be corrected by stating that: Chemical reactions take place when substances react with each other.
Teaching for conceptual change:	Mix iron filings and sulfur powder. Mixing gives a mixture Fe and S. The mixture can be separated by physical means (magnet). NO chemical reaction takes place. $Fe + S \rightarrow FeS$ A chemical reaction takes place when the two reactants are heated together and then produce FeS. A different substance with different properties is formed and the original reactants can only be obtained with separation by chemical means. The chemical substances, iron and sulfur, react in a fixed ratio of 1:1.
Misconception 2	"Chemical reactions are reactions which produce irreversible change" (Horton, 2007)
Origin	Language and macroscopic observation. Students observe magnesium burning in oxygen and there is no way they can recover the magnesium. In the same way Na reacts with water.
Correct concept	"Chemical reactions are reactions which produce irreversible change". All chemical reactions are reactions which produce reversible change. (Indicated by equilibrium constant.)
Teaching for conceptual change:	Cobalt chloride and water $[Co(H_2O)_6]^{2+}(aq) + 4Cl^-(aq) \rightleftharpoons [CoCl_4]^{2-}(aq) + 6H_2O(l)$ pink blue Cobalt chloride dissolved in ethanol is blue. If water is added it turns pink. If hydrochloric acid is added it turns blue again. The equilibrium can be moved backwards and forwards.
Misconception 10	"When Mg is placed in aqueous HCl, the acid is the driving force, because it (the acid) is very strong." (Horton, 2007)
Origin	Students know that HCl is a strong acid (according to theory) and decide the strong acid is the driving force. Students lack scientific understanding of the concept of the driving force of a reaction (the chemical phenomenon).
Correct concept	When Mg is placed in aqueous HCl, the electron transfer is the driving force of the reaction. Electron transfer will be the driving force of the reaction between an acid and a metal whether the acid is strong or weak.
Teaching for conceptual change	React magnesium with different acids (strong and weak) and observe what happens. Both strong and weak acids react with magnesium thus the argument about the strength of the acid, as reason for the driving force, is not valid. If the strength of the acid is not the driving

	force what is the driving force? Careful explanation to proceed from macroscopic observation, to sub-microscopic theory and symbolic representation is necessary. Half reactions of oxidation and reduction to the complete redox reaction need to be understood by students.

Informal workshops

In informal workshops no formal written reports are required. The main drive is discussion, argumentation, teamwork and even debate. The participants of the workshop had to answer the questions in box 1, write their own 'reports' and present an oral summary of their experience. Conceptual change strategies were used to address a subset of the documented misconceptions (Box 1). Conceptual change strategies were implemented in the form of practical activities during workshops using the MYLAB kits.

For example, in the workshops that focussed on misconceptions, teachers received an internationally acknowledged misconception (Barke *et al*., 2009; Horton, 2007; Taber, 2002) which they had to correct by answering certain questions:

- What is the misconception?
- What is the scientifically correct concept?
- What is the possible origin of the misconception?
- How can the concept be corrected? (Teaching for conceptual change.)

Teachers were supplied with a MYLAB kit each and they had to show the conflict between the misconception and the scientifically correct concept. They had to illustrate the correct concept by doing an experiment and to explain the concept to a peer. The workshop presenter facilitated the process. In the workshop report, the educators had to answer the four questions convincingly. Correcting misconceptions is a very important part of teaching and thus teachers should receive appropriate training in how to perform conceptual change in practice (Niaz, 1995; Riordan, 2012).

During these "misconception experiments" no pre-set worksheets were given. The workshop participants received the misconception as a statement and they had to analyse, discuss and correct the misconception by doing an experiment. Each teacher had to complete their own report and each group had to make their own oral presentation. Groups could receive a different misconception that they had to solve as a group OR each teacher received a different misconception that they could solve individually or in collaboration with their group members.

Box 1: A typical example of a misconception assignment at an informal workshop (Du Toit, 2015).

Example from a workshop at the University of Venda on November 2015
How to address misconceptions.

1. What is the scientifically incorrect conception?
2. What is the origin of the incorrect conception?
3. What is the correct scientific conception?
4. How can the teacher teach with practical experiments to change the alternative concept to the correct scientific concept? (teaching for conceptual change)

Misconceptions.

1. Solute (salt, sugar) disappears when dissolved.
2. Weightless matter can exist.
3. Substances prepared in different ways cannot be the same substance; the way of preparing a substance is one of its properties.
4. Water disappears as it evaporates
5. Air weighs less when it is expanded.
6. Less dense means weighs less
7. A kilogram of lead weighs more than a kilogram of water.
8. The weight of a substances changes when it changes phase.
9. The products of chemical reactions need not have the same mass as the reactants.
10. Objects float because they are light.
11. A balloon is lighter if air is blown into it.
12. A small paper clip floats better than a large paper clip.
13. Hot and cold are different kinds of substances.
14. Drops of water on the outside of a cold bottle come from inside the bottle.
15. Drops of water on the outside of a cold bottle are from hydrogen or oxygen combining.
16. Bubbles mean boiling.
17. Melting and dissolving is the same thing.
18. Sugar (or salt) dissolving in water is a chemical change.
19. A rusting nail will lose weight.
20. In electrolytic cells, water is unreactive towards oxidation and reduction.
21. No reaction will occur if inert electrodes are used
22. Endothermic reactions cannot be spontaneous.

