

Combination of Phenomenography with Knowledge Space Theory to study students' thinking patterns in describing an atom[†]

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Abstract: This study compares Hungarian 7th to 11th graders' and American 9th to 11th graders' thinking patterns in describing an atom. A new evaluation method, the combination of phenomenography and knowledge space theory was used to explore students' reasoning and to follow the change in students' cognitive structures. According to the phenomenographic analysis of the responses, three main categories, 'units of matter', 'constituents of atoms' and 'model of atoms', were identified. Connections between these categories were determined by adapting Knowledge Space Theory to the hierarchy of categories. Results showed that during the instruction, the initial uniform model for representation of students' knowledge structure became more diffuse but at the end of the instruction the organisation of the categories in students' minds could be represented again by a single model. In the initial model, the 'units of matter' category was independent of the 'constituents of atoms' and 'model of atoms' categories, and the 'model of atoms' category was built on the category 'constituents of atoms'. Significant change in connections among categories could be detected only in the case of Hungarian students. In the reasoning of Hungarian 11th graders, the hierarchy between 'constituents of atoms' and 'model of atoms' was reversed. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 327-336.]

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Introduction

The atomic hypothesis is a primary concept of scientific knowledge. When we teach about atoms, we give the key to unlock many of the doors of the sciences. However, there is a lack of agreement about when students should be introduced to the concepts of an atom and molecule. There is a view (AAAS, 2001; Taber, 2002) that says the ideas should be left until near the end of the secondary school, because only a few students can comprehend the idea of atomic and molecular particles. Research in science education during the last twenty years has shown students' difficulties and misconceptions about the atom concept (see for example: Lee at al. 1993; Harrison and Treagust, 1996; Taber, 2002; Cokelez and Dumon, 2005), as well as the problems and possibilities of teaching the atom concept (see for example: Tsaparlis, 1997; Toomey at al. 2001; Nelson, 2002; 2003; Tsaparlis and Papaphotis, 2002).

Unal and Zollman (1999) investigated students' ideas about an atom using phenomenography as research method. They did not attempt to develop a catalogue of students' misconceptions of atoms. Instead, they were interested in learning how students describe atoms when they are presented with an open-ended question. Responses were evaluated not as 'right' or 'wrong' but with identifying categories using an iterative process.

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Students' descriptions fell into six categories; three of these ('Units of matter', 'Constituents of atoms' and 'Model of atoms') were used to classify students' reasoning levels in a hierarchical system suggested by the authors. Their research showed that in describing the atom, most of the students fall into a low hierarchical level of reasoning categories. The majority of the students did not include an atomic model in their descriptions of an atom. The authors established that students did not seem to retain what they have learned from previous courses or years.

This paper (Unal and Zollman, 1999) initiated our present work on studying students' thinking patterns in describing an atom. In addition to evaluating data of our survey among Hungarian students, data in the Unal and Zollman's paper were subjected to a secondary analysis. Thus, we could compare the characteristic thinking patterns and their changes between Hungarian and American students. Furthermore, we tried to use a new evaluation method, combination of phenomenography with knowledge space theory to explore students' reasoning about an atom.

Phenomenography

Phenomenography is an area of research which focuses on identifying and describing the qualitatively different ways in which people understand phenomena in the world around them (Marton, 1981, 1986). The major premise of phenomenography is that although individuals will have different experiences and conceptualisations of a phenomenon in a given context, the number of qualitatively different conceptualisations is limited. These different conceptualisations are the focus of a phenomenographic study rather than each individual learner's conceptualisations. One major assumption of phenomenography is that individuals can accurately express their experiences and conceptualisations.

Once the data for a group of individuals has been collected, it is then organised and reviewed several times in order to identify the limited number of ways a phenomenon has been experienced and conceptualised. There are three main principles for this identification process: (1) categories should be extracted from the student's responses; (2) categories should not be mutually exclusive or inclusive, but distinguishable; (3) responses must be explicit to be capable of being categorised. These categories of description are the main outcome of the research. The categories often are presented in increasing levels of understanding.

Phenomenography is different from other qualitative approaches (e.g. field research, grounded theory, etc.) in its major premise, the assumption (cited above) and the principles for categorisation.

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), and Tóth and Kiss (2006). 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. In the study reported here we combined phenomenography with KST.

