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Relationship between Students' Knowledge Structure and Problem-Solving Strategy in Stoichiometric Problems based on the Chemical Equation

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Abstract

Relationship between students' knowledge structure and problem-solving strategy was studied using a written test containing one complex stoichiometric problem based on the chemical equation and four simple problems similar to the steps of two known strategies (mole method and proportionality method) for solving the complex problem. Based on the strategy used in solving the complex problem students (N = 1072, grades 7-10) were divided into three groups: (1) mole method group; (2) proportionality method group; and (3) others (unidentified strategy or no strategy). The knowledge structure characteristic of each group was determined by using knowledge space theory. There was no significant difference between the success (ca. 70%) of the student groups applying any strategy (groups 1 and 2), but the achievement of the students not using any strategy (group 3) was significantly lower (ca. 20%). We found significant difference between the characteristic knowledge structure of the three groups. The knowledge structure of the group 3 is very similar to the experts' knowledge structure. However, the knowledge structure of the student groups using any strategy shows that students typically used these problem-solving strategies as algorithms instead of the conceptual understanding. For example in the characteristic knowledge structure of group 1 the knowledge necessary to solve the complex problem is built on both the proportionality and the molar mass, while in case of the student group 2 it is built on only one simple knowledge, the proportionality.

Key Words

Chemistry, Knowledge Structure, Problem Solving, Stoichiometry

Introduction

Problem solving is an evergreen topic in science education research. Many study deal with the modelling of problem solving (for example: Bodner & Domin, 2000; Johnstone & El-Banna, 1986; Bodner, 2003; Bennett, 2008; etc.), the types of problems (for example: Johnstone, 2001; Bennett, 2008; etc.), the possibilities for developing problem-solving skills (for example: Johnstone, 2001; Bodner, 2003; Cardellini, 2006; Johnstone & Otis, 2006; Wood, 2006; Cooper et al., 2008; etc.), the cognitive variables of the successful problem solving (Lee, 1985, Lee and Fensham, 1996, Lee et al., 1996, 2001), and so on. Relatively few papers has appeared in the literature on the question how students choose their problem-solving strategy and what is the difference between the cognitive structures characteristic for student groups using different problem-solving strategies.

Being familiar with a special evaluation method for exploring students' knowledge structure (by using so-called knowledge space theory) we could determine the characteristic hierarchy of knowledge for the student groups applying different problem-solving strategies.

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This method has already been used successfully for mapping students' knowledge structure in understanding basic physical and chemical quantities and their application in calculations (Tóth, 2007).

The aim of the study

Recent research focuses on the questions:

1. How the Hungarian secondary school students solve problems in stochiometry based on the chemical equation?
2. Are there any differences in characteristic knowledge structure between the student groups using different problem-solving methods?

Background

Cognitive variables to problem solving in chemistry

Lee and co-workers studied the importance of the cognitive variables to problem solving in chemistry (Lee, 1985, Lee and Fensham, 1996, Lee et al., 1996, 2001). They assumed that the success of the problem solving is basically determined by three block variables containing six predictor variables:

1. Prior knowledge:
   - Specific knowledge: knowledge directly related to the problem.
   - Non-specific but relevant knowledge: knowledge related to the subject area of the problem.
2. Linkage
   - Concept relatedness: relatedness between concepts involved in problem solving.
   - Idea association: linkage between the information retrieved from the existing knowledge structure and the external cues.
3. Problem recognition skill
   - Problem translating skill: the capacity to comprehend, analyse, interpret and define a given problem.
   - Prior problem solving experience: the prior experience in solving the similar problems.

Based on empirical research they found that the significance of the above variables depends on the topics and level of the chemistry problems, however these differences in topics and levels have little effect on the importance of these variables on problem-solving performance. Their studies showed that in the topic of grade 12 electrochemistry five cognitive variables (specific knowledge, non-specific but relevant knowledge, concept relatedness, idea association, problem translating skill) were the important predictors of problem-solving performance (Lee at al., 1996). In problem-solving in mole concept of grade 9 chemistry they found four cognitive variables (specific knowledge, concept relatedness, idea association, problem translating skill) to be significant in predicting problem-solving performance with idea association being the most significant (Lee at al., 2001).