At one of the informal workshops, for example, 48 participants (in-service teachers) were divided into eight teams of six teachers each. Each team had the instructions as given in box 1. They could choose any misconception and answer the questions, write a short report and presented the report to all the workshop participants as an audience. Each team were provided with a facilitator (one of the workshop presenters or a knowledgeable person or a subject specialist).

Results

Results of formal workshops

The results are discussed in the form of case studies. Each box gives an example of a misconception or misconceptions and related questions. For instance, in example 1 shown in Box 2, the misconception M1 is given with four sub-questions Q1 to Q4 that the teachers have to answer and discuss.

Box 2: Example 1: One of the questions asked in a **formal** practical workshop in 2012. The abbreviations are used in appendix B to indicate the quantitative scores students achieved for this example (E1) and the related questions in their workshop reports.

There is one misconception (M1) in example 1 (E1) with four sub-questions asked (Q1, Q2, Q3, Q4). Learners have the following misconception (M1): ***"When Mg is placed in aqueous HCl, the acid is the driving force, because it is very strong."*** Q1 What type of chemical reaction takes place between Mg and HCl? Q2 What is the driving force of the reaction? Q3 What is the specific misconception in the given statement? Q4 How is the teacher going to teach for conceptual change to correct this misconception?

All four questions (in box 2) were seen as challenging and difficult to answer. In a group of 24 fourth year pre-service teachers the following results (see also Appendix B) were obtained for example 1. The average mark for the complete question was 30.8%. The average mark for Q1 was 29%. Seven students identified the chemical reaction type correctly. Ten students decided it was an acid-base reaction and some added that it was ion-exchange. One student decided the reaction was a substitution reaction. Three students identified the reaction as a gas forming reaction. One mentioned that the gas forming reaction was also an ion-exchange. Two students decided on the reaction as a precipitation reaction and one indicated that the precipitation reaction was also a redox reaction. One student identified the reaction as an exothermic reaction. The average mark for Q2 was 40%. The chemical phenomena responsible for the reaction was given as electron transfer (9 students; the correct answer), proton transfer (7 students), formation of an insoluble gas (3 students), ion-exchange (3 students), the formation of an insoluble compound (1 student) and the rearrangement of atoms (1 student). Two students considered acid-base reactions as the reaction type, but electron transfer as the driving force of the reaction. One student gave both electron transfer and proton transfer as the driving forces for an acid-base reaction. The average for identifying the specific misconception in the statement was 36.5%. The average for how the teacher is going to teach for conceptual change was 28.6%.

Misconception 2 of example 1, with similar related questions as Box 2, compared covalent bonds and intermolecular forces. For a statement: "***The strength of covalent bonds and intermolecular forces are similar***," three (out of 24) students could neither give the incorrect concept nor the correct concept, eight students identified the misconception correctly. Sixteen students could say that covalent bonds are stronger than intermolecular forces, but not say why they believed that the bonds are stronger. Five students could correctly define covalent bonds and intermolecular forces, but could not formulate the argument to prove the statement wrong. One student stated that more energy is needed to break covalent bonds, but not why that is her conception. Two students used the distance between atoms for covalent bonds and the distance between molecules in intermolecular forces as grounds for their argument to refute the statement. None of the students could propose a practical experiment to help learners to comprehend the correct concept instead of the incorrect statement given.

Misconception 1 of example 2 is shown in box 3. Example 2 consists of five different misconceptions and we are only giving the results of the first misconception as a case study. According to appendix C it is clear that the question about conceptual change gave poor results. Similar results were obtained for the other four misconceptions, thus indicating the same inefficiency in using conceptual change strategies to address specific chemistry misconceptions.

Box 3: Example 2: One of the questions, asked in a formal practical workshop (2011) for 24 students. Students' achievement scores are indicated in appendix C.

Misconception 1 (M1) of five misconceptions in question 1 (Q1). Learners have the following misconception (M1): "**Oxidation is the addition of oxygen in a reaction"** How is the teacher going to teach for conceptual change to correct this misconception?

The average mark for the question (Q1) in example 2 (Box 3) was 42.7% (see also Appendix C). Students could give the generic answer of the four steps for conceptual change, but they could not describe the specific experiment they were going to use to confront the concepts of the learners and what specific explanations, assignments, tasks, they were going to give to facilitate the change. They did not know how to teach for conceptual change as was also found by Hewson (1992). Only 4 of the fourth year pre-service teachers could indicate correctly that a redox reaction comprises two half reactions (one half reaction is oxidation and the other half reaction is reduction). In the answers of the 24 pre-service teachers ten other misconceptions were identified. Five misconceptions were about writing chemical reaction equations and considering only oxidation without reduction. One student talked about reduction of the oxidation number instead of a chemical substance (ion, element, molecule or compound) and oxidation of the oxidation number. One student said oxidation and reduction is the same as ion-exchange. One student considered oxidation not only as addition of oxygen in a reaction, but also of addition of other elements. One student had the common mistake of "oxidation is the gain of electrons" and "reduction is the loss of electrons". Eight students completely ignored reduction and only considered oxidation.

In example 3 (box 4) five misconceptions were listed and the same question was asked about each misconception. Workshop participants were only asked to determine the origin of the mentioned misconception.

Box 4: Example 3, a question about the origin of CRT misconceptions. Students' achievement scores are indicated in appendix C.