For this analysis, responses were scored in a binary fashion, according to whether they contained the given category (1) or not (0). As we construct three-item groups from the categories, theoretically we can have 8 (2^3) possible response states, from the null state [0] where none of the above categories were used to the final state [Q] where all the categories appeared in the student's description. A set of response states for a student group 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: (i) lucky-guess and careless-error parameters (most often 0.1) are estimated for each item; (ii) the knowledge structure has to be well graded (e.g. each knowledge state must have a predecessor state 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 categories (represented by the so-called *Hasse diagram*) by a systematic trial and error process to minimise the χ^2 value. (The χ^2 value was 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) was used. Details of the KST analysis will be presented in the Results and discussion section.

The aim of the study

We used KST to explore the connections among the categories obtained from the phenomenographic analysis of students' responses and to answer the following research questions:

1. What is the characteristic hierarchy of the categories regarding the concept of the atom?
2. Is there any change in students' thinking patterns during their instruction?
3. Is there any difference and similarity between the Hungarian and American students' ideas about an atom?

Research methodology

Instruments and subjects

Students were asked - among other items - to describe an atom on a paper-and-pencil questionnaire: 'Describe the following concepts: atom, molecule, ion etc.'

Data were collected at the end of the school year of 2002/2003. A random sample of 724 out of 2954 Hungarian secondary school students (grades 7 to 11, age 13 to 17) from 17 schools participated in the test. (7th graders: 171, 8th graders: 165, 9th graders: 136, 10th graders: 135 and 11th graders: 117.) The 7th graders have 1 or 2, 8th to 10th graders have 2 chemistry lessons per week, respectively. Just a few students have chemistry lessons in the 11th grade. It is noted that in Hungary the concepts of atoms and molecules are introduced in the 7th grade. Hungarian chemistry textbooks give various definitions of an atom in grade 7: (1) an atom could not be divided up; (2) the atom could not be divided by chemical methods; (3) constituents (protons, neutrons, electrons) of an atom; (4) simple models (Rutherford, Bohr) of an atom. In the 9th grade, chemistry textbooks (and lessons) deal with the basic quantum mechanical description of an atom. Later each book completes the description of the atom but does not give new definitions.

Data about the American students were obtained from the paper of Unal and Zollman (1999). In their survey a total of 239 high school students were asked to describe an atom at the end of the Spring Semester of the 1995/96 academic year. Most of the students in all grade levels were taking or had taken a physical science course at the time of the survey. The majority of the 11th and 12th graders were taking a chemistry course. In our research the data of the students in grades 9-12 (9th graders: 69, 10th graders: 51, 11th graders: 88 and 12th graders: 29) were used.

Results and discussion

Categorisation of the students' responses

Similarly to the Unal and Zollman (1999) results, students' responses were divided into six categories: (0) No response; (1) I don't know; (2) Units of matter; (3) Constituents of atoms; (4) Model of atoms; (5) Other. Among these categories 'Units of matter', 'Constituents of atoms' and 'Model of atoms' were used for further analysis.

Response was marked with 'Units of matter' (*U*) if the student defined the atom as a constituent (or the smallest particle) of matter. For example, 'An atom is the smallest particle/unit of matter.' 'An atom can not be divided chemically.'

The 'Constituents of atoms' (*C*) category includes students' responses containing the name of the constituents of an atom. For example, 'An atom contains electrons, protons and neutrons.' 'The atom is a neutral particle involving electrons, protons and neutrons.'

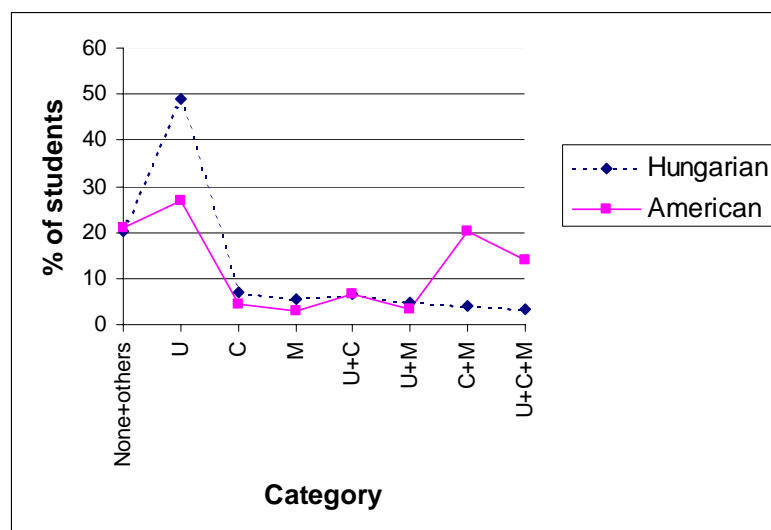
When the student described any atomic models his or her response was listed into the category 'Model of atoms' (*M*). For example, 'An atom consists of a nucleus and an electron cloud around it.' 'In an atom electrons circle around the nucleus.' Note, that in spite of the fact that chemistry textbooks for 9th graders discuss the basic principles of the quantum mechanical models, practically none of the students used these terms (e. g. atomic orbital, electron density, quantum numbers etc.) in describing an atom.

