

Using Concept Maps in Teaching Organic Chemical Reactions

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Abstract

An elaborated concept map that includes reactions of three types of organic molecules: hydrocarbons, organic halides and oxygen-containing compounds, can be used as a tool for teaching and learning organic chemistry at the secondary school level. A concept map can enable a better construction of cognitive structure, including concepts and correlations between them. At some point in the teaching/learning process the elaborated concept map can facilitate problem solving and in completing reaction schemes.

Key words: concept map, oxidation number of carbon atom, transformations, problem solving, meaningful learning

Introduction

Concept maps are visual/spatial representations of ideas and concepts as well as their interrelationships. They are “tools intended for organizing what the learner knows” and for “engaging learners in relating new ideas to what they already know”.¹ The latter concept is central to Ausubel’s² assimilation theory for meaningful learning,^{3,4} and for Deese’s⁵ association memory theory.

The concept map is a graphic metacognitive tool,^{6,7,8} which provides an external representation of structural knowledge – a visual image – in the form of a two-dimensional semantic network.^{9,10} The concept maps developed by Novak and Gowin,¹¹ which represent scientific concepts graphically, should be: (1) hierarchical with superordinate concepts at the apex; (2) labelled with appropriate linking words; (3) crosslinked so that relations between sub-branches of the hierarchy are identified. The hierarchy expands according to the principle of progressive differentiation. New concepts and new links can be added to the hierarchy, thus creating new branches or differentiating among the existing ones.

A concept map is a structural representation consisting of nodes and labelled lines. The nodes correspond to the concepts in the domain. The lines denote a relation between a pair of concepts (nodes); and the combination of two nodes and the label on the line is informative on how the two concepts are related. The combination of two nodes and a labelled line is

called a proposition. A proposition is the basic unit of meaning in a concept map and the smallest unit that can be used to judge the validity of the relation (line) drawn between two concepts.^{12,13} Typically, these maps have a vertical and horizontal hierarchical structure. The vertical hierarchy is reflected downward from general to more specific concepts, with appropriate relationship linkages along the way. In the horizontal hierarchy, related concepts are structured along the same horizontal line. This hierarchical structure can be represented by the ordered-tree technique. Then there are also the so-called circular concept maps,¹⁴ which consist of concentric circles expanding from the general concept in the centre. The farther the circular line is from the centre, the less specific are the concepts positioned along it (vertical hierarchy). In this map, related concepts are to be found along the same circular line (horizontal hierarchy). When complex concepts are being represented with a concept map, the map is divided into individual modules.

Concept maps have been used extensively and have been validated for designing instructional units and curriculum materials to facilitate inquiry-based science, and are well suited for science instruction,^{15,16,17} problem solving, and for presenting students with meaningful knowledge as well as for promoting positive attitudes.^{18,19}

Research has established a relationship between concept mapping and student achievement,²⁰ and it is worth determining whether students who are exposed to concept maps throughout their general chemistry

course do in fact make more connections between concepts than those not exposed to concept maps in this way. Concept maps are potentially powerful tools with which conceptual change can be effected.^{21,22} According to Novak,²³ conceptual change is necessary for meaningful learning to occur. Meaningful learning requires well-organised relevant knowledge structure and high commitment to finding the relationship between new and existing concepts. When concept maps are used to facilitate learning, they serve as metacognitive tools. Concept mapping requires students to identify important concepts and show how they are interrelated. It enables them to give personal meaning to subject content by thinking in multiple directions. In this manner, concept mapping is helpful in promoting meaningful learning. Some research studies related to concept mapping indicated that concept mapping had positive effects both on students' achievement as well as on their attitude.^{24–27}

The present study deals with the difficulties third year high school students (17 years old) experience in understanding organic reactions. An analysis of how they arrived at solutions to tasks involving organic reactions of hydrocarbons, organic halides and organic oxygen-containing compounds indicated that they were acquainted with individual organic reactions but were incapable of relating them with one another. There was evidence of familiarity with how to write individual reaction schemes but not the circumstances under which these reactions occur. It therefore becomes evident that students simply memorise how to write the reactions schemes. For example, products of individual reactions can be reactants for other reactions, but such relationships are often not understood. On this basis it is clear that in learning organic reactions a level of meaningful learning remains unattained. In order to improve students' understanding, concept maps presenting the interrelationships among organic reactions of hydrocarbons, organic halides and organic oxygen-containing compounds have been developed. We believe that their inclusion in instruction will prompt a cognitive conflict in the students, which in turn will bring about conceptual change and finally enhance meaningful learning.