Misconception 1 (M1) to misconception 5 (M5) in question 2 (Q2) of example 3.
Learners have the following **five** misconceptions (M1, M2, M3, M4, M5):

M1 Chemical reactions are phase changes
M2 The original substance vanishes completely and forever in a chemical reaction.
M3 The H_2 bonds are not broken in forming H_2O
M4 Chemical reactions are caused by mixing of substances.
M5 Heat supplied or absorbed is the driving force in a burning candle.

What is the ORIGIN of the above-mentioned misconceptions?

The average mark for the question (Box 4) was 42.1% for the 24 participants of the workshop. The marks for M1 to M5 were respectively 29%, 50%, 76%, 29% and 26%. Students have little or no concept of (M1) phase changes. 21 out of 24 thought the different physical states of matter in a chemical reaction equation indicates a phase change. Three of the 21 could correctly argue their way out of the misconception. The correct understanding of physical change and chemical change is also problematic. Chemical reaction, phase change, chemical bonding, chemical change and physical change are misunderstood (misinterpreted). Students used incorrect arguments to indicate the origin of the misconception because they themselves had the misconception (M1).

The results for M2 were better. Students mentioned the conservation of mass and reversible chemical reactions in their arguments to disprove the misconception of "vanishes completely and forever" (M2). Five students used the example of NaCl in water as their explanation, and revealed the misconception that dissolution and evaporation are chemical reactions.

M3 was answered with few mistakes. Three students had three different misconceptions: one stated that because H_2 is a gas there is no bond to see; another stated that learners use the chemical equation $H_2 + O \leftrightarrows H_2O$ but when teachers use the crystal lattice as well to explain the misconceptions will be fewer; and the last one stated that bonds are broken because every H sits on a different orbital.

For M4 pre-service teachers and learners thought macroscopically and thus, believed the evidence of their eyes: the reactants are mixed and a chemical reaction takes place. No sub-microscopic explanations were given. The difference between mixtures and chemical compounds were not used in the arguments. Only one student talked about chemical reactions and reactants reacting in the correct ratio to form products. Seven students had random misconceptions. One saw the mixing of coffee powder and water as a chemical reaction. Another stated that not all reactants mixed together react with each other; a force is needed to start the reaction and the fact that reactions can start spontaneously without mixing is mentioned. Another student stated that a reaction is the result of a mixture of two different substances, because they believed “one substance has to loose [*sic*] electrons onto the other substance”. One student stated that learners observe the mixing and don’t know about “electron structures” that must be filled to become a noble gas and that “the learners also don’t know about activation energy and the influence of the environment”. One student stated that learners “don’t understand that a chemical reaction occurs when particles collide according to the collision theory until the substances have minimum kinetic energy which is the activation energy”. Another student had the previously mentioned misconception that if salt and water are mixed, there is a chemical reaction. According to this student not enough variety in examples of reactions is responsible for the misconception about mixing, but the student’s suggestion about using reactions with oxygen and combustion to prevent the misconception have no clear reasoning.

M5 produced the most misconceptions as indicated by box 5. Heat as the driving force for the burning candle (M5) received the lowest marks (26%) from the students. One out of 24 students gave the correct argument. Three students did not even attempt to answer the question. Ten students had misconceptions. Two students gave meaningless answers. Eight students believed learners think macroscopically: “when the flame is there the candle burns, when the flame is gone, the candle is out so the flame must be the driving force for the burning candle”. These misconceptions are listed in box 5.

Box 5: The misconceptions of the students about a burning candle (M5)

- The driving force of the reaction is when the wick of the candle reacts with oxygen and an open flame.
- Some reactions have too much energy and liberate the energy in the form of heat, light, sound and so forth.
- Activation energy supplied or absorbed is the driving force in a burning candle.
- Learners don't understand the concept of the combustion of oxygen, because a candle liberates heat and light.
- The power is not the heat that is supplied, but the reaction between oxygen in the surroundings and the candle. The heat is caused by the gas or the reaction and it just starts the reaction.
- Learners associate the flame with heat and thus believe that the heat keeps the flame burning. In truth oxygen is the driving force of the combustion and heat is the result. Energy is released in the form of heat.
- Learners don't understand the concept of transfer of energy. They don't understand that the wax of the candle serves as the energy source. The chemical reaction is the driving force and the heat only serves to accelerate the proses.
- Because the candle is ignited by a match that provides the heat, the learners assume that the heat provided to the candle lets the candle burn. They then don't know that oxygen really is the driving force that keeps the candle burning. The match is equal to the activation energy. They think that because the candle releases heat it keeps on burning, because they can feel the heat but not the oxygen.
- Heat absorbed is driven by the energy required to make the reaction take place so that is activation energy needed for reaction.
- Learners see that a match that burns is the cause of the candle burning and that heat is released. The candle was never put into a closed system so that the oxygen could become depleted to enable the learners to see that heat is just the activation of the reaction between oxygen and the candle wax and that oxygen is the driving force behind the burning candle.

