Concept Maps in Chemistry Education

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During the first half of this century, ideas about the nature of scientific knowledge radically changed owing to the work of epistemologists and science historians such as Bachelard, Koyré, Cassirer, Popper, Kuhn, Lakatos, Feyerabend, Laudan, and Putnam. At the beginning of this century, epistemologists held an empiricist/positivist conception of science. This latter was conceived as a realistic description of the world "as it is", a body of established knowledge obtained by uncovering scientific principles (concepts, laws, and theories) "hidden" in nature. Scientific knowledge was considered the result of inductive inferences, starting with simple, unprejudiced observations, the secure base from which generalizations may be drawn, leading infallibly to conceptual explanations.

Science is at the present conceived as a human activity, a "fabrication" of scientists, elaborating "models" for interpreting the empirical world and for inventing new experiments (*1*). According to contemporary philosophical views, scientific principles do not find their source in the facts, but they are invented by scientists to give significance to the facts. Science is not the result of inductive inference, but a hypothetical knowledge fabricated by human beings in order to understand the world and put some order in it.

These revolutionary changes in the conception of the nature of scientific knowledge (in the field of epistemology) have been accompanied by radical changes in the conception of how learning occurs (in the domain of educational psychology): the dominant view is no more the behavioral psychology but the cognitive one. Learners are actively engaged in constructing knowledge: the acquisition of new knowledge has to be firmly anchored to existing concepts, and conceptual frameworks play a key role in the acquisition, retention, application of new conceptual knowledge and in the problem-solving exercises of the school laboratory (*2*). Epistemology and educational philosophy have then a common ground. Science is fabricated by scientists, in order to understand the world and to make predictions on natural and artificial phenomena, moving from the scientific principles already defined by the scientific community. Scientific learning is constructed by students starting from their "initial" conceptions of a subject matter.

More than twenty years of research on students' alternative frameworks leads to the conclusion that teachers have to take them into account if they want to help learners to acquire meaningful scientific knowledge, so proving the soundness of Ausubel's fundamental assumption of cognitive learning:

> *The most important single factor influencing learning is what the learners already know. Ascertain this and teach accordingly* (*3*).

To be successful in learning, students have to take possession of knowledge actively, by seeking explicit, conceptual linkages between new concepts and those they already possess. This process of elaborating personal, meaningful knowledge takes place by restructuring the already existent conceptual frameworks.

The concept map (CM) is a tool, based upon the cognitive psychological theory of constructing meaning, developed by Novak and Gowin (*4*) as a convenient and concise representation of the learner's concept/propositional framework of a domain-specific knowledge. The concepts with their linking relationships would be "visible" in a CM as *concept labels* and *verbal connectives*, illustrating the organization of the concepts in the learner's cognitive structure. It would then be possible, at least partly, to follow the restructuring and the evolution of the cognitive structure by comparing successive CMs elaborated by the student himself at different stages of the teaching/learning process of a given topic. CMs could so reveal:

- the concepts already present in a student's mind (initial concepts);
- the conceptual linkages between the concepts (context);
- the evolution that takes place as a consequence of teaching/learning activities (conceptual change).

This is the hypothesis on which we based our use of CMs, being fully aware that CMs can not give a complete view of the mental structure of a student.

We report here on our experience with the students (16–18 years old) enrolled in the final three years of the chemistry specialization in a technical school. CMs were used as vehicles for visualizing the students' knowledge structures and for documenting and exploring changes in these structures resulting from learning.

Training of Students

The first class sections are devoted to training the students in the concept mapping technique by introducing them to operational definitions of terms applied to CMs: concept, concept label, context, linking relationship, proposition, cross-link. Some maps are constructed on non-chemical subjects, taken from common sense knowledge. Acetate transparencies of students' constructed CMs served as models for discussion. The extent of practice needed for students to acquire proficiency in the construction of CMs depends on several factors, even psychological ones. On the average, 4 to 6 normal class sessions (45 minutes each) are required by students to learn how to construct CMs.

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How to Make Concept Labels Available to Students

Three different ways of assigning concept labels are used, leaving the students the choice of the linking relationships.

Known Terms CM

At the first stage, students are invited to produce what we call a *known terms CM*. In this case:

- a fixed number of concept labels are assigned;
- each student constructs his own map by using only the terms given, choosing the linking relationships and the concept structure he considers most suitable.

For example, third-year students who had already followed a first course on general chemistry were asked to develop a CM on the topic "oxidation–reduction" using the following concept labels: atom, battery, (electrical) current, electrical conductor, electrolysis, electron, ion, nucleus, oxidation, reduction. Since the objective was to point out the eventual changes in the cognitive structure following teaching of the topic, the same terms were given before and after teaching. The maps were drawn up individually during a normal class session. During the drawing up of the postinstruction map, students did not have their preinstruction CM at their disposal.

