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Reasoning Pattern of Grade 10 Physical Science Students about Basic Chemical Phenomena at Sub-Microscopic Level

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Abstract:

This paper reports on issues and findings as part of the main study on how Grade 10 Physical Science students' reason when working with basic chemical concepts such as elements, compounds, molecules, mixtures, and solutions of acids and bases, based on sub-microscopic representations. The study adopted a non-experimental, exploratory and descriptive method based on the ex-post facto research design using a concurrent embedded mixed method strategy. A paper and pencil Test of Basic Chemistry Knowledge (TBCK) and focus group discussions (FGDs) based on the three levels of chemical representation of matter were administered to 280 Grade 10 physical science students in Tshwane North District of South Africa. The results revealed that most Grade 10 students find it easy to identify pure elements and states of matter but find it difficult to negotiate between the three levels of chemical representation of matter when dealing with concepts of molecular elements, compounds, concentration and solution chemistry. It concluded that students find it difficult negotiating the three levels of chemical representation of matter. Recommendations that will enable students overcome the observed problem are well highlighted.

Keywords: Basic chemical concepts, concentration and solution chemistry, macroscopic phenomena, particulate nature of matter, Pictorial diagrams, symbolic representations.

Introduction and Background

South African secondary school learners obtain a National Senior Certificate (NSC) upon completing and passing the Grade 12 National Senior Certificate examinations, as an entry qualification into universities and other tertiary institutions as well as for general employment. The preparation for the NSC examination takes three years of further education and training (FET), comprising Grades 10, 11 and 12. The recent South African Department of Education national school certificate examinations have revealed poor performance in physical sciences by Grade 12 learners (DoE National results, 2008, 2009). In Gauteng Province for instance it was reported that learners experience more difficulties in the chemistry component of the physical sciences examination than in the physics component (Gauteng DoE Internal Moderators' Report, 2009). The November 2009 physical science examination results recorded a record failure rate of 63.1% (36.9% pass rate) in South Africa. Performance in grade 12 physical science has been on a continuous downward trend and this is a cause for concern to most universities in South Africa (Onwu and Randall, 2006; Potgieter et al., 2008).

According to DoE National Results (2009), the candidates are said to have had difficulties specifically with concepts such as collision theory, differences between atoms, ions and molecules, balancing of equations and topics concerning organic chemistry and oxidation-reduction reactions. This interesting finding prompted the authors to undertake an armchair analysis of the November 2009 senior certificate chemistry test items in terms of conceptual level demand. The paper was analyzed using the three components in which chemistry is generally portrayed, namely, macro, sub-micro and symbolic levels of representation (Johnstone, 1993). It then became illuminating to undertake a study to evaluate learners' reasoning and thinking about chemical ideas, using an assessment tool that is modeled on the three representational levels of chemistry thinking. In their study about learning difficulties experienced by grade 12 South African students in chemical representation of phenomena, Umesh and Aleyamma (2012) noted that students find it more difficult to answer questions demanding transformation (connecting the three levels of chemical representation).

According to Johnstone, (1993); Treagust, Chittleborough, and Mamiala (2003); Nahum, Hofstein, Mamlok-Naaman and Bar-dov, (2004); and Sirhan, (2007), the macroscopic level is real and may take the form of experiments which are visible; the sub-microscopic level is invisible but real and deals with atoms, molecules and ions; and the symbolic level is the chemical language expressed as formulae, symbols, pictorial representations, and graphs. These levels of chemical representation in line with what Devetak et al, (2004, 2009), envisage to constitute chemistry thinking. It is against this conceptual framework that an attempt was made to analyse the November 2009 chemistry paper in order to gain insight into the nature and type of questions that were predominantly set and to establish whether it was or not a possible source of difficulty.