Results of informal workshops

Teachers received the misconceptions in box 1 and had to use conceptual change strategies to demonstrate the correct scientific concepts. The assignment was given to the teachers at the University of Venda in November 2015. The simplest or easiest misconceptions were chosen by the teacher teams and furthermore, the teachers could not progress in their assignment without guidance from the facilitators. The teachers were enthusiastic and participated eagerly in trying to find a solution to the assignment, but due to lack of chemistry background knowledge and scientific creativity, they needed a little guidance to make progress. The teachers worked well in groups and lively discussions resulted. Colleagues helped each other to clarify misconceptions and to devise possible experiments to address the misconceptions. The informal workshops were very interactive and cooperative problem-solving took place. Each group had to assign different tasks to different people to achieve optimum results. Groups with too many chiefs did not prosper. Groups that quickly, and correctly for their specific group, assigned the roles of manager, strategist, recorder, experimenter and presenter, were the most successful. The emphasis was on the process and not so much on the presentations at the end. Teachers needed practice in teaching for conceptual change, but the teachers were motivated and the activities were appreciated. A number of the misconceptions were changed to correct scientific concepts with the help of colleagues, workshop facilitators and workshop presenters. The results of informal workshops are qualitative and not quantitative.

General feedback from workshops

The feedback of the approximately 260 workshops is overwhelmingly positive. (Box 6) (Du Toit, 2006, 2014, 2015, 2016).

Box 6: Some feedback and comments from the more than 260 workshops.

- I think this workshop is the beginning of a bright future to our learners. I will be improving in the next workshop. It was nice being here. I enjoyed it!
- This was fantastic. I wish this can be done (educators be workshopped) until being confident when teaching learners.
- If more of this work can be done quarterly, our results can improve drastically.
- Need more workshops to produce A's at matric level.
- Keep on shaping the nation by conducting the workshops, so as to build the future of our children, our country and the world as well.
- I believe that MYLAB will definitely improve science teaching and learning because it is easily accessible and easy to use by all learners and teachers.
- Thank you very much for dispelling the fear I had for doing practical work. My clumsiness suddenly disappeared. I would say that the next workshop will greatly improve my practical skills.

Discussion of results

Formal workshop discussion

If one considers the results of the 24 pre-service teachers of a 2012 **formal** workshop (Box 2, example 1), the conceptual problems are more far reaching than just not having the correct conceptual understanding (example question average 30.8%). The students can only give general explanations e.g. the steps for teaching for conceptual change without being able to give the specific chemical concept and chemical experiment they will use to teach in order to correct the misconception (Q4 average 28.6%). They themselves have numerous misconceptions and lack sufficient theoretical chemistry knowledge to address the problems. Incorrect chemical reaction types (CRT), however, and incorrect driving forces can be addressed and was addressed by doing a series of experiments of the same reaction type.

Guided inquiry worksheets (MYLAB experiment 8, grade 10) lead the students to see the patterns and to identify the CRT and the driving force correctly. The comprehensive MYLAB kit and short SSC experiments made such an investigation possible and easy. Nonetheless, students needed the hints and probing questions of the facilitators to nudge them in the right direction of finding an appropriate practical experiment to help learners to comprehend the correct concept instead of the misconception.

Additionally, evaluation of the results of the 24 pre-service teachers of a 2011 **formal** workshop (Box 3, example 2), confirmed that these teachers had the same misconceptions about redox reactions as those given by Horton (2007) and Taber (2002): namely: oxidation is the addition of oxygen and reduction is the removal of oxygen; if a reaction does not involve oxygen it is not oxidation; oxidation and reduction can occur independently and most often only oxidation is considered and reduction completely ignored. For example, a series of experiments about redox reactions with guided-inquiry worksheets confronted the teachers with the fact that not all redox reactions contain oxygen (MYLAB experiment 8, grade 10). These misconceptions in chemistry are not only found in South Africa but internationally as well (Barke, Hazari, & Yitbarek, 2009; Barker, 2000; Levy Nahum, Hofstein, Mamlok-Naaman, & Bar-Dov, 2004; Mulford & Robinson, 2002).

The results of example 3 (Box 4) for the same group of students indicated that “what they see is what they believe”. The students get stuck on the macroscopic “explanation” of their observations and that is the cause of most of the misconceptions they have. The use of the chemistry triplet of easy transfer from macroscopic level to sub-microscopic level to symbolic level is not evident (Gabel, 1999; Sirhan, 2007). Therefore, lack of adequate subject knowledge is apparent (Kamau, 2012; Marais & Mji, 2009; Nbina, 2012). Consequently, the guided-inquiry worksheets provided for the MYLAB kits are a great help to direct student to the correct conclusions about a specific misconception. The worksheet contains questions that range from direct observations to analysis, evaluation and critical thinking (Du Toit, 2012a).

Informal workshop discussion

The results from the informal workshop for 48 in-service teachers where measured more on the affective level (Bybee *et al*., 2008): attitude, enjoyment, enthusiasm, co-operation and motivation. Teachers learned process skills by being assigned a specific task in the team. Teams with the most effective role assignments, made the best progress. They had to take joint responsibility for the successful outcome of the assignment. With a more personal and relaxed approach, misconceptions could be changed to correct scientific concepts, without formal confrontation. With much colleague cooperation, conceptual change could be brought about.