By comparing the two maps drawn up by each student, changes in the structure of the maps were found in more than three quarters of the students, even if not all the changes were improvements. It is reasonable to think that changes in the maps correspond to similar changes in the conceptual structure of the students due to learning. In Figure 1 two successive maps, produced by the same student, are shown. The concept label electron, which is linked only to current and atom labels in the first map, has four other linking relationships in the second one.

The changes in the links between the labels battery, current and electrolysis are also interesting. In the second map, it is the battery that generates the electrical current and not electrolysis. In one class, after teaching, 19 of 24 CMs linked electrolysis with battery wrongly: the linking relationship explained that battery worked by means of electrolysis. This was interesting since:

- electrolysis had never been mentioned in our lessons, and we had deliberately inserted this concept label, which is dealt with in other courses (physics, for example);
- the students had come from different classes with different chemistry teachers.

The very high frequency of the wrong connection suggested that there must have been some event that had influenced all students in the class. During the discussion of the maps, we found that the error was the consequence of the teaching in another course: the teacher had certainly been successful!

Analysis of these "noted terms CMs" gave us the possibility of recognizing a first type of cognitive event, which we called *"Cognitive Event fix" (CEfix)*. concept that is incorrectly inserted in a student's conceptual structure is no longer accepted in the same position after learning (Figure 2). The destabilization of the mental structure due to meaningful learning has a favorable outcome when the concept in question is stabilized correctly. The connected concepts are partially reordered so that the conceptual framework is restructured.

This type of map allows one to follow the evolution of the cognitive structure after the teaching/learning activity. Moreover, since the number of concept labels is fixed, this kind of map is particularly useful for identifying recurrent alternative conceptions held by students.

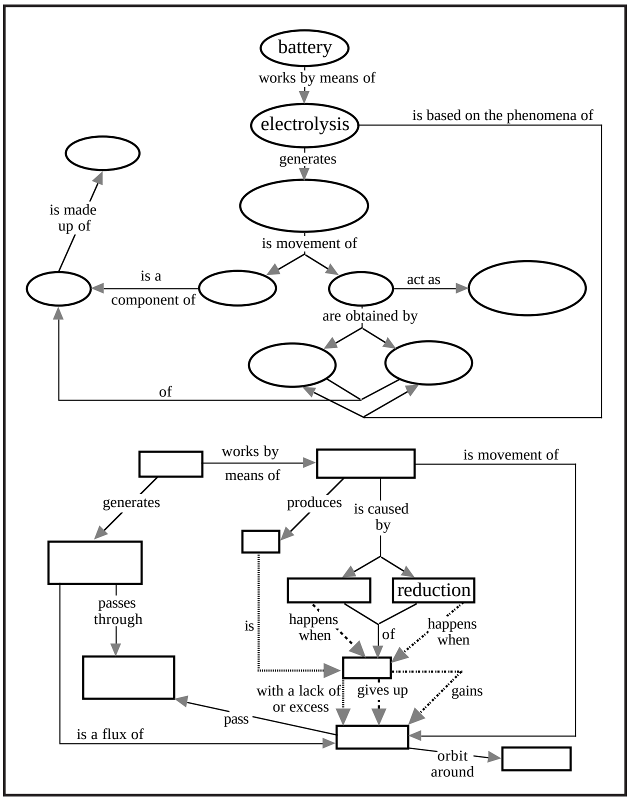

Figure 1. Oxidation and reduction: two successive maps produced by the same student.

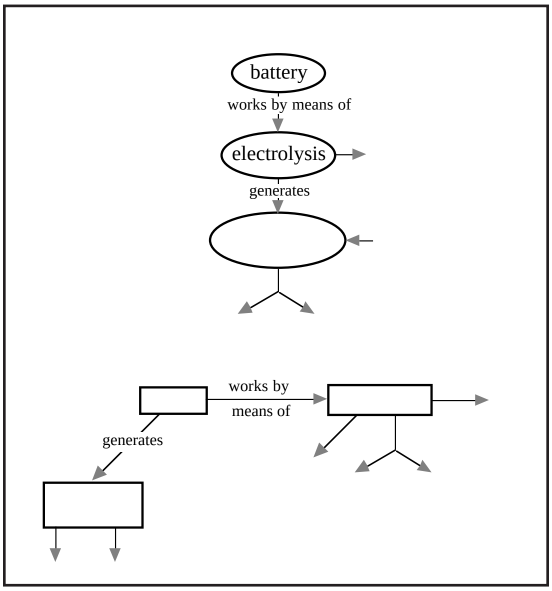

Figure 2. Cognitive Event fix (CEfix). In this case, a concept which is incorrectly inserted in a student's conceptual structure is no longer accepted in the same position.