Research into school chemistry teaching and learning has become cogent in the South African context because of the increasing awareness that first year post-matriculation learners who gain admission into chemistry courses or science teacher education courses at FET (Further Education and Training) level, still hold misconceptions or overly simplistic conceptions of the particulate nature of matter (Harrison, 2000; Harrison and Treagust, 2002; De Jong et al., 2005; Onwu and Randall, 2006). Recent studies (Onwu and Randall, 2006; Potgieter et al., 2008) led one to conclude that in some South African universities many first-year students have inadequate understanding of basic chemistry concepts that ought to have been understood at secondary school level. While students show some evidence of learning and understanding in their performance in public examinations, researchers also found evidence of misconceptions and rote learning in certain areas of basic chemistry even at degree-level (Johnstone, 1984; Bodner, 1991; Harrison and Treagust, 2002; de Jong et al., 2005; Onwu and Randall, 2006; Sirhan, 2007).

According to Onwu & Randall (2006), "the experienced chemist is comfortable on all three levels of communicating chemical concepts and can easily move from one level to the other, while the novice learner is comfortable in none of these levels and has difficulty relating one level to the other". Other studies (Johnstone, 1991; Johnson, 1998; Gabel, 1999) also show that learners find it easier and more fun to deal with observable chemical activities, in other words macroscopic chemistry such as practical work involving experiments rather than handling theoretical concepts (concepts by definition) which require proper conceptual understanding, and the language facility to express the latter. Arguably, for learners' conceptual understanding in physical science lessons, the physical science educator's instructional approach ought to be presented in ways that seek to emphasize and incorporate in a balanced way of all three levels of representational thinking for optimal learners` understanding and performance. Indeed, the more recent textbooks in chemistry or

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physical science, for example the current Grade 10 and 11 'Spot On' Physical Sciences textbooks by Elferink et al., (2008) are now incorporating concepts that are presented and assessed using all three representational levels.

Although the particle theory serves to explain some chemical phenomena, chemistry learners generally have difficulty transferring from one level of representational thinking to another. As has been noted in South Africa, learners find particle concepts difficult to conceptualize and there is limited instruction about particles in Grades 8 and 9. It was then useful to direct research attention at finding out what Grade 10 chemistry learners do not know about concepts like particle theory and how they reason about the particulate model with a view to making appropriate instructional recommendations.

Although several studies of secondary school learners' conceptions about the particulate nature of matter have been undertaken (Harrison and Treagust, 2002; Justi and Gilbert, 2002; Singer et al., 2003; Emine and Adadan, 2006; Onwu and Randall, 2006), it is not clear *how* learners' reason with regard to the way sub-microscopic particles are presented in representational models. This paper therefore focuses on how learners' reason about the particulate nature of matter to relate macroscopic phenomena to sub-microscopic particles. The results analysis and discussions of the main findings of the study are presented.

Statement of the Problem

The problem of the study was to determine how Grade 10 learners' reason about the particle theory using representational models (diagrammatic) of sub-microscopic entities to solve tasks in basic chemistry.

Research Questions

The following research questions have been addressed in this paper:

(a) What is Grade 10 physical science learners' levels of achievement in reasoning about basic chemical phenomena using sub-microscopic representational models?

(b) How do Grade 10 physical science learners' reason about basic chemical phenomena using sub-microscopic representational models?

(c) Why do Grade 10 physical science learners' reason the way they do about basic chemical phenomena using sub-microscopic representational models?