Method

The elaborated concept map includes reactions for three types of organic molecules. The starting point for the elaboration of the concept map is the oxidation number of a carbon atom. In order to determine the oxidation number of a carbon atom, one must take into account the electronic affinity of the carbon atom as compared to the hydrogen atom or a hetero atom. This number is determined so that for each bond between

a carbon atom with a hydrogen atom a value of -1 is utilized, for each bond with another carbon atom the value is 0 , and for each bond with a hetero atom (halogen, oxygen, nitrogen, sulphur) the value is $+1$. Thus a carbon atom can have the oxidation number -4 (as in the case of methane) and all oxidation numbers up to value $+4$ (as in the the case of carbon dioxide). Changes connected with the changing of oxidation numbers from -4 to $+4$ represent oxidations, changes in the opposite directions represent reductions.

The methane molecule (carbon oxidation number = -4) can be transformed into halogenomethane by a radical halogenation reaction. In this resultant molecule, the oxidation number of the carbon atom = -2 , so halogenation reaction represents oxidation at the carbon atom with the halogenating molecule functioning as an oxidizing agent. The substitution of the halogen atom with the hydroxyl group causes the formation of methanol. In this molecule, the oxidation number of the carbon atom is also -2 , which means that the conversion is neither an oxidative nor a reductive process at the carbon. The reaction of converting methanol to methanal takes place with an acidic solution of potassium dichromate(VI). In the methanal molecule, the oxidation number of the carbon atom is 0 . Thus the reaction is an oxidation, with potassium dichromate(VI) as an oxidising agent. The further reaction of methanal with acidic solution of potassium dichromate(VI) leads to the formation of methanoic acid in which the carbon atom has the oxidation number $+2$. Here is again a case of oxidation with potassium dichromate(VI) as the oxidant. The conversion of methanoic acid into carbon dioxide and water, with the carbon atom having the highest oxidation number, represents the final stage of oxidation.

The change of oxidation numbers of a carbon atom can be used for the explanation of the reversed sequence of conversions. By using specific reducing agents, we can convert methanoic acid into methanal, the reaction of methanal with LiAlH_4 leads to the formation of methanol, which can be converted into a halomethane by reaction with PX_3 . This conversion does not effect a change in the oxidation number of the carbon atom, which remains -2 , and therefore does not represent reduction. Catalytic hydrogenation of halomethane then results in methane, which has the lowest oxidation number value and represents the most reduced form of an organic molecule.

The carbon atom of the methyl group has the oxidation number -3 . Using a similar set of conversions at this carbon atom as in the case of methane, the oxidation number is changed from -3 to -1 after radical halogenation and from -1 to $+1$ and from $+1$ to $+3$ after step-by-step oxidation resulting in aldehyde or carboxylic acid formation.

The carbon atom of the methylene group (secondary carbon atom) can have the oxidation number -2 . It is connected with two carbon atoms with single bonds or a carbon atom of the methylene group with a double bond. Conversions of the methylene group differ from those of the methyl group in that after radical halogenation the halogen atom is bonded to the secondary carbon atom, which, after hydrolysis, results in the formation of secondary alcohol. Further oxidation results in the formation of a ketone. This can be oxidized only under strenuous reaction conditions, wherein oxidation involves breaking of the carbon–carbon bond. The methylene group on the other hand, which is a constituent of the carbon–carbon double bond, can undergo addition reactions. The addition of hydrogen halides in cases when reaction takes place according to the anti-Markovnikov rule results in the formation of a saturated compound, which has a halogen atom bonded to this carbon atom. Here the oxidation number of the carbon atom changes from -2 to -1 , which means that this carbon atom undergoes an oxidation. All further conversions are analogous to the conversion of the methyl group. In the case of the halomethylene group, a reverse reaction, i.e. the elimination of hydrogen halogenide can occur. This happens with a base and results in the formation of the corresponding alkene. Since the value of the oxidation number of the carbon atom bonded to the halogen atom is reduced, this reaction is a reduction.