Students' problem solving in stoichiometry

Several papers discussed the students' problem solving in stochiometry in the last three decades. Two main results of these researches can be summarised as follows:

(1) Students' problem solving has little connection to their conceptual understanding of chemistry (for example: Nurrenbern and Pickering, 1987; Nakhleh, 1993; Nakhleh and Mitchell, 1993; Cracoline et al., 2008; etc.). Students can correctly solve numerical

problems involving stoichiometry without understanding the underlying molecular perspective of that problem. Recently it was showed by Tóth (2007) that there was significant difference in the characteristic knowledge structure of the students who learned the basic physical and chemical quantities (molar mass, molar volume, mass percent etc.) by conceptual understanding and that of the students who learned these concepts by rote learning. It was also shown that rote learning made the finding of the connections between concepts hard and gave separated and non-mobilizable knowledge.

(2) The problem-solving strategy a student applies depends on different factors (for example: Schmidt, 1990, 1994, 1997; Schmidt and Jignéus, 2003; Tóth, 2004; Tóth and Kiss, 2005 etc.). Schmidt reported that the high school students in Germany (Schmidt, 1994, 1997) and in Sweden (Schmidt and Jignéus, 2003) successfully used their own strategy in solving simple stoichiometric problems on composition of binary compounds, but tended to use algorithmic methods thought at school in case of difficult problems. Contrary these results Tóth and Kiss (2005) found, that Hungarian secondary school students applied the strategies learned at school even in case of simple stoichiometric problems. In balancing chemical equations Tóth (2004) found that Hungarian high school students created their own balancing strategy (mainly the trial-and-error) before learning the oxidation number method at school, and they stuck to their own strategies of low efficiency even in case of complicated redox equations.

Solving methods for stoichiometric problems based on the chemical equation

There are several strategies for solving stochiometric problems based on the chemical equation similar to that of problems on composition of binary compounds (Schmidt, 1997). These methods will be characterised on an example from the written test discussed later:
'How many grams of hydrochloric acid (M = 36.5 g/mol) gives 10.0 dm^3 of carbon dioxide at STP (V_m = 24.5 dm^3/mol) according to the following chemical equation? Na_2CO_3 + 2 HCl = 2 NaCl + CO_2 + H_2O'

Strategy 1: *mole method*

1. Calculate the amount of substance for CO_2 using the volume and the molar volume data:

   $n(CO_2) = V(CO_2) \div V_m = (10.0\ dm^3) \div (24.5\ dm^3/mol) = 0.408\ mol$

2. Based on the chemical equation convert the amount of substance for CO_2 into amount of substance for HCl:

   $n(HCl) = 2 \times n(CO_2) = 2 \times (0.408\ mol) = 0.816\ mol$

3. Convert the amount of substance for HCl into the mass of HCl using molar mass:

   $m(HCl) = n(HCl) \times M(HCl) = (0.816\ mol) \times (36.5\ g/mol) = \underline{29.8\ g}$

Typical of strategy 1 are steps (1) and (3), which form the relations between given and required substances via amount of substance. During solution two amount of substances (for both the given and the required) are calculated.

Strategy 2: *proportionality method*

1. Based on the chemical equation realise that the amount of CO_2 is directly proportional to the amount of HCl, that is:

   24.5 dm^3 CO_2 is given by 2 × 36.5 g HCl

2. This ratio of the amount of HCl to CO_2 obtained from the chemical equation is equal to the ratio of the actual amounts:

$m(HCl) / V(CO_2) = (2 \times 36.5\ g) / (24.5\ dm^3) = (x\ g) / (10.0\ dm^3)$,

or as it usual in Hungary

if 24.5 dm^3 CO_2 is given by 2 × 36.5 g HCl

then 10.0 dm^3 CO_2 is given by x g HCl

3. Calculate the mass of HCl (x):

$x\ g = (10.0\ dm^3) \times (2 \times 36.5\ g) \div (24.5\ dm^3) = \underline{29.8\ g}$

Typical of this strategy are steps (1) and (2), by which a relation between given and required amounts is found to be a direct proportion. The amount of substance does not appear directly.