Discussion about the materials

The first objective was to indicate the effectiveness of the MYLAB kit as a laboratory. The MYLAB kits are ideal for resource constrained schools as no physical resources are required from the school. No laboratories, expensive equipment, water or electricity is necessary and not even classrooms (Tesfamariam, Lykknes, & Kvittingen, 2015). Everything is supplied in the kit. The only extra equipment is a 2-liter milk bottle with water, 2 empty plastic containers (one for water waste and one for paper waste) per kit, and one toilet roll (called "micro-towels") to dry apparatus and clean-up spills. Therefore the availability, versatility and cost-effectiveness of SSC kits make them particularly successful in providing teaching assistance for under-resourced schools and as a tool to re-establish practical work. The only requirement is the willingness and enthusiasm of the teachers attending the workshops. The versatility of the kits makes it possible to address any concern or misconceptions the teachers have. The kits can be used easily and effectively to confront learners and teachers with the correct scientific phenomena through practical experiments. Moreover, students usually observe experiments through watching the teacher perform them, they never have the opportunity to do it themselves. The MYLAB kits address this gap by supplying not one but many 'laboratories' allowing students to do the work themselves. This allows individual problems and misconceptions the students might have to be identified. Thus, students learn better when doing the practical work themselves (Abdullah, Mohamed, & Ismail, 2009; Hofstein & Mamlok-Naaman, 2007; Mafumiko, 2008; Tobin, 1990).

The second objective was to use the MYLAB kit as intervention tool to address misconceptions. The value of the MYLAB kit as a tool to make chemistry available for the masses can be measured by its comparison to other small scale endeavours. Most of the other researchers utilizing small scale apparatus only focus on a few experiments, i.e. gas exchange (El-Marsafy, Schwarz, & Najdoski, 2011; Mattson, Anderson, & Mattson, 2006), whilst others have very expensive components (Singh, Szafran, & Pike, 1999; Tantayanon, 2005). The comprehensiveness of the MYLAB kits make them very suitable for the range of experiments that schools need for all the different grades. Moreover, this also makes them excellent tools for addressing an assortment of misconceptions occurring under teachers and learners. No extra chemicals or apparatus were needed to teach for conceptual change when correcting misconceptions. All apparatus and all general chemicals are available to conduct experiments. Small apparatus and little amounts of chemicals makes experimental times short, therefore, a large number of experiments can be done in a limited time. To clarify misconceptions numerous experiments can be done in a short time and a series of similar experiments to discern a pattern can be conducted (Du Toit, 2012a).

The third objective was to reach remote areas. Due to the size and comprehensiveness of the MYLAB kits, it was possible to take it with me to visit numerous rural schools. Workshops in inaccessible places were possible. With highly portable kits, any school with or without resource barriers can be reached. Indeed, some of the areas where we presented workshops were very remote with only rutted, dirt, access roads. Moreover, these schools also have no shops or pharmacies within easy reachable distances to buy or replenish consumables.

Limitations of the study:

- The workshops are presented on demand and no organized plan is followed.
- Some schools have little support from their district offices, and begged us to come regularly once a quarter. Time, money and other obligations are the biggest deterrent to additional visits. Follow-up visits are almost impossible due to money and time constraints. The lack of follow-up visits can partly be solved with support groups in the local communities.
- Lack of Department of Basic Education involvement (and thus government involvement) makes organized planning and support of at-risk schools impossible. This absence of involvement still happens despite a very positive report from the Quality Assurance Chief Directorate (Tholo *et al*., 2006).
- The presentation of workshops depend on the generosity of private institutions and sponsors.
- The status quo of school problems were taken as is.
- All the learners and teachers are second language users.
- Only a little insight is gained in teachers' qualifications and PCK from pre-workshop questionnaires.
- The poor subject-knowledge background of teachers and learners requires more time spent on support than is possible during single workshops.

Conclusion and summary

Objective 1

MYLAB kits are quick and cost-effective replacement for traditional laboratories. The results from this study and other international studies (Tesfamariam *et al*., 2014; Tesfamariam *et al*., 2015) bear witness to the effectiveness of the SSC kits. We have post-workshop evaluation for all the approximately 260 workshops and all the feedback is positive. However, consideration must be given to the fact that from no practical work to individual opportunity for practical work will produce positive results. Nevertheless the feedback indicates the need and gratitude for the support given.

Objective 2

This study demonstrated how SSC experiments can be used successfully to address and improve misconceptions in teaching for conceptual change. The ease with which experiments can be done, the help the worksheets provides, the comprehensiveness of the kit, and the short time it takes to complete an experiment, all contribute towards the ability of the MYLAB kit to address the misconceptions encountered in class. As seen from the results misconceptions are prevalent and an active way to address misconceptions is relevant. The MYLAB SSC kit are thus useful in teaching for conceptual change (Niaz, 1995, 2006; Riordan, 2012).

Objective 3

The value of onsite workshops are clear from the positive feedback that we receive from post-workshop evaluation from every workshop given. Due to the compactness, comprehensiveness and portability of the MYLAB kits it is possible and easy to pack-up and reach remote communities (Du Toit, 2014, 2015, 2016). The map of places in South Africa (Figure 1) where workshops were presented is an indication of how easy it is to take a small bus or mini-van to reach a remote venue and perform a workshop. These remote schools are usually the schools with the largest resource barriers, and the schools that receive the least support from the Education Department and other education support groups. They are the schools that value the support the most and they have enthusiastic teachers hungry for help and academic support.