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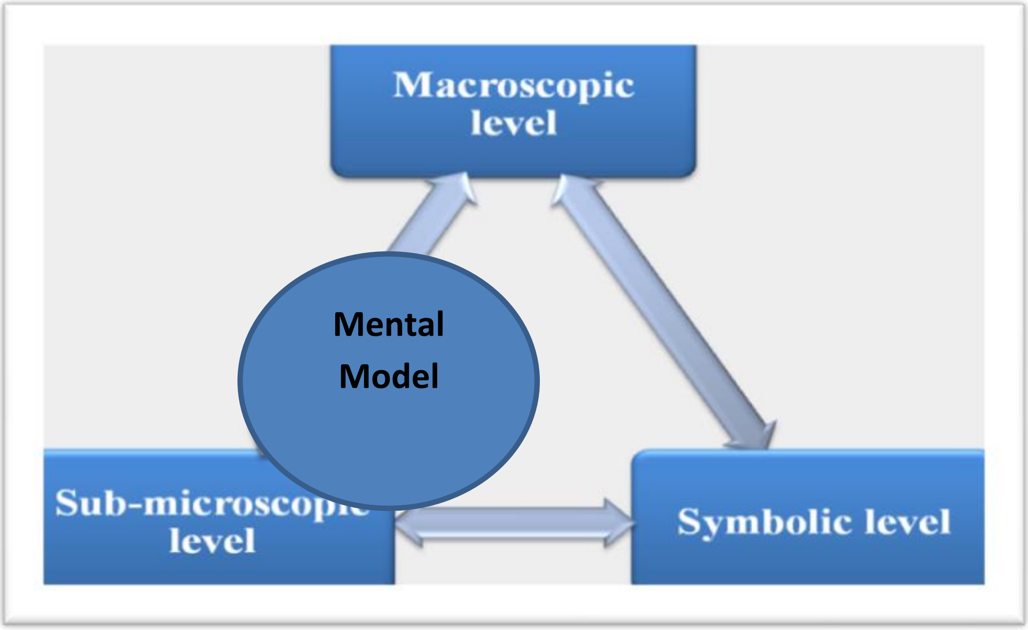
Conceptual Framework

The study was about evaluating learners' reasoning about chemical phenomena using a model that requires learners to think at particle level. The conceptual framework is based on the 'chemistry thinking triangle' model (Johnstone, 1993, 2000; Chittleborough et al., 2002; Treagust et al., 2003; Nahum, 2004; Devetak, 2005; Sirhan, 2007; Devetak et al, 2004, 2009) shown in Figure 1.0 below. The model comprises three levels in which chemical concepts are conceptualized, namely, macroscopic, sub-microscopic and symbolic levels.

Figure 1.0 (Chemistry thinking model)



Chemistry Triangle Model adapted from (Johnstone, 1993, 2000; Chittleborough et al., 2002; Nahum, 2004; Devetak, 2005; Sirhan, 2007; Devetak et al., 2004 & 2009;

The chemistry triangle is a learning, teaching and assessment model which is in accord with the three levels into which chemistry is conceptualized, namely, the macroscopic, sub-microscopic and symbolic. The macroscopic level takes the form of experiments which are observable and easily visualized by the student, the sub-microscopic level is that which cannot be seen and takes the form of atoms and molecules represented by particles, and the symbolic level is given in the form of chemical equations, symbols and formulae which is the language in which chemical concepts are expressed.

Sub-microscopic representations such as pictorial diagrams of solutions (solvent and solute particles), and atoms and molecules that depict matter at particle level, are thought to be a sensible way of teaching and assessing beginner learners. The approach enables students to understand what happens at the macroscopic level from the particle point of view, while the symbolic level is the chemical language as it were that seeks to describe and explain events at both the macroscopic and sub-microscopic levels through the use of chemical symbols, formulae, chemical equations etc, (Chittleborough, 2002; Sirhan, 2007; Gilbert & Treagust, 2009).

The model entails thinking that requires operating between all three levels by the learner during teaching, learning and assessment of chemical concepts and shows the interdependence of the three levels which manifests itself in the 'mental model' of the learner (Devetak, 2009), and it is on the attainment of this interdependence that chemical concepts begin to make sense to the learner. Because awareness of this interdependence as a way of conceptualizing chemistry is not always apparent to novice chemistry learners, there seems to be a cognitive gap or deficit between how learners view chemical phenomena and the way they go about reasoning to try and connect the same to the sub-microscopic and the symbolic worlds (Gilbert & Treagust, 2009).

The triangle in figure 1.0 symbolizes the connectedness and interdependence of the three levels of chemical conceptualization, hence the mental model of the learner. The three levels are inseparable as there is constant interplay between them (Sirhan, 2007). They form the elements of the conceptual framework used in the development of data collecting instruments and data analysis. The test of basic chemical knowledge (TBCK) consisted of items meant to assess students in tasks based on diagrams or schemas that depicted atoms, molecules, mixtures and compounds and ions (behaviour of sodium chloride, a base and hydrochloric acid in water) and concentrations of solutions at sub-microscopic level. The test was designed in line with the elements of the conceptual framework.