Strategy 3: *mixed methods*

Variation (a):

1. Calculate the amount of substance for CO_2 using the volume and the molar volume data:

   $n(CO_2) = V(CO_2) \div V_m = (10.0\ dm^3) \div (24.5\ dm^3/mol) = 0.408\ mol$

2. Based on the chemical equation realise that the amount of substance for CO_2 is directly proportional to the amount of HCl, that is:

   1 mol CO_2 is given by 2 × 36.5 g HCl

3. This ratio of the amount of HCl to CO_2 obtained from the chemical equation is equal to the ratio of the actual amounts:

   $m(HCl) / n(CO_2) = (2 \times 36.5\ g) / (1\ mol) = (x\ g) / (0.408\ mol)$,

   or as it usual in Hungary

   if 1 mol CO_2 is given by 2 × 36.5 g HCl

   then 0.408 mol CO_2 is given by x g HCl

4. Calculate the mass of HCl (x):

   $x\ g = (0.408\ mol) \times (2 \times 36.5\ g) \div (1\ mol) = \underline{29.8\ g}$

Variation (b):

1. Based on the chemical equation realise that the amount of CO_2 is directly proportional to the amount of HCl, that is:

   24.5 dm^3 CO_2 is given by 2 mol HCl

2. This ratio of the amount of HCl to CO_2 obtained from the chemical equation is equal to the ratio of the actual amounts:

   $n(HCl) / V(CO_2) = (2\ mol) / (24.5\ dm^3) = (x\ mol) / (10.0\ dm^3)$,

   or as it usual in Hungary

   if 24.5 dm^3 CO_2 is given by 2 mol HCl

   then 10.0 dm^3 CO_2 is given by x mol HCl

3. Calculate the amount of substance for HCl (x):

   $x\ mol = (10.0\ dm^3) \times (2\ mol) \div (24.5\ dm^3) = 0.816\ mol$

4. Convert the amount of substance for HCl into the mass of HCl using molar mass:

m(HCl) = n(HCl) × M(HCl) = (0.816 mol) × (36.5 g/mol) = <u>29.8 g</u>

Typical of this strategy that only one amount of substance (for either the given or the required) is calculated.

Strategy 4: *dimensional analysis* (factor-label method)

$x \text{ g HCl} = (10.0\ \cancel{dm^3\ CO_2}) \times [(1\ \cancel{mol\ CO_2}) / (24.5\ \cancel{dm^3\ CO_2})] \times [(2\ \cancel{mol\ HCl}) / (1\ \cancel{mol\ CO_2})] \times [(36.5 \text{ g HCl}) / (1\ \cancel{mol\ HCl})] = \underline{29.8 \text{ g HCl}}$

This is not a widely known method in Europe, however it is the most popular strategy in the US.

Strategy 5: *balance method* (a solution method without balanced chemical equation)

1. Calculate the amount of substance for CO_2 using the volume and the molar volume data:

$n(CO_2) = V(CO_2) \div V_m = (10.0\ dm^3) \div (24.5\ dm^3/mol) = 0.408$ mol

2. Write down the skeletal chemical equation:

$Na_2CO_3 + HCl \rightarrow NaCl + CO_2 + H_2O$

3. Sign the amount of substance for every substance involving the skeletal equation:

	Na_2CO_3	+	HCl	$\rightarrow$	NaCl	+	CO_2	+	H_2O
n(mol):	x		y		z		0,408		w

4. Write down the atom conservation law for C, Cl and Na:

	Na_2CO_3	+	HCl	$\rightarrow$	NaCl	+	CO_2	+	H_2O
n/mol:	x		y		z		0.408		w
n(C)/mol:	x			=			0.408		
n(Cl)/mol:			y	=	z				
n(Na)/mol:	2x			=	z				

5. Solve the obtained algebraic equations:

$x = 0.408$

$2 \times 0.408 = z$

$y = 2 \times 0.408 = 0.816$

6. Convert the amount of substance for HCl into to mass of HCl using molar mass:

m(HCl) = n(HCl) × M(HCl) = (0.816 mol) × (36.5 g/mol) = <u>29.8 g</u>

Details of the balance method are described in Tóth (1999).