Specific CRT conclusions

- Teachers had the same misconception as the documented misconceptions used in the workshops and they had a number of their own misconceptions as well.
- They had difficulty in identifying the exact incorrect concept in the given statements, and as a result had difficulty with the consecutive questions.
- The teachers had difficulty in identifying chemical reaction types correctly. A redox reaction was seen correctly as a redox reaction and incorrectly as an acid-base reaction, an ion-exchange reaction, a substitution reaction, a gas forming reaction, a precipitation reaction and an exothermic reaction. These results can be ascribed to poor background knowledge, or incomplete conception or misconception. One student thought it was a redox reaction and a precipitation reaction. These answers to one question are an indication of terminology confusion (substitution versus displacement) and misperceptions about classification system levels (acid-base versus ion-exchange; acid-bases versus gas forming reaction). An exothermic reaction indicate the role of energy in chemical reactions and is not one of the CRT.
- The identification of the chemical phenomenon that is responsible for a certain reaction was also problematic for teachers. Ion-exchange, according to some teachers, was considered a chemical phenomenon and the chemical phenomenon for acid-base reactions was electron transfer. The depth of the incorrect concepts points to a lack of adequate scientific background knowledge.
- Teachers know the theory of conceptual change models, but the implementation of the model for specific chemistry misconceptions they find extremely difficult.
- There is an urgent need to re-assess the instruction of CRT. If teachers, who are the instructors, have so many misconceptions, and they transfer these misconceptions to their learners the outcome would be disastrous. A standardized classification system and standard terminology is needed to minimize confusion and misconceptions, and to advance deeper understanding.

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3.3 Supplementary information

Appendix A: List of names of places on the map where South African workshops were held (Figure 1).

Place	Province	Position
Bela-Bela	Limpopo	S24 53 04.3 E28 17 37.6
Bloemhof	North West	S27 39 06.5 E25 36 19.1
Boshof	Free State	S28 32 21.3 E25 14 10.2
Bothaville	Free State	S27 23 35.2 E26 36 58.3
Brits	North West	S25 38 06.1 E27 46 43.0
Bultfontein	Free State	S28 17 30.4 E26 09 11.9
Cape Town	Western Cape	S33 55 25.6 E18 25 24.0
Durban	Kwazulu-Natal	S29 51 25.2 E31 01 29.2
East London	Eastern Cape	S33 00 48.4 E27 54 15.1
Ganyesa	North West	S26 35 30.4 E24 10 15.1
Giyani	Limpopo	S23 18 34.4 E30 41 29.1
Johannesburg	Gauteng	S26 12 05.2 E28 02 43.7
Kimberley	Northern Cape	S28 44 16.1 E24 45 58.4
Kleinmond	Western Cape	S34 20 26.4 E19 01 51.8
Klerksdorp	North West	S26 52 13.8 E26 39 52.1
Kroonstad	Free State	S27 39 42.1 E27 14 04.5
Kuruman	Northern Cape	S27 27 43.7 E23 25 52.0
Ladybrand	Free State	S29 11 47.9 E27 27 24.7
Lichtenburg	North West	S26 09 04.7 E26 09 37.3
Mafikeng	North West	S25 51 52.3 E25 38 32.5
Middelburg	Mpumalanga	S25 45 57.9 E29 27 28.1
Mokopane	Limpopo	S24 11 01.4 E29 00 38.8
Monsterlus	Limpopo	S25 01 29.8 E29 43 52.2
Mookgophong	Limpopo	S24 31 09.2 E28 42 42.1
Moretele	North West	S27 19 21.0 E24 41 25.7
Phuthaditjhaba	Free State	S28 30 06.1 E28 49 07.0
Polokwane	Limpopo	S23 54 44.1 E29 27 12.8
Potchefstroom	North West	S26 42 56.9 E27 05 41.7
Pretoria	Gauteng	S25 44 45.6 E28 11 13.6
Relela	Limpopo	S23 40 50.9 E30 19 39.4
Rustenburg	North West	S25 40 06.6 E27 14 32.6
Saint Lucia	Kwazulu-Natal	S28 22 35.6 E32 24 46.9
Sasolburg	Free State	S26 48 58.0 E27 49 47.0
Secunda	Mpumalanga	S26 30 24.6 E29 11 59.5
Sekgopo	Limpopo	S23 37 06.3 E29 58 53.6
Sekhukhune	Limpopo	S24 45 11.3 E30 00 36.3
Stanford	Western Cape	S34 26 26.7 E19 27 30.9
Taung	North West	S27 31 40.0 E24 47 10.3
Thohoyandou	Limpopo	S22 57 07.3 E30 28 23.7
Tierkloof	North West	S27 03 20.4 E24 45 25.7
Turkey	Limpopo	S24 19 14.9 E30 31 43.7
Tzaneen	Limpopo	S23 49 36.7 E30 09 45.0
Virginia	Free State	S28 06 23.5 E26 52 03.8
Vredenburg	Western Cape	S32 54 25.9 E17 59 25.9
Vryburg	North West	S26 57 37.1 E24 43 35.7
Welkom	Free State	S27 58 50.4 E26 44 05.8
Winburg	Free State	S28 31 11.1 E27 00 41.4
Zeerust	North West	S25 32 40.4 E26 04 40.3