Methodology

The study adopted an ex-post facto research design (survey) and a mixed method research approach to collect both quantitative and qualitative data. The design implies that all the variables have already occurred. A mixed method research approach was used as primary data was quantitative and secondary data qualitative.

Sampling and Sampling Procedure

The population for this study was Grade 10 beginner physical science learners in Tshwane North District (D3)'s township secondary schools. Grade 10 physical science marks the entry point into a three-year physical science preparation for the National Senior Certificate examinations, hence the choice of that grade. The sample comprised good, average and poor performing schools that have been offering National Senior Certificate examinations for the period 2005-2009. To ensure representation of all abilities, stratified random sampling was carried out in two stages: firstly, based on performance and secondly, based on whether the schools have been offering National Senior Certificate examinations since 2005. Simple random sampling usually referred to as *epsem* sampling or the 'equal probability of selection method' (Ross, 2005) was then used to select six (two from each stratum) schools, so as to ensure equal probability of selection for all elements in the population. The sample comprised 280 students (80 from two good performing, 100 from two average performing and 100 from two poor performing schools) and six of their physical science teachers.

Research Instruments

A paper and pencil multiple choice *Test of Basic Chemical Knowledge (TBCK)* to determine the learners' achievement as well as their reasoning (justifications to choices) when solving basic chemical concepts using sub-microscopic representations was given to learners during the first phase (survey) of collecting data, and interviews with learners (Focus Group Discussions) and teachers during the second phase were used. The structure of these interviews was developed based on the performance by learners in the *TBCK* and the elements of the conceptual framework (macroscopic, sub-microscopic and symbolic).

The *TBCK* instrument comprised multiple choice questions as well as problem items that involved reading of sub-microscopic representations and translations of sub-microscopic representation of the phenomena. The *Test of Basic Chemistry (TBCK)* consisted items on ionic solutions (base, acid and sodium chloride), concentration, atoms, molecules, elements, compounds and mixtures. Four of the five TBCK tasks have already been validated and were adapted with permission from Devetak et al., (2004 & 2009). The fifth TBCK task was developed by the authors and is modelled on Onwu and Randall, (2006)'s instruments.

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Data presentation, analysis and interpretation

Data for each school were presented in table and graph forms. A further analysis of the data collected in the form of item analysis (n=55) was carried out in order to have a deeper understanding of problem encountered by learners. For the purposes of this paper only the results from school no. 1 and the overall sample results were used. Figure 2: TBCK score analysis per question for school 1 shows every participant's score and how he or she faired in each of the tasks given in the test (TBCK), the school average score and percentage pass and failure rates per each task. In addition, a summary table and graph on the levels (according to Department of Education) achieved by learners is also presented. The tasks presented and analysed were the multiple-choice questions and the justifications thereof. The key given at the bottom of the first table refers to correct, incorrect and no responses as well as justifications (reasoning) in terms of how participants performed in the test (TBCK) presented in this section. Further descriptions and explanations are given after every table and graph. For clarity purposes only, a few tables (for school no. 1 and summaries for all schools) have been presented and individual results of the other five schools (2-6) were presented and analysed in the same away.