Research Methodology

Instruments and subjects

For this study we developed a written test containing one complex stochiometric problem based on chemical equation (problem 5), and four simple problems (a set of ‘specific knowledge', after Lee et al., 2001) regarding molar volume (problem 1), molar mass (problem 2), chemical equation (problem 3), and proportionality (problem 4). Items of the test:

Item *'molar volume'*: using molar volume in a simple calculation,

'1. How many moles of molecule are there in 6.00 dm^3 of chlorine gas at STP? (V_m = 24.5 dm^3/mol)'

Item *'molar mass'*: using molar mass in a simple calculation,

'2. Calculate the mass of 5.00 moles of methane. (M = 16.0 g/mol)'

Item *'chemical equation'*: mole relationship based on chemical equation,

'3. How many moles of hydrogen evolves, if 0.300 mol aluminium reacts with sulphuric acid? $2\ Al + 3\ H_2SO_4 = Al_2(SO_4)_3 + 3\ H_2$'

Item *'proportionality'*: a simple proportionality problem in chemical context,

'4. The reaction of 12.0 g magnesium with sulphuric acid gives 11.21 dm^3 hydrogen. Calculate the volume of the evolved hydrogen, if 8.00 g of magnesium reacts with sulphuric acid.'

Item *'complex'*: a stochiometric calculation based on the chemical equation,

'5. How many grams of hydrochloric acid (M = 36.5 g/mol) gives 10.0 dm^3 of carbon dioxide at STP (V_m = 24.5 dm^3/mol) according to the following chemical equation? $Na_2CO_3 + 2\ HCl = 2\ NaCl + CO_2 + H_2O$'

Data were collected among the 7-10th graders (age 12-16) at 42 different Hungarian schools. The total number of students involved in this survey was 1072 (7th graders: 160; 8th graders: 210; 9th graders: 364; and 10th graders: 338). The 7th and 8th graders had 1 or 2 chemistry lessons per week, and 9th to 10th graders had 2 chemistry lessons per week. It is noted that in Hungary the stochiometric calculations based on the chemical equation are introduced in the 7th or 8th grades. Textbooks generally discuss both solving methods (mole method and proportionality method). Similar calculations are very important part of the different chemical competitions and the final examination in chemistry.

Evaluation of the responses

Responses were scored in a binary fashion, as they were right (1) or wrong (0), and these databases were used for statistical and structural analysis. Based on the strategy used in solving the complex stochiometric problem (problem 5, item 'complex') students were divided into three groups:

- group 1: mole method group;
- group 2: proportionality method group;
- group 3: others (unidentified method or no method).

It is noted that only a few students used the mixed method, and nobody was in the sample that tried to calculate the mass of hydrochloric acid via dimensional analysis.

Because of the very different population in the above groups 150-150 students were randomly selected from each group for further analysis.

For the statistical analysis we used EXCEL and SPSS softwares, and knowledge structure characteristic of each group was determined by using knowledge space theory.

Knowledge space theory

Knowledge space theory (KST) was developed by Doignon and Falmagne (1999), and its application to science concepts have been previously demonstrated by Taagepera et al. (1997, 2000, 2002), Arasasingham et al. (2004, 2005), Tóth et al. (2006, 2007, 2007a, 2007b, 2008, 2009) and Vaarik et al. (2008). In this theory, the organisation of knowledge in students' cognitive structure is described by a well-graded knowledge structure. Although KST was originally developed for modelling the hierarchical organisation of knowledge needed to answer a set of problems in science and mathematics, the formalism of this theory can be extended to any hierarchically organised input data (see for example: Tóth and Ludányi, 2007a, 2007b).