All possible combinations of the above three categories (*U*, *C*, *M*, *U+C*, *U+M*, *C+M*, *U+C+M*) were detected in the students' responses.

Frequency and distribution of the students in the categories and their combinations

Figure 1 shows the students' distribution in each category and combination of categories. Both similarity and significant difference can be seen in distribution of Hungarian and American students. The similarity is that the proportion of the students is the same in the category 'None + Others', is the highest in category 'Units of matter', and is low in categories 'Constituents of atoms', 'Model of atoms', 'Units of matter + Constituents of atoms' and 'Units of matter + Model of atoms'. However, the percentage of American students is much higher in categories 'Constituents of atoms + Models of atoms' and 'Units of matter + Constituents of atoms + Model of atoms' than the percentage of Hungarian students. These general features of the distribution curves do not change significantly through the grade levels (Table 1).

Figure 1. Comparison of Hungarian and American students' distribution in each category or combination of categories



The differences between the Hungarian and American students in the distribution of categories can be explained by the different instructions regarding the atomic concept. As mentioned earlier, Hungarian students learn about the atom in chemistry courses, while the American students who participated in the Unal and Zollman's survey learned the atomic concept mainly in physical science courses. "...most of the students in all grade levels were taking or had taken a physical science course at the time of our survey. The majority of 11th and 12th graders were taking chemistry. Almost half of the 12th graders and a few 11th graders had taken or were enrolled in the high school physics course" (Unal and Zollman, 1999, p. 6). Physicists emphasise the constituents and the models of the atom rather than the indivisibility, and the smallest particle as well as the units of matter characters of the atom.

Table 1. Students' distribution in each category or combination of categories.

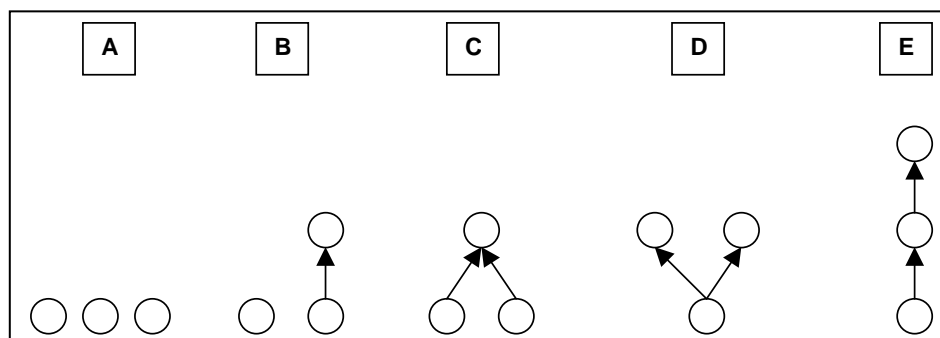
Grade level	Hungarian students					American students			
	7 th	8 th	9 th	10 th	11 th	9 th	10 th	11 th	12 th
None + others	22%	25%	18%	16%	20%	20%	25%	18%	24%
U	48%	49%	49%	47%	52%	12%	33%	36%	24%
C	8%	7%	2%	12%	4%	6%	4%	4%	7%
M	6%	8%	7%	1%	3%	3%	6%	2%	0%
U + C	6%	4%	10%	8%	5%	9%	2%	10%	0%
U + M	1%	3%	4%	8%	10%	4%	2%	4%	3%
C + M	5%	3%	5%	4%	3%	26%	16%	16%	28%
U + C + M	4%	1%	5%	4%	3%	20%	12%	10%	14%

U: Units of matter; C: Constituents of atoms; M: Model of atoms.