Figure 2: TBCK score analysis per question for school 1

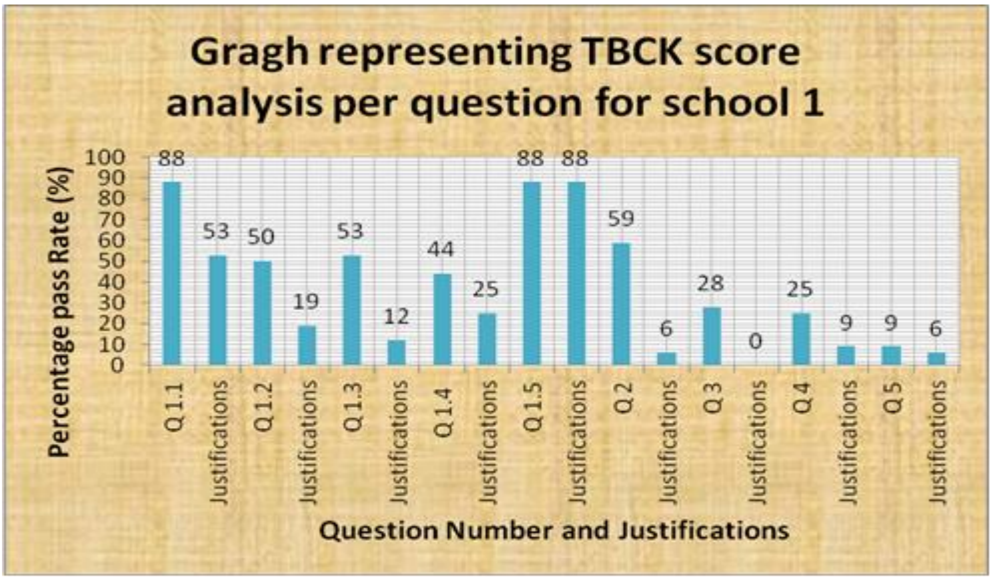

Figure 2: TBCK score analysis per question for school 1 above for school participant number 1 clearly shows that participants scored extremely well in questions Q 1.1 (88%) and Q 1.5 (88%). Justification scores to the same questions although lower than the multiple-choice scores were fairly

high as well. Interestingly Q 1.5's score was the same as its justification score. Question Q 1.1 required participants to identify the pictorial diagram (schema) that depicted a pure element whilst question Q 1.5 required them to identify the pictorial diagram that depicted a substance in its solid form. Apparently, it is the same schema for both tasks that they needed to identify. It therefore appears that the concepts of pure elements and the kinetic molecular theory of matter were easily conceptualised by the participants during instruction.

However, the case was different with the rest of the tasks with the majority of the participants scoring lowest in Q 5 (9%) as well its justification (6%). Generally, all justification scores were lower than the multiple-choice scores for all tasks and in the case of Q 3 no participant got the correct justification. Notably, it appears as if participants were not used to questions that required them to give explanations to multiple choice questions. Task Q 3 required participants to identify the schema that represented an aqueous solution of a base whereas Q 5 required them to identify the schema that depicted an aqueous solution of sodium chloride. Interestingly, participants scored 59% on task 2 (Q 2) which required them to identify the schema that represented an aqueous solution of hydrochloric acid at the particle level even though the tasks (Q 2, Q 3, Q 4 and Q 5) demanded similar levels of conceptualization, thinking at particle level about solutions and chemical reactions. It therefore seems that those who got correct responses to Q 2, Q 3, Q 4 and Q 5 had to put their trust in luck (guess work). Analysis of some of the wrong justifications indicated that participants resorted to guessing, without proper understanding.

Tasks Q 1.2, Q 1.3 and Q 1.4 were more difficult than Q 1.1 and Q 1.5 although they were all in the same category. These tasks required participants to identify atoms, elements in general, molecular elements, molecular compounds and the states of matter. These tasks had similar conceptual level demands, differentiating between atoms, elements, molecules and states of matter. It can therefore be concluded that learners find it is easier to understand pure elements but it becomes increasingly difficult as one develops the concept to higher order thinking levels when it involves molecular elements and molecular compounds. This is probably because molecular elements and molecular compounds require the understanding of chemical bonding, thus these concepts become more difficult to comprehend. In all, school no.1 participants scored an average of 36% (sample average was 37%). This is a worrisome observation as it means that the majority of the participants did not score above 50%. Only a few participants (22%) got scores above 50%.