For KST analysis responses have to be scored in a binary fashion (right = 1; wrong = 0). Theoretically we can have 2^n possible response states (where n: the number of the items), from the null state where none of the problems were answered correctly to the final state where all the problems were solved. A set of response states gives the response structure. Starting from this response structure, one can recognise a subset of response states (so called knowledge structure) fitted to the original response structure at least at the $p = 0.05$ level of significance. There are several methods to find the knowledge structure from the response structure. These methods have two common features: (1) lucky-guess and careless-error parameters (most often 0.1) are estimated for each item; (2) the knowledge structure has to be well graded (e. g. each knowledge state must have a predecessor and a successor state except the null state and the final state). Based on the knowledge structure we can determine the most probable hierarchy of the items (represented by the so-called Hasse diagram) by a systematic trial-and-error process to minimise the χ^2 values. The χ^2 value calculated on the basis of the difference between the predicted and the real populations on the knowledge states in the assumed knowledge structure. For the calculations, a Visual Basic computer program (Potter, no date) was used. Details of the KST analysis were published earlier (Tóth, 2007).

Results and Discussion

Frequency and success rate of different problem-solving methods

As it was mentioned earlier, students were divided into three groups according to the problem-solving method they used.

We found that only ca. 40% of the Hungarian students used any strategy in solving the complex stoichiometric problem. Students mainly used only two methods thought at school: mole method (strategy 1) or proportionality method (strategy 2). Only a few students used the mixed method (strategy 3), and nobody tried to calculate the mass of hydrochloric acid via dimensional analysis (strategy 4) or balance method (strategy 5). Figure 1 show the distribution of the students used mole method or proportionality method or given unidentified or no answer. It is seen that the frequency of the two problem-solving strategies used by students is nearly equal to each other. It can be also seen that the number of the students using any strategy increasing only in grade 8, but there is no significance difference between the distributions in 8^{th} to 10^{th} grades.

Figure 2 shows that there is no significant difference between the total scores on the whole test (ca. 70%) of the students group applying any strategy (group 1 and 2), but the success of the student group not using any strategy (group 3) is significantly lower (ca. 20%).

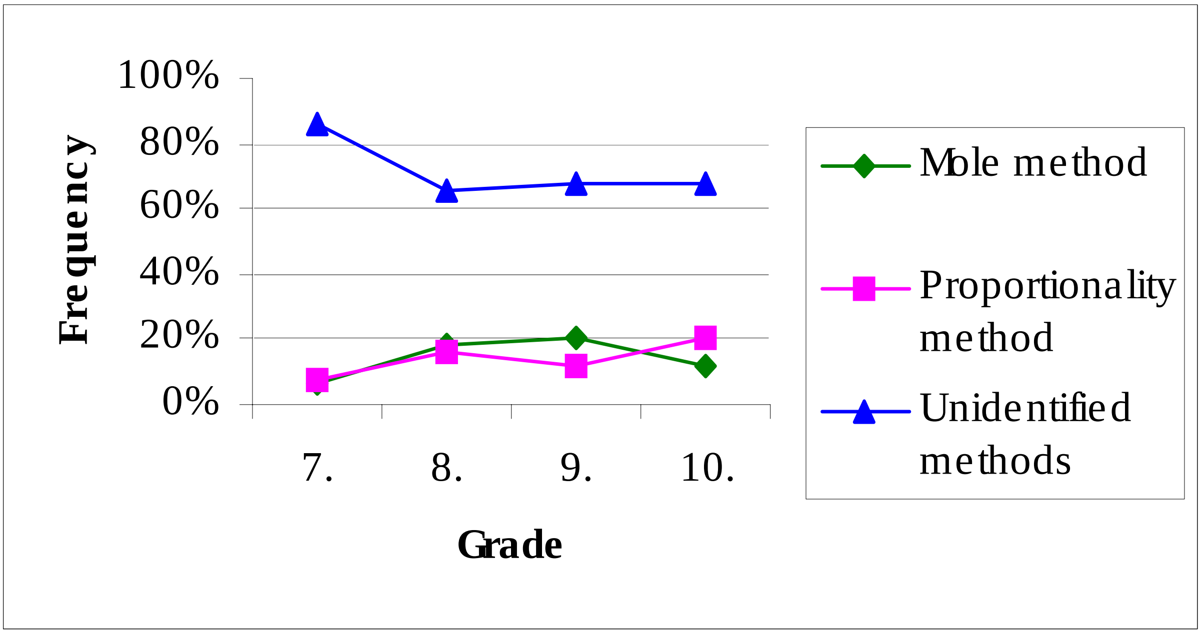

Figure 1. Frequency of different methods used by 7th to 10th graders in solving a 'complex' stoichiometric calculation based on chemical equation