Appendix B: Results 2012 of example 1

student	M1 of E1 Total marks (mark/12)	Q1 (mark/1)	Q2 (mark/1)	Q3 (mark/2)	Q4 (mark/8)	Number of misconceptions in answers
1	5 (41.7%)	0	0	1	4	two
2	1 (8.3%)	0	0	0	1	one
3	1 (8.3%)	0	0	0	1	one
4	1 (8.3%)	0	0	1	0	
5	1½ (12.5%)	0	0	1	½	
6	7 (58.3%)	1	1	0	5	one
7	2½ (20.8%)	0	0	1	1½	
8	6 (50%)	1	1	1	3	
9	0 (0%)	0	0	0	0	two
10	4½ (37.5%)	1	1	1	1½	one
11	½ (4.2%)	0	0	½	0	two
12	2½ (20.8%)	0	0	½	2	one
13	6 (50%)	0	½	1	4½	
14	3 (25%)	0	0	1	2	two
15	5 (41.7%)	1	1	1	2	
16	2 (16.7%)	0	1	1	0	two
17	3 (25%)	0	0	1	2	
18	2 (16.7%)	0	0	½	1½	
19	6 (50%)	0	1	1	4	
20	4 (33.3%)	1	1	0	2	
21	4½ (37.5%)	0	0	1	3½	
22	5 (41.7%)	0	0	1	4	one
23	9 (75%)	1	1	1	6	
24	7 (58.3%)	1	1	1	4	
average	**3.7**	**0.29**	**0.40**	**0.73**	**2.29**	
	30.8%	**29%**	**40%**	**36.5%**	**28.6%**	

Appendix C: Results 2011 of example 2 and example 3*.

student	Total (mark/20)	E2 Q1 (mark/10)	E3 Q2 (mark/10)	E3 Q2 M1 (mark/2)	E3 Q2 M2 (mark/2)	E3 Q2 M3 (mark/2)	E3 Q2 M4 (mark/2)	E3 Q2 M5 (mark/2)
1	11.5	7.5	4	1	1	2	0	0
2	14.5	8	6.5	2	2	2	0.5	0
3	4.5	2.5	2	0	0	1	0	1
4	10.5	4.5	6	0	2	2	1	1
5	6	4.5	1.5	0	0.5	0	1	0
6	16.5	7	9.5	2	2	2	1.5	2
7	3	0	3	0	0	2	1	0
8	11	5.5	5.5	2	1	2	0	0.5
9	11.5	4	7.5	0.5	2	2	2	1
10	5	1	4	1	0	2	0	1
11	12	5	7	1	1	2	2	1
12	9	4.5	4.5	0	2	2	0	0.5
13	4.5	3	1.5	0	1	0	0	0.5
14	5.5	4	1.5	0	1	0	0	0.5
15	8.5	2	6.5	1	2	2	0.5	1
16	9.5	7	2.5	0	1	1	0	0.5
17	3.5	3	0.5	0	0	0.5	0	0
18	6	4.5	1.5	0	0.5	0	0.5	0.5
19	8	4	4	0	1	2	1	0
20	8.5	5	3.5	0.5	0	2	0.5	0.5
21	9.5	3	6.5	1	2	2	1	0.5
22	7.5	5	2.5	0	0	2	0.5	0
23	10	4.5	5.5	1	1	2	1	0.5
24	7.5	3.5	4	1	1	2	0	0
average	8.48	4.27	4.21	0.58	1.00	1.52	0.58	0.52
Top marks				**3**	**7**	**17**	**2**	**1**
%	**42.4**	**42.7**	**42.1**	**29**	**50**	**76**	**29**	**26**

*E1 is example 1, E2 is example 2, E3 is example 3.

M1 is misconception 1, etc.

Q1 is question 1, etc.

Chapter 4: Conclusions and recommendations

4.1 Conclusions

The problem that initiated the study on CRT and interventions for misconceptions on CRT was the difficulties first year chemistry students have with this topic. The aim of this study was twofold: (1) to investigate why students struggle with chemical reaction types and the extent to which textbook related problems and teacher induced problems play a role, and (2) how practical work can be used as an intervention to address CRT misconceptions.

The problems must come from somewhere and literature suggested that textbook related problems, time constraints and teacher induced problems were the source of these misconceptions or incomplete conceptions. Textbooks are a major source of information[1] for lecturers and students and as such became our first line of investigation. The lack of consensus on CRT and CRT terminology in the textbooks, initiated the new proposed theoretical framework (fig.1, paper 1) and TFM (fig.2, paper 1) for CRT. Furthermore, the subsequent misconceptions had to be identified and addressed; therefore, we used the MYLAB SSC kit to teach for conceptual understanding. Misconceptions are resistant to change, thus, you need different conceptual change models and instructional strategies to help or support different individual students.

The first objective, to conduct a review of textbook representations of chemical reaction types was met successfully. In the process of the review, 102 General Chemistry textbooks were investigated. A third of the textbooks gave no indication of chemical reaction types; a third preferred three CRT and the other third had anything from two to sixteen CRT (with the highest preference for four or five CRT). Therefore, it is clear that there is great ambiguity about CRT and also there is no progression towards a preferred or unanimous CRT choice. As a result of these findings, a new theoretical framework (fig.1, paper 1) was proposed, as well as a theoretical framework model (TFM, fig.2, paper 1). The view is that this clarification and simplification will lead to better conceptualization for students. This comprehensive analysis of CRT classification was the first of its kind globally.

The second objective of the study, namely to identify inconsistent and problematic chemical reaction type terminology, was also successfully met. A number of inconsistent and problematic chemical reaction type terms were identified (chapter 2, article 1, table 2). Words like displacement and replacement that have a slight difference in meaning, which by some authors are reckoned as important and by others as completely unimportant, are problematic for students. The term displacement was favoured by the majority of authors (textbook and journal). The whole issue of double displacement (metathesis, double replacement, double decomposition) where reality and model meet or differ can be avoided by talking of non-redox reactions. The request would be for standardized CRT terminology to enhance understanding and knowledge construction.