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Table 1: TBCK Sample Results Analysis by task per school

Sample Results Analysis by Task																				
Group % Pass rate	School No.	Q 1.1	Justifications	Q 1.2	Justifications	Q 1.3	Justifications	Q 1.4	Justifications	Q 1.5	Justifications	Q 2	Justifications	Q 3	Justifications	Q 4	Justifications	Q 5	Justifications
	1	88	53	50	19	53	12	44	25	88	88	59	6	28	0	25	9	9	6
	2	88	43	48	19	44	17	51	14	84	70	65	13	41	2	13	3	16	8
	3	77	26	37	26	56	7	40	2	79	56	63	16	44	2	14	2	7	5
	4	91	53	42	21	74	26	47	19	95	84	74	2	51	2	16	12	9	5
	5	83	68	72	47	68	23	81	49	94	87	51	9	26	4	34	19	13	6
	6	84	51	40	24	56	22	51	13	76	64	49	16	24	2	22	7	7	4
	Av	85	49	48	26	59	18	52	20	86	75	60	10	36	2	21	9	10	6

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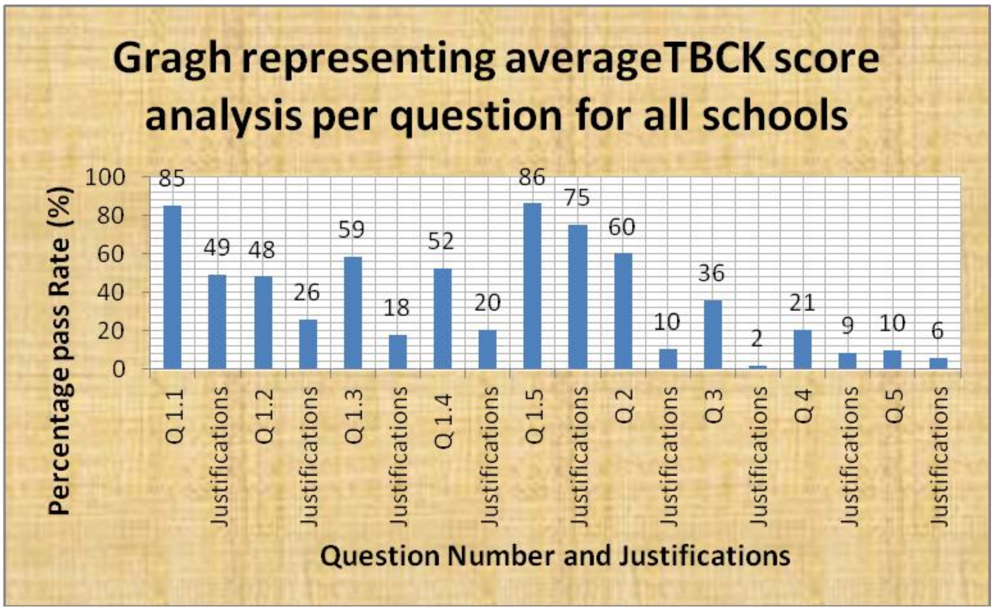
Figure 3: Sample average TBCK score analysis per question for all schools