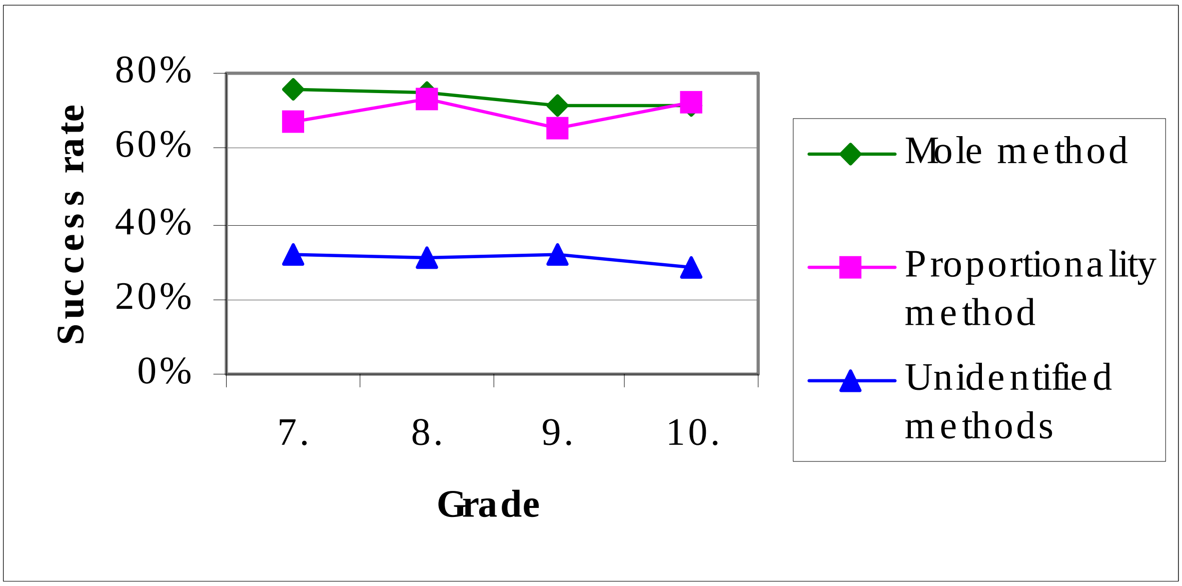

Figure 2. Success rate of 7th to 10th graders using different methods in solving a 'complex' stoichiometric calculation based on chemical equation (maximal score: 5 points)

These results show that the two applied strategies (mole method and proportionality method) are equivalent to each other both in their frequency and in success rate.

Knowledge structures of the student groups using different problem solving methods

Starting from the initial data (response structure) using a systematic trial-and-error process and χ^2 analysis, we determined the hierarchies of the concepts (problems) characteristic of the cognitive organisation of the students' knowledge (Figures 3-5). We used Hasse diagrams (see for example: Albert and Held, 1994) for the representation of these hierarchies. Accordingly, the first hierarchy in Figure 3 means, for example, that the knowledge needed to answer problem 2 ('molar mass') correctly is essential knowledge for items 2 ('molar volume') and 3 ('chemical equation'). To solve item 3 ('chemical equation') students have to have knowledge required both for item 2 ('molar mass') and for item 4 ('proportionality'). However, knowledge for problem 5 ('complex') is built on only the knowledge needed to answer correctly item 4 ('proportionality').