Thirdly, the objective, to compile documented international misconceptions on CRT, was achieved and a number of conceptual change models were studied.[2-5] Well documented international misconceptions were obtained from literature (i.e. refer to Table 1 in chapter 3, paper 2) and used as starting points for teaching for conceptual change.[6-8] The workshop participants had to familiarize themselves with the alternatives for the misconceptions, the correct scientific concepts, students learning styles and the process of learning, before starting the interventions. Taber[8-9] has a number of articles, especially helpful in Chemistry, to guide lecturers and teachers in Chemistry instruction. In addition, students' misconceptions are tenaciously resistant to change due to various reasons: students do not know they have a misconception, students are well satisfied with their own conception, they do not find the scientific conception acceptable, and they do not find the scientific conception useful for better understanding.[3, 5, 10] A sound knowledge of a variety of conceptual change models it thus necessary before the instructor can undertake interventions to effect change.

Lastly, the fourth objective, to evaluate the MYLAB small scale chemistry kit as intervention tool to teach for conceptual change of misconceptions on CRT, was achieved. Interventions for conceptual change can be numerous. Lucariello[3] discussed about different ways of instruction, metacognitive activities for students, cognitive conflict activities, demonstrations and experiments, discussions about conflicting concepts, "interactive conceptual instruction" or peer instruction that can have many forms, argumentation and reasoning, developing thinking skills and giving expression to thought processes to mention a few. For a number of these interventions the MYLAB small scale chemistry (SSC) kit is eminently suitable. The MYLAB kits are quick and cost-effective replacement for traditional laboratories. The results from this study and other international studies[11-12] underline the usefulness of the SSC kits. A number of the instructional strategies for conceptual change regarding CRT were successfully implemented by the MYLAB kits. The portability and the versatility of the kits make them very useful in or outside class to address misconceptions.

The interventions via structured experiments or open experiments, both used during formal and informal workshops, comprise many of the conceptual change instructional strategies including amongst others metacognitive activities. The short time necessary to perform experiments, makes multiple experiments possible and enhances pattern recognition, and CRT identification through series of similar chemical reactions.[13] The short time used for experimental procedure allows extra time for discussions, argumentation and reasoning about results and even re-doing experiments or further experiments or investigations to prove or disprove the point under discussion. The MYLAB kits facilitate opportunities for evaluating students' argumentative and reasoning skills, developing their thought processes and improving their thinking skills. It is possible to ask and test a lot of 'why', 'what if' and 'how' questions. Shallow understanding can be challenged and higher level thinking can be encouraged and developed. Importantly, as seen from the workshop results, misconceptions are prevalent and an active way to address misconceptions are relevant. Therefore, the MYLAB SSC kit can be a highly effective tool in the teaching for conceptual change.[14-16] If accessibility and Chemistry for all, are the aim, the compactness, comprehensiveness and portability of the MYLAB kits make them exceptionally suitable as vehicles for change and success. For example, it is possible and easy to pack-up and reach remote communities[17-19] with poor infrastructure and inadequate teaching resources. On-site workshops are of great value to struggling and inadequately supported teachers of rural schools.

Therefore, the basic hypothesis was that misconceptions about chemical reaction types are symptomatic of textbook related problems and problems with other related Chemistry concepts was indicated.

4.2 Implications for science teaching and learning

Practical workshops on chemical reactions indicate that students are confused and lack the ability to correctly apply theory to given problems. Students have insufficient theoretical knowledge, and often fail to make the link between theory, practical work and problem solving. Moreover, students do not retain enough theoretical knowledge. During workshops, despite practical work on all reaction types, misconceptions still appeared and no noticeable improvement in theoretical and conceptual knowledge were identified. This intervention, of practical work with MYLAB kits, needs to be repeated for maximum effect on students' incomplete conceptions and knowledge construction.

Standardized classification for CRT would be helpful to simplify and clarify the complex concept. We, as experts, often forget the depth of information embedded in a chemical formula or chemical equation that is not noticeable or obvious to novice students.[20] The new proposed theoretical framework (fig.1, paper 1) and TFM (fig.2, Paper 1) would do much to reduce the working memory overload for students. Standardized CRT terminology would also reduce confusion and uncertainty about word meanings that can lead to misconceptions.

Teachers need to familiarize themselves with documented CRT misconceptions in literature and must be able to use those examples to teach for conceptual change. Furthermore, they must be able to identify students' misconceptions to facilitate better understanding and knowledge construction. Therefore, to facilitate the student in the process to complete understanding the teacher needs an arsenal of instructional strategies and conceptual change models. The teacher must also be able to analyse and teach all the contributing subtopics that forms part of the complex topic, CRT.[21] Deeper understanding and advanced skills are necessary for the comprehension of CRT, thus, deeper understanding and advanced skills must be taught to achieve success. Sub-concepts learned well, helps learning with the main concept.[21]

The importance of practical work can never be underestimated. For example, the MYLAB SSC kits are useful tools to implement different teaching strategies and conceptual change models effectively. Individual, hands-on activities with the kits open up time for discussion, reasoning, debating, further experimental investigation and also metacognition.

4.3 Recommendations

- We propose that IUPAC could investigate our new proposed TFM as a possible new standardized classification system. Moreover, they could also standardize terminology for CRT.

- Future studies could answer the following question: What interventions can be suggested to specifically improve the conceptual knowledge of students of chemical reaction types in order to improve understanding and recognition of chemistry reactions and the ability to correctly write down reaction equations?

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