Hierarchy of the categories

Unal and Zollman (1999) in their paper suggest the following hierarchical structure of the categories: 'Units of matter' → 'Constituents of atoms' → 'Units of matter + Constituents of atoms' → 'Model of atoms' → 'Units of matter + Model of atoms' → 'Constituents of atoms + Model of atoms' → 'Units of matter + Constituents of atoms + Model of atoms'. This is a so-called expert's hierarchy. However, we are interested in the hierarchy of the categories which is characteristic of the students' group at different grade levels. Theoretically there are 19 possible connections between three categories (Figure 2) from the totally separate state (A) to the strictly hierarchical order (E). Among these hierarchical schemas we tried to find the one(s) fitted best to the input data (response structure of the students' group) using KST analysis as follows.

Figure 2. Theoretically possible schemas for connection between three categories (Number of variations in schemas: A = 1; B = 6; C = 3; D = 3; E = 6).



Using KST for determining the connection between the categories

As an example, let us consider the case of Hungarian 7th graders. Table 2 contains the response states of the Hungarian 7th graders in binary fashion, which is the first input file for the calculations. The second one contains the knowledge states derived from one of the connection schemas we assumed as a model for describing the organisation of the categories in students' cognitive structure. For example, Figure 3 shows one possible hierarchy of categories with the knowledge structure and knowledge states.

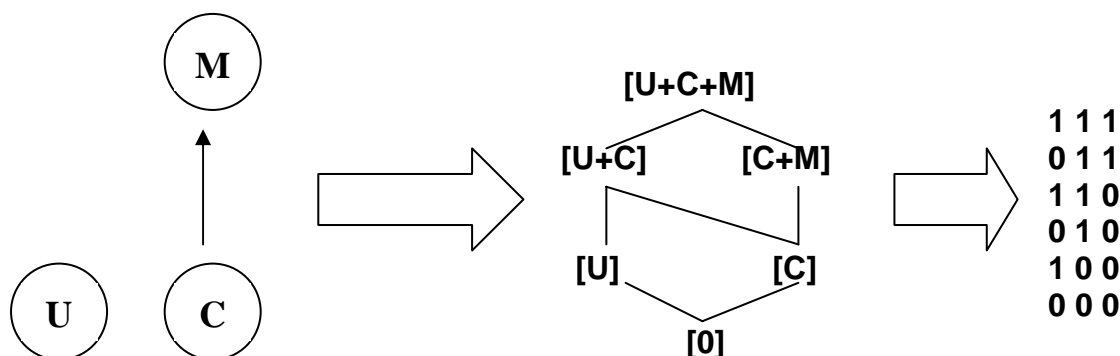
We used Hasse diagrams for presentation of this hierarchy. How should these be read? Hierarchy in Figure 3 means, for example, that the knowledge (category) 'Models of the atom' is built on the knowledge (category) 'The constituents of the atom', but both the categories 'Models' and 'Constituents' are separated from the knowledge (category) 'Unit of matter'. It means that one does not need to know that an atom is a small unit of matter before describing the constituents and the models of an atom, but one does need to know the constituents of an atom before describing the models of an atom. From this Hasse diagram we can deduce the assumed knowledge structure as it is shown by the Figure 3.

The second input file also contains the estimated probabilities of lucky-guess and careless error. In KST analysis we used 0.1 (10%) value for each parameter.

Table 2. A set of response states of Hungarian 7th graders.

Units of matter	Constituents of atoms	Model of atoms	Number of students
0	0	0	38
1	0	0	81
0	1	0	14
0	0	1	11
1	1	0	11
1	0	1	2
0	1	1	8
1	1	1	6

Figure 3. Deriving knowledge states and knowledge structure from the hierarchy of categories.



In the output file (Figure 4) we can see the two input files ('Response states' and 'Knowledge states') and the knowledge states in the assumed knowledge structure, the calculated probabilities of these knowledge states ('Prob'), the predicted populations ('Pred Pop'), the original populations ('Pop') and the χ^2 value ('Chi Sq') for each knowledge state, and finally the total χ^2 ('ChiSqT'). This total χ^2 together with the degree of freedom characterise the degree to which the assumed knowledge structure fits to the original response structure. The degree of freedom (d. f.) can be calculated as follows: d. f. = the number of knowledge states in the knowledge structure + the number of estimated parameters (lucky-

guess and careless error) – 1. The numbers appearing on the first column in the output file are the codes of the knowledge states in decimal system. The last column in the input file ('Response states') shows the real population. Because of the similar form of the other input file ('Knowledge states') we used zeros for creating this last column.

Figure 4. A typical output of KST analysis using Potter's software.