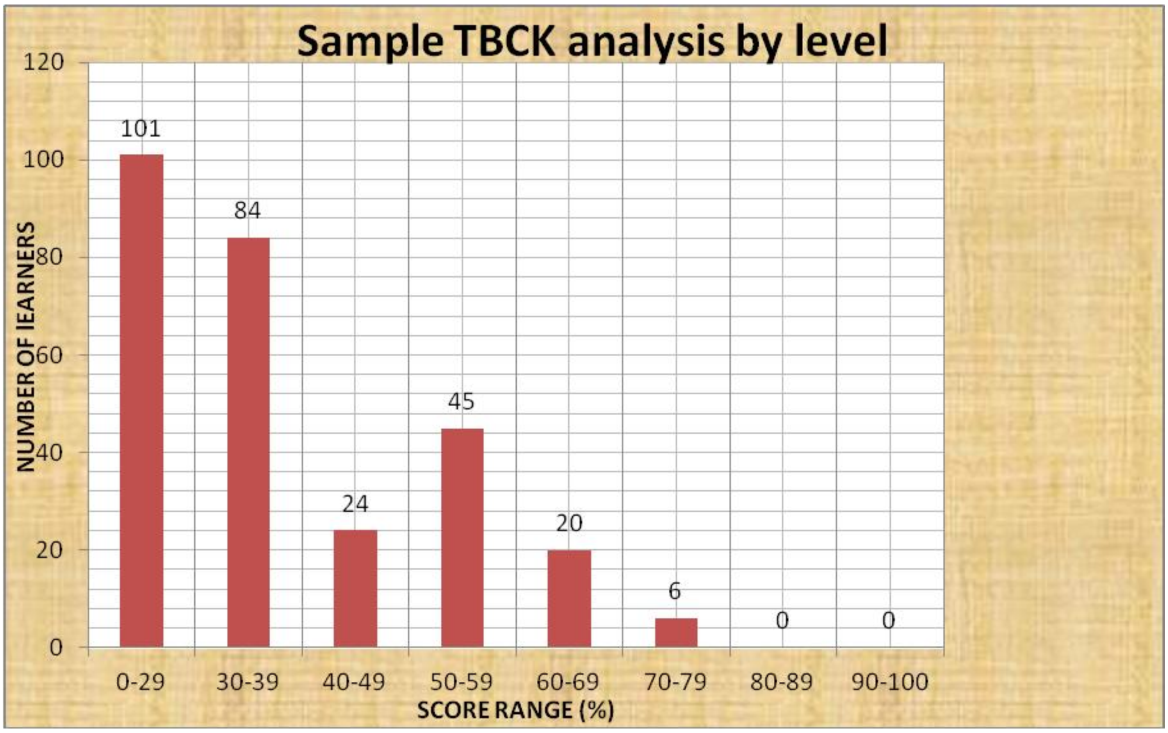
The above graph in Figure 3: Sample average TBCK score analysis per question for all **schools** shows the average of all the six schools' graphs that have been presented and analysed in the main study and compares very well with school no 1's graph. It should be noted that graph in Figure 3: Sample average TBCK score analysis per question for all **schools** looks like a replica of that of school no. 1 described above, indicating similar problems in all the schools that participated in the study. The graph shows common successes as well as common problems in Grade 10 physical science learners in the study sample. Identification of pure elements and solid substances together with their justifications were the major achievements in all the schools whilst the rest of the items were a huge challenge to most of the participants. It is therefore concluded that many learners find it difficult to make transitions between the three levels in which chemistry is conceptualised. Reasoning at particle level is not always apparent to most learners.

Table 2: Sample TBCK analysis by level below shows the sample TBCK analysis by level as per the South African grading system. The levels range between 1 and 7. Learners are considered not having achieved the matric pass requirements when they score level 1 (0-29%). Levels 2-5 (30-69%) are considered as ordinary matric passes while levels 6 (70-79%) and 7 (80-100%) are taken as university entry qualification passes for those who may enrol for science and science education programmes.

Table 2: Sample TBCK analysis by level

Sample TBCK analysis by level								
Score range (%)	0-29	30-39	40-49	50-59	60-69	70-79	80-89	90-100
No. 0f learners	101	84	24	45	20	6	0	0
Level	1	2	3	4	5	6	7	8

Figure 4: Sample TBCK analysis by level



The sample analysis by level in Figure 4: Sample TBCK analysis by level shows serious and far reaching implications of the study to the teaching and learning of basic chemical concepts. Out of the 280 participants only 6 (2.1%) obtained at least level 6 (70-79% score range) in the TBCK test and this suggests that very few of the Grade 10 physical science learners go through their basic chemical concepts without proper understanding. South African universities require students with levels 6 and 7 at matric level to enrol for science related programmes. Grade 10 learners are most likely going to carry basic chemical misconceptions through to Grade 12. This is in line with the findings of the preliminary study of 2012 in which the same TBCK test was administered to Grade 12 learners. In the preliminary study, it was found that most of the Grade 12 learners had the same misconceptions as the Grade 10 learners. This is supported by Umesh and Aleyamma (2012) in their study "Learning difficulties experienced by grade 12 South African students in the chemical representation of phenomena" in which it was revealed that students find it more difficult to answer questions demanding a transformation. This seems to suggest that chemical misconceptions are carried throughout the entire 3-year (grade 10-12) matric programme. It can therefore be concluded that thinking at particle level is not always apparent to most Grade 12 candidates and this will always have a negative impact on Grade 12 candidates' performance in their physical science national certificate examinations.