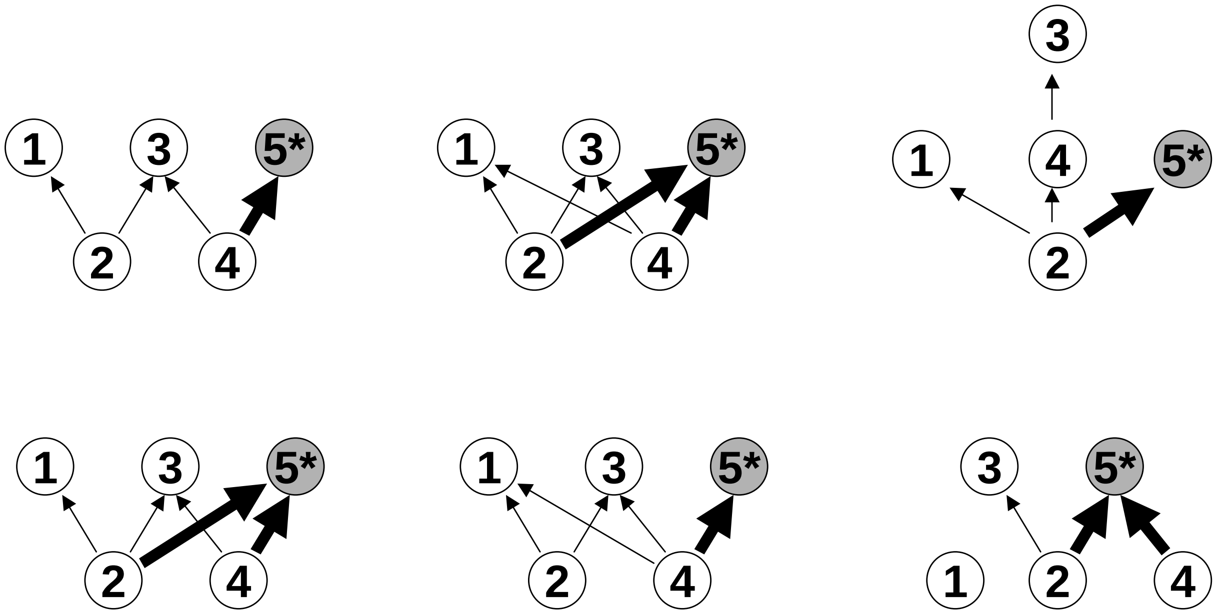

Figure 3. The best models for the organisation of knowledge in students' mind in student group 1 (mole method group) ($p < 0.02$; >98%)
1: molar volume
2: molar mass
3: chemical equation
4: proportionality
5^*: complex

Figure 3 shows that in the best models for the characteristic knowledge structure of mole method group knowledge needed to solve the 'complex' problem (item 5) correctly is built either on only the knowledge 'proportionality' (item 4) or on both 'proportionality' and 'molar mass' (items 4 and 2). And what is more, in the best models obtained in case of proportionality group (Figure 4) this 'complex' problem is built on solely knowledge 'proportionality' and is independent from the other items ('molar volume', 'molar mass', and 'chemical equation'). How can we explain these findings? It is known from several research (for example: Nurrenbern and Pickering, 1987; Nakhleh, 1993; Nakhleh and Mitchell, 1993; Cracoline et al., 2008; etc.) that students often used problem-solving strategies thought at schools as algorithms instead of the conceptual understanding. Our results underline these findings: the characteristic knowledge structures clearly show that students do not use all their specific knowledge related to the problem they want to solve.

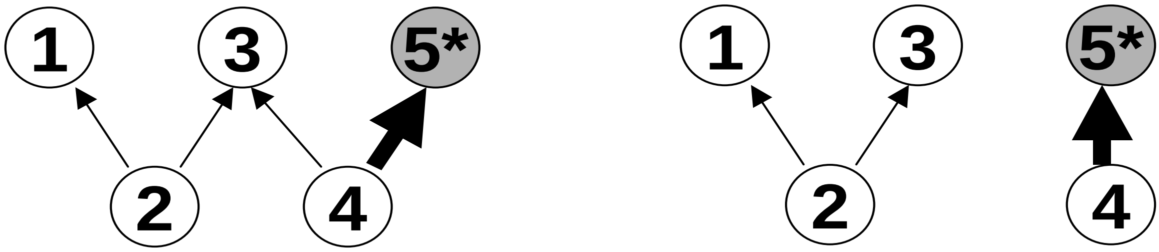

Figure 4. The best models for the organisation of knowledge in students' mind in student group 2 (proportionality method group) ($p < 0.001$; >99.9%)
1: molar volume
2: molar mass
3: chemical equation
4: proportionality
5*: complex