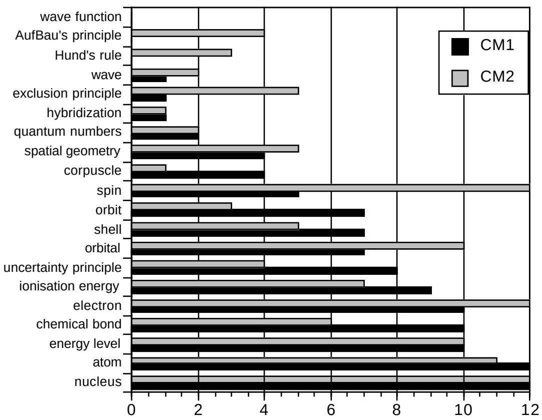

Figure 3. The *X*-axis indicates the number of students who used the various concept labels that are indicated on the *Y*-axis. The darker bars show the original choice and the lighter ones represent the choice made at the end of the unit.

Guided Choice Terms CM

A second way of assigning concept labels is to give the students a number of terms greater than what is requested to construct the map. The criteria to follow is:

- a fixed number of concept labels related to the knowledge being investigated are assigned—e.g., 20;
- each student must choose only a fixed part of these labels—e.g., 10—to construct his own map using the linking relationships and structure that he considers most suitable.

For example, third-year students were invited to construct a *guided choice CM* on atomic structure during a normal class session. Before teaching the topic, the following twenty terms were supplied to assist the subjects with the task: atom, Aufbau principle, chemical bond, corpuscle, electron, energy level, exclusion principle, Hund's rule, hybridization, ionization energy, nucleus, orbital, orbit, quantum numbers, shell, spatial geometry, spin, uncertainty principle, wave, wave function. The students were then asked to choose ten terms and develop a CM. This procedure was repeated at the end of the teaching/learning activities, leaving the students the possibility of using ten terms they considered most suitable—not necessarily the same terms used for the first map, which was not at their disposal.

Figure 3 summarizes the number of students who used the different concept labels in the CMs. The darker bars refer to the choices made for the first map (before teaching) and the lighter ones concern the choices made for the second map (after teaching).

Analysis of the maps shows that before teaching, seven students out of ten chose the concept label "orbital", but no one associated it with the label "wave function". Four of these seven use the labels "orbit" or "shell" to structure their knowledge. The concept "orbital" does not seem to be an alternative one for "orbit", but rather complementary. After teaching, the label "orbital" is used by ten out of twelve students; three of these ten still associate this concept with the label "orbit", while the label "wave function" is still not used by any student.

Figure 4 shows two maps that were constructed by the same student before and after teaching. They are quite different.

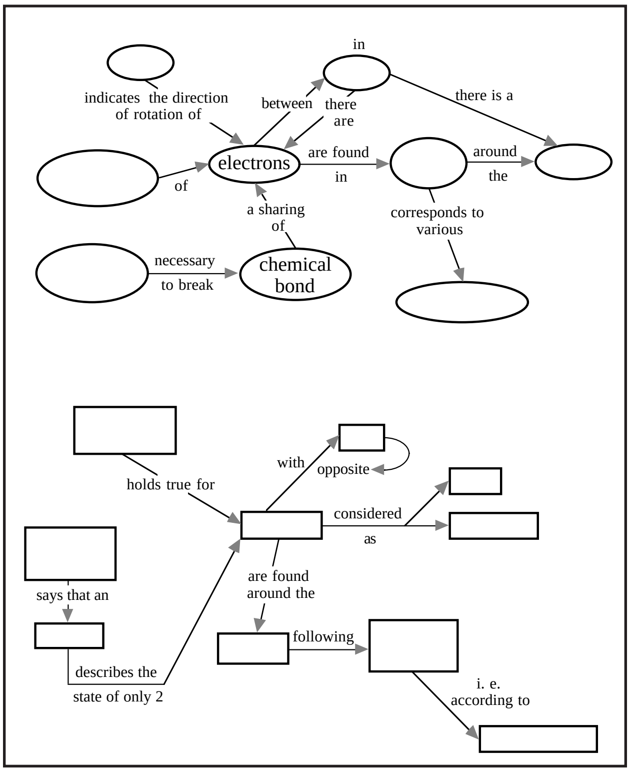

Figure 4. Atomic structure: an example of two successive maps constructed by the same student.

We can identify two types of cognitive events in these maps. The first, which we call *"Cognitive Event in" (CEin)*, occurs when a concept label, in this case "orbital", enters the conceptual framework (Figure 5). The second, which we call *"Cognitive Event out" (CEout),* occurs when a concept label, in this case "orbit", of the first map is excluded from the second one (Figure 6). As can be seen, the concept "orbit" is not simply replaced by the concept "orbital", since the latter occupies a different position with completely different links. It can reasonably be assumed that the student's cognitive structure is undergoing a conceptual reconstruction.

Concept Stimulus CM

In the preceding approaches, the teacher gives the students the concept labels referring to a specific domain of chemical knowledge. But it is also possible to ask the students to identify the most suitable or important concept labels and to construct what we call a *Concept stimulus CM*. In this case:

- only one concept label (stimulus) is assigned;
- the number of labels the students can add is fixed;
- each student elaborates his own map using the concept labels, the relationships, and the structure that he considers most suitable.

Fifth-year (final-year) students were invited to construct this kind of map on a very vast subject, thermodynamics. The aim of the