Conclusion and Recommendations

Based on the above results and discussions, it can be concluded that grade 10 physical science learners are unable to distinguish between atoms, elements, molecules (diatomic elements) and compounds. It is amazing that 52% of the learners could not identify a pure compound. However, the majority of the learners appear to have mastered the concept of the kinetic theory of matter and as a result they were able to determine the state of matter (macroscopic level) from pictorial diagrams (sub-microscopic level) but it became increasingly challenging for learners concerning questions demanding higher cognitive levels of thinking. For example, distinguishing between pure compounds and mixtures of compounds, and between a compound and mixture of mono-atomic and diatomic elements presented a major challenge to learners. Some learners took a pure compound for a mixture because they saw different kinds of atoms but ignored the fact that these atoms were bonded together.

It can also be concluded that grade 10 physical science learners do not clearly understand the behaviour of ionic compounds in water. For example, learners do not understand that when an ionic compound such as sodium chloride dissolves in water ions (Na^+ and Cl^-) are simply separated into the ratio they were in before the dissolution process and are surrounded by the water molecules. They think that the aqueous solution of sodium chloride contains molecules of sodium chloride. This is in line with what Devetak et al., (2009) observed in their study of grade 8 and 9 pupils' knowledge of electrolyte chemistry and their intrinsic motivation.

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Learners also do not fully understand the difference between dissolution and chemical reactions that involve water. For example, learners did not realise that HCl reacts with water to give rise to H_3O^+ and Cl^- ions. In many responses the hydronium ion (H_3O^+) was thought to represent the water (H_2O) molecule. Thus, those learners with the correct responses had very wrong justifications. According to Devetak (2005), similar misconceptions are also common among the secondary school students and university students alike (Segedin, 2001; Devetak et al., 2004). It also was evident that learners do not understand the nature of a basic solution. In some cases, learners failed to express themselves precisely. They lack the chemical language. Learners struggled to come up with meaningful justifications at times. This may be due to the fact that most multiple-choice tests do not require them to explain their choices. The use of explanations by learners would enable the teacher to gain insights into their understanding of the content of the chemistry discipline. It is also true that some learners relied on guessing to get multiple choice responses right. This was very evident in cases where unpalatable explanations were given for the correct responses in this study.

Furthermore, the concept of concentration is not always clear to grade 10 physical science learners. They are not familiar with the concept of concentration (particles per unit volume). Most of the learners only concentrated on the number of particles and ignored the idea of volume. Most learners seemed to be unfamiliar with the use of pictorial diagrams that depict matter at sub-microscopic level. Nevertheless, it remains not clear whether the learners did not have the knowledge of the concepts tested or the learners were not used to the teaching and assessment that require the use of sub-microscopic representations.

Justifications to responses had higher failure rates than those of the multiple-choice tasks. Majority of those who got multiple choice responses correct, got the justifications wrong indicating the way they reasoned, thus they mostly relied on guessing. Evidence from Focus group discussions (FGD), document analysis and teacher interviews revealed that teachers do not teach for understanding but instead they drill learners for examinations.

It is against this background that the following suggestions or recommendations are made; teachers should try to include the use of sub-microscopic representations in order to simplify the abstract chemical ideas about the particle theory of matter; teachers should be explicit about the use of sub-microscopic representations as these are models of an already abstract model (atomic model); teachers should try and help learners make connections between the three levels of chemical

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thinking when teaching chemical concepts (thus scaffolding the learner) in order to develop a metal model in the learner about the particle theory; South African education system should provide relevant teacher support materials which include training in the use of sub-microscopic representations; teacher education programmes should lay emphasis on the constant interplay between chemical phenomena (macroscopic events), sub-microscopic and symbolic representations as most teachers are not confident in the usage of such representations; and finally, the South African chemistry curriculum must include a hands-on practical examination (macroscopic level) on chemical concepts from grade 10 to12 as this would probably enhance learners' understandings (at present, only symbolic representations are predominantly used in South African schools) about the macroscopic world.

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