In contrast, the models (Figure 5) obtained for the student group 3 (unidentified or no strategy in solving 'complex' problem) are very similar to the experts' knowledge structure: the knowledge needed to solve the 'complex' problem (item 5) is built on all of the elementary knowledge ('molar volume', 'molar mass', 'chemical equation', and 'proportionality'). However, as it is shown in Figure 2, the success of these students are much more lower than that of the students using one of the algorithms. These results are agreement with the findings of Lee et al. (2001) that specific knowledge is only one of the variables among the cognitive variables required for successful problem solving.

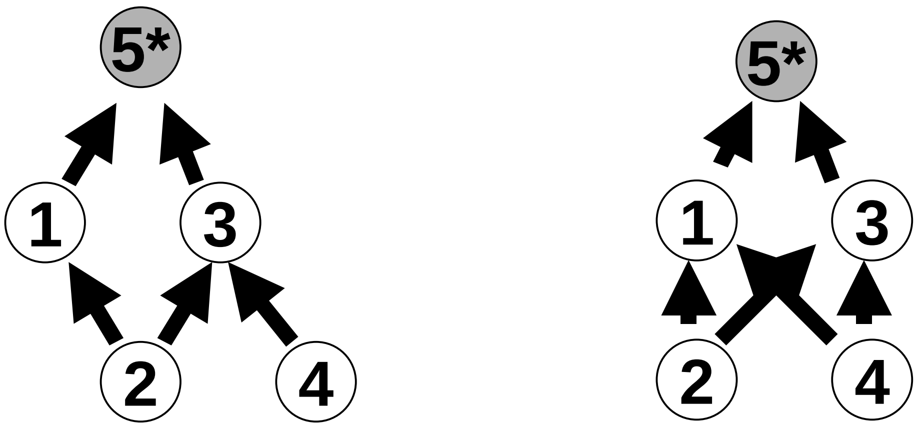

Figure 5. The best models for the organisation of knowledge in students' mind in student group 3 (unidentified or no method group) ($p < 0.005$; >99.5%)
1: molar volume
2: molar mass
3: chemical equation
4: proportionality
5*: complex

It is noted that in all the models for characteristic knowledge structure independently the applied problem-solving method the 'molar volume' (item 1) is built on the 'molar mass' (item 2). It is also great agreement with our early results on mapping students' knowledge structure in understanding density, mass percent, molar mass, molar volume and their application in calculations. KST analysis of the responses also showed a very strict hierarchical connection between molar mass and molar volume: in students' cognitive structure the concept of molar volume is always built on the concept of molar mass (Tóth, 2007).

Conclusions

The results and conclusions of our study can be summarised as follows:

1. Hungarian secondary school students apply two strategies thought at schools for solving stoichiometric calculations based on the chemical equation. However, only ca. 40% of the students used any of the two strategies (mole method or proportionality method).
2. These two strategies were equivalent to each other both in their frequency and in success rate.
3. We found significant difference between the knowledge structure of the three student groups using different strategies or unidentified method. The knowledge structure of student group 3 (unidentified or no method) was very similar to the experts' knowledge structure. However these students' success was very low indicating that the specific knowledge is only one of the cognitive variables required for successful problem solving.
4. In the knowledge structures of the student groups using any strategy (groups 1 and 2) the knowledge needed to answer the 'complex' problem (item 5) is built on either only 'proportionality' (in case of proportionality method group), or on both 'proportionality' and 'molar mass' (in case of mole method group). This finding shows, that students typically use the strategies thought in school as algorithms instead of the conceptual understanding. Therefore teachers and textbook authors should pay much more attention to the conceptual understanding during the chemical calculations.

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