Response states:					
0	000	38			
4	100	81			
2	010	14			
1	001	11			
6	110	11			
5	101	2			
3	011	8			
7	111	6			
Knowledge states:					
0	000	0			
4	100	0			
2	010	0			
6	110	0			
3	011	0			
7	111	0			
n=8	m=6	Population =171			
Knol.st.	Prob	Pred Pop	Pop	Chi Sq	
0	000	0.24609	42.08157	38	0.39588
4	100	0.42811	73.20646	81	0.82970
2	010	0.10595	18.11735	14	0.93571
6	110	0.11226	19.19698	11	3.50006
3	011	0.05992	10.24616	8	0.49240
7	111	0.04767	8.15148	6	0.56786
ChisqT(6)= 6.722					

Hungarian students' knowledge structure

Figure 5. The best models for representation of Hungarian students' knowledge structure.

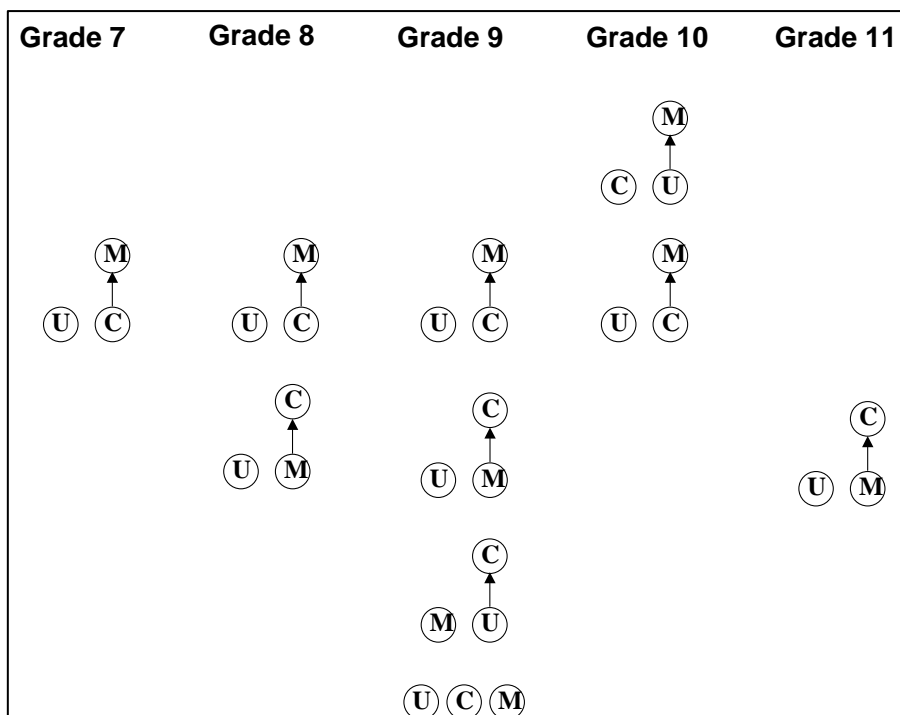
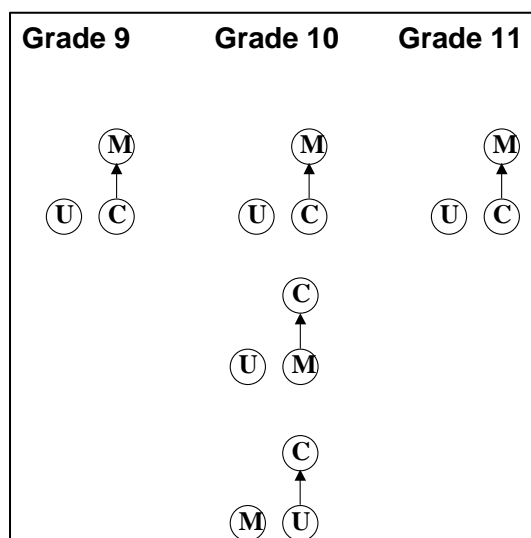