The oxidation number for a tertiary carbon atom in CH group, which is bonded with three carbon atoms with single bonds, or the carbon atom of $-\text{CH}=\text{}$ group connected by double bond with another carbon, or a carbon atom of $\text{CH}\equiv$ group being connected by a triple bond to another carbon, is -1 . Radical halogenation of the tertiary carbon atom leads to the formation of a corresponding halide. The hydrolysis of this halide results in the formation of a tertiary alcohol. In this reaction, the oxidation number of the carbon atom does not change and remains in both cases $+1$. Thus, this transformation is an oxidation although an oxygen atom has been added. The oxidations of tertiary alcohols can take place only under very vigorous reaction conditions and are therefore similar to the oxidations of ketones wherein breaking of the carbon–carbon bond must occur.

The oxidation number 0 can appear in a carbon atom of a double bond, bonded with two more alkyl groups. The addition of hydrogen halides following Markovnikov's rule causes the formation of alkyl halide with a halogen atom bonded to the tertiary carbon atom. Thus, this carbon atom undergoes oxidation since its oxidation number changes from value 0 to value $+1$. Further transformations of this halide are analogous to the transformations mentioned earlier in

connection with the radical halogenation at the tertiary carbon atom. Higher oxidation numbers, numbers $+2$ and $+3$, are present mainly in compounds where several heteroatoms are bonded to the carbon atom or if the carbon atom is bonded via a double bond (carbonyl group), or via a triple bond (cyano group) to a heteroatom. These transformations have been discussed together with the previous ones, since the aldehydes as well as ketones and carboxylic acids appear as oxidation products of previously mentioned compounds.

Results and discussion

The applicability of the concept map (Scheme 1) is in the identification of possible transformations and conditions under which they can occur. One can move along the concept map either in the vertical or in the horizontal direction.

Vertical movement along the concept map from top downwards pertains to transformations of the carbon atom with oxidation numbers from -4 to $+4$ and represents oxidation of this centre. Such changes can be effected when there is an oxidising agent present in the reacting mixture. Vertical movement along the concept map from bottom upwards pertains to transformations of the carbon atom with oxidation numbers from $+4$ to -4 . Since only the carbon atom in the carbon dioxide molecule has the oxidation number $+4$, the map starts with the oxidation number $+3$ of the carbon atom in carboxylic acids and their derivatives. Changes of the carbon atom oxidation number from $+3$ to -4 represent a reduction which happens only in the presence of a reduction agent.

Horizontal movement along the concept map pertains to transformations where the oxidation number of the atom does not change. It does, however, effect a change in the nature of the functional group. Thus, for example, an alkyl halide can yield a corresponding alcohol or vice versa. Similarly, transformation of the carboxylic acid to the corresponding acid halides, anhydrides, esters and amides does not alter the oxidation number of the carbon atom in this group. It does, however, represent a reaction connected with the change of the nature of the functional group.

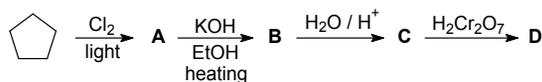
Another advantage of the concept map (Scheme 1) is also the fact that one can enter it at any position, even in the middle. The direction of movement selected then, depends on the chosen reaction conditions.

Conclusions and implications for chemical education

The applicability of the concept map can be demonstrated with the solution of the problem task shown below.

Task

Complete the reaction scheme.



This is a typical example of a task where, on the basis of the given starting compound and reaction conditions for the individual steps, the student is asked to identify intermediate as well as the end products (Scheme 2). Table 1 presents tested concepts and content clusters included in the task. According to Bloom's scale, the cognitive stage is knowledge synthesis.

Tested concepts	Content clusters
Radical substitution	Reactivity of organic compound molecules
Hydrolysis of haloalkanes	From hydrocarbons to alcohols <ul style="list-style-type: none"> Defining and presenting the impact of the reagent substrate and reaction conditions on the breaking of the bond Hydrocarbons and halogenated derivatives
Addition of water to alkenes	Electrophilic additions to multiple bonds
Oxidation of secondary alcohols	From alcohols to acid derivatives <ul style="list-style-type: none"> Oxidation and oxidizing alcohol decomposition

Solving the task**Stages in the process**

1. The initial compound is cyclopentane. This molecule is comprised of methylene groups where the carbon atom has the oxidation number -2 . The first stage of the reaction is chlorination of cyclopentane in the presence of light. The concept map shows that in radical chlorination of the methylene group the $-\text{CHCl}-$ group is formed, whereby the carbon atom oxidation number changes and is now 0. Compound A is thus chlorocyclopentane.

2. The next stage is the reaction of chlorocyclopentane with an ethanolic solution of potassium hydroxide and heating the reaction mixture. From the concept map we can see that from the $-\text{CHCl}-$ group under base conditions two competing reactions can take place: (1) hydrolysis which generates the formation of a corresponding alcohol or (2) elimination of hydrogen chloride and the formation of alkene. Using ethanol as solvent, and heating the reaction mixture favours the process of elimination reaction. Following the elimination of hydrogen chloride, chlorocyclopentane is transformed to cyclopentene. Carbon atoms with a double bond have the oxidation number -1 . The oxidation number of the carbon atom with a bonded chloro atom changes from 0 to -1 . On

the basis of this fact, students can deduce that this is a case of reduction with the strong base as the reducing agent. But it must be taken into account that in the elimination of hydrogen halide not only does the oxidation number of the carbon atom with the bonded halogen atom change but also the oxidation number of the neighbouring carbon atom from which a proton has dissociated. The oxidation number of this carbon atom increases by one, which means that this carbon atom has oxidized.

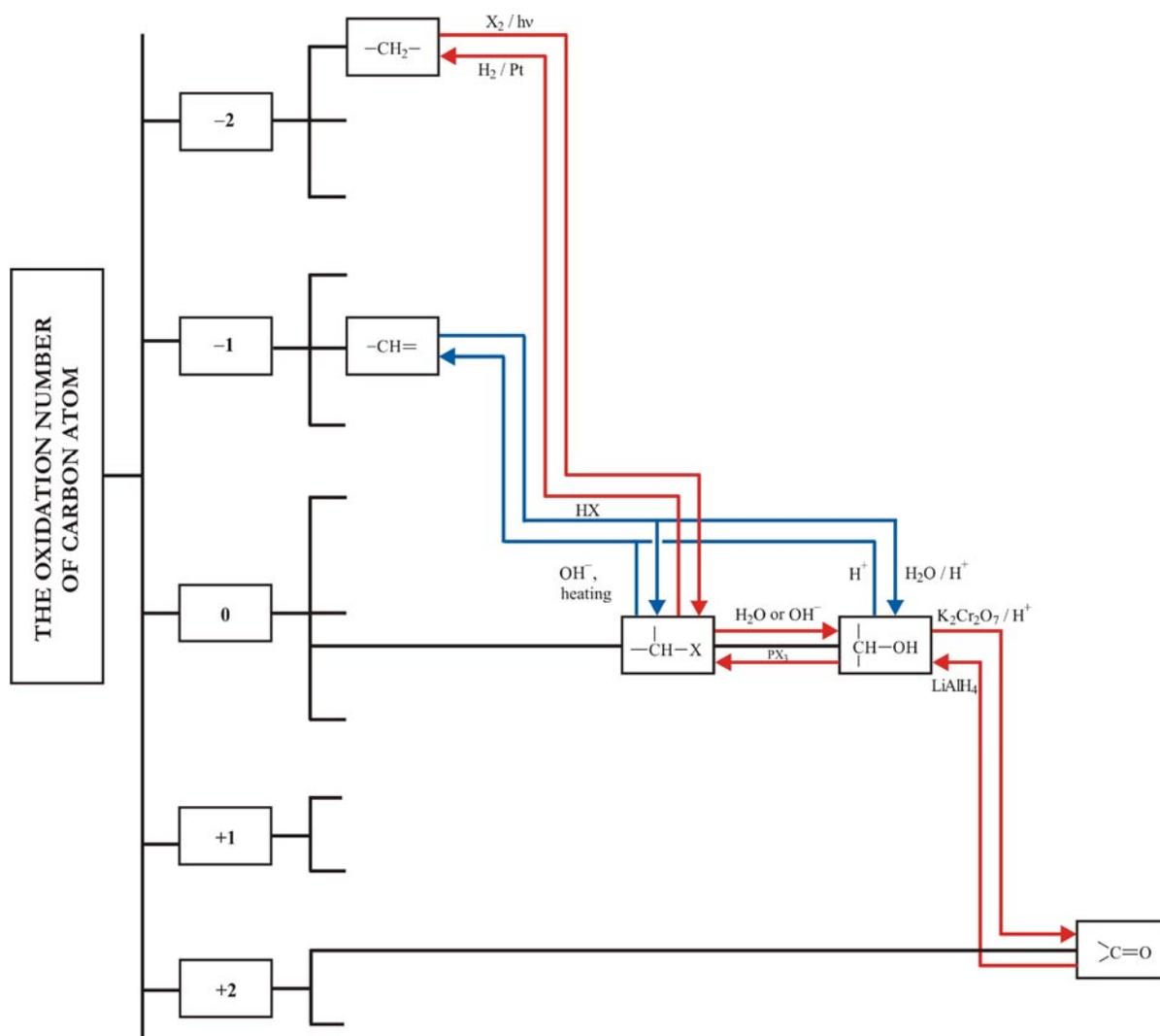
3. The next stage of the reaction scheme is the reaction of cyclopentene with water in the presence of a strong acid. The concept map shows that under these reaction conditions acid catalysed water addition can take place, whereby a corresponding alcohol is formed. Under these conditions cyclopentene is converted to cyclopentanol. This is a secondary alcohol, which under oxidizing conditions can be converted to the corresponding ketone.

4. The last stage in the reaction scheme is the conversion of cyclopentanol with $\text{H}_2\text{Cr}_2\text{O}_7$ to compound D. Since in this conversion an oxidising agent is used, the secondary alcohol is oxidized to a ketone. Under these reaction conditions cyclopentanol is converted to cyclopentanone, along with the change in the carbon atom oxidation number from 0 to $+2$, which implies oxidation.

The next question is: how should teachers implement the concept map when consolidating subject matter (Scheme 1)? There are several possible approaches. One of them is solving problem tasks involving multistage transformations and covering several basic types of organic compounds such as hydrocarbons, organic halides and organic oxygen-containing compounds. On the basis of the concept map, students can determine in which direction of the elaborated concept map these transformations proceed. From the change in the oxidation number of a carbon atom at which the transformation has taken place they can establish which reaction conditions and which order of transformations are needed in order to obtain the desired product from the initial compound.

On the other hand the students can establish whether the reagents in specific stages cause changes related to oxidation or reduction of intermediate products or whether transformation does not lead to the change of the oxidation number of the carbon atom undergoing transformation.

Depending on the discussed contents, the teacher can gradually focus on a specific part of the concept map and again use the whole map when consolidating certain contents, or for the synthesis of the discussed concepts. In this way the elaborated concept map enables students to integrate concepts successfully.



Scheme 2. Part of the elaborated concept map which helps students to solve the task.

References

1. D. Jonassen, K. Peck, B. Wilson, *Learning With Technology*, Merrill, Columbus, OH, 1999.
2. D. P. Ausbel, *Educational psychology: a cognitive view*. Holt, Rinehart and Winston, New York, 1968.
3. J. D. Novak, D. B. Gowin, *Learning how to learn*, Cambridge University Press, New York, 1984.
4. J. Novak, *A view of the current status of Ausubel's assimilation theory of learning*. Paper presented at meetings of the American Educational Research Association, San Francisco, CA, 1992.
5. J. Deese, *The structure of associations in language and thought*, John Hopkins Press, Baltimore, 1965.
6. S. Johnson, R. Thomas, *Tech. Teach.* **1992**, 51, 7–12.
7. J. Novak, in: L.H. West, A.L. Pines (Eds.): *Cognitive structure and conceptual change*, Academic Press, Orlando, FL, 1985, 101–115.
8. C. West, J. Farmer, P. Wolff, *Instruction design: Implications from cognitive science*. Englewood Cliffs, Prentice Hall, NJ, 1991.
9. D. Jonassen, *Computers in the classroom: Mindtools for critical thinking*. Englewood Cliffs, NJ: Prentice-Hall, 1996.
10. J. A. Rye, P. A. Rubba, *J. Res. Sci. Teach.* **1998**, 35, 521–546.
11. J. D. Novak, D. B. Gowin, *Aprender a Aprender*, Martinez Roca, Barcelona, Spain, 1988.
12. M. A. Ruiz-Primo, R. J. Shavelson, *J. Res. Sci. Teach.* **1996**, 33, 569–600.
13. F. J. R. C. Dochy, in: M. Birenbaum & F. J. R. C. Dochy (Eds.): *Alternatives in assessment of achievements, learning process and prior knowledge*, Kluwer Academic, Boston, 1994, 93–129.
14. S. A. Glažar, A. Kornhauser, *Vzgoja in izobraževanje* **1990**, 21, 8–20.

15. J. D. Novak, *J. Res. Sci. Teach.* **1990**, *27*, 937–949.
16. J. D. Novak, *Sci. Teach.* **1991**, *58*, 45–49.
17. L. Odom, P. V. Kelly, *Sci. Teach.* **1998**, *65*, 33–37.
18. V. Mellado, in: B. J. Fraser, K. G. Tobin: *International Handbook of Science Education, Part Two*, Kluwer Academic Publisher, Dordrecht/Boston/London, 1998, 1093–1110.
19. M. A. Ruiz-Primo, M. L. Shultz, R. J. Shavelson, *J. Res. Sci. Teach.* **2001**, *38*, 260–278.
20. M. S. Stensvold, J. T. Wilson, *Sci. Educ.* **1990**, *74*, 473–480.
21. G. Nicoll, J. Francisco, M. Nakleh, *J. Chem. Educ.* **2001**, *78*, 1111–1117.
22. C. R. Hynd, *J. Reading* **1991**, *34*, 596–601.
23. J. D. Novak, *Learning* **2002**, 548–571.
24. U. Zoller, *J. Res. Sci. Teach.* **1990**, *27*, 1053–1065.
25. J. V. Ebenezer, *J. Chem. Educ.* **1992**, *69*, 464–467.
26. P. B. Horton, A. A. McConnolly, M. Gallo, A. I. Woods, G. J. Senn, D. Hamelin, *Sci. Educ.* **1993**, *77*, 95–111.
27. E. Uzuntiryaki, Ö. Geban, *Instruct. Sci.* **2005**, *33*, 311–339.

Povzetek

Namen izdelane pojmovne mreže za transformacije določenih vrst organskih spojin, to je ogljikovodikov, organskih halogenidov ter organskih kisikovih spojin, je uporaba le-te pri učenju in poučevanju določenih vsebinskih sklopov organske kemije v srednjih šolah. Pojmovna mreža bo dijakom omogočala lažje razumevanje posameznih pojmov in njihovih soodvisnosti ter jim na ta način olajšala reševanje problemskih nalog, med njimi tudi reševanje reakcijskih shem.