Figure 5 summarises the results of the KST analysis in the case of Hungarian students. It can be seen that there are some significant changes in the best models through the grade levels. The number of the best models for organisation of knowledge is varied with the grade levels. Only one model was found in the case of 7th and 11th graders, but in contrast, the organisation of knowledge could be described with two equivalent models in the case of 8th and 10th graders, and in addition we found four models in the case of 9th graders. These suggest that from the viewpoint of knowledge structure students' groups are uniform at the beginning of the chemical studies (in grade 7). Moving forward in their instruction students' knowledge structure becomes more complex, and in grade 9, where students study the models of an atom in detail, this organisation of knowledge is the most complex one. In grades 10 and 11 a unification process is taking place, and at the end of their chemistry studies (in the 11th grade) the knowledge structure of the students again becomes uniform. Figure 5 also shows that there is a change in the knowledge organisation from 7th to 11th grades. In the early chemistry courses the category 'model of atoms' is built on the category 'constituents of atoms', and the category 'units of matter' is independent of the other two categories. After changes in connections between the categories, at the end of their chemistry studies in students' mind the category 'units of matter' remains independent of the categories 'constituents of atoms' and 'model of atoms', but the connection between the two latter categories is reversed. In contrast to the knowledge structure of the 7th graders, the category 'model of atoms' becomes fundamental in the knowledge structure of the 11th graders.

American students' knowledge structure

We found similar trends in changes in the number of the best models in the case of American 9th to 11th graders (Figure 6). The results of the KST analysis of 12th graders were omitted because of the small number of the students ($N = 29$) in this group. In contrast to the patterns with the Hungarian students, KST analysis could not show any lasting change in the knowledge structure between the 9th and 11th graders. Similarly to the Hungarian 7th graders in the characteristic model the category 'units of matter' is independent of the other two categories, and the category 'model of atoms' is built on the category 'constituents of atoms'. This is a typical shape of the process of conceptual change. The initial model is a simple one but during the instruction this model becomes more complex and finally 'crystallises' the new model.

Figure 6. The best models for representation of American students' knowledge structure.



Conclusions and implications for teaching

Using phenomenography combined with knowledge space theory we could study the main categories of students' descriptions about an atom and the characteristic hierarchies between these categories. Our results can be summarised as follows.

1. Both the Hungarian and American students' responses to describe an atom fell readily into six categories: 'No response'; 'I don't know'; 'Units of matter'; 'Constituents of atoms'; 'Model of atoms'; and 'Other'. From these categories 'Units of matter', 'Constituents of atoms' and 'Model of atoms' were used for further analysis.
2. We established that the percentage of American students is much higher in categories 'Constituents of atoms + Models of atoms' and 'Units of matter + Constituents of atoms + Model of atoms' than that of the Hungarian students', and this general feature of the distribution does not change significantly through the grade levels. The differences between the Hungarian and American students in the distribution of categories can be explained by the different instruction regarding the atomic concept: Hungarian students learned the atomic concept in chemistry courses, while the American students learned it mainly in physical science courses.
3. Using knowledge space theory (KST) we could find the best models among the theoretically possible schemas for representation of connection between the three categories. Results show that during the instruction the initial uniform knowledge structure of the students becomes more diffuse, the number of the best models increases but at the end of the instruction the organisation of the categories in students' mind can be represented again by one model.
4. In the initial model 'Units of matter' category is independent from the 'Constituents of atoms' and 'Model of atoms' categories, and there is only one connection between the latter two categories: the category of 'Model of atoms' is built on the category of 'Constituents of atoms'. (This is a very acceptable model of describing an atom: one does not need to know that an atom is a small unit of matter before describing the constituents and the models of an atom.) Although the connection between the categories changes with the instruction, the initial model remains the same in the case of American students. In contrast, in the characteristic model of the Hungarian 11th graders the hierarchy between the categories of 'Constituents of atoms' and 'Model of atoms' reverses, and the 'Constituents of atoms' category is built on the 'Model of atoms' category.
5. These results show that even though the instruction brings about significant changes in students' knowledge structure, the final model is the same or very similar to the initial model in hierarchy between categories used by the students when describing an atom.
6. Our work demonstrates that combination of phenomenography and knowledge space theory is a powerful method for exploring students' thinking patterns.

The small effect of the instruction on the initial thinking patterns of the students regarding the description of an atom shows that teachers and textbooks authors should pay much more attention to the description of the atom. It is not enough to give a definition of the atom at the beginning of the instruction and to complete the description without giving newer and newer definitions. Our results of the survey among Hungarian students show that most of them like to use definitions. Because their 7th grade chemistry textbooks define the atom in as the unit of matter, Hungarian students use this definition even at the end of their instruction, in the 11th grade, too. There could be considerable benefit gained from teachers revisiting some of the fundamental concepts in subsequent years, perhaps by offering more sophisticated definitions, to bring their students' understanding of these into line with what they had learned in their later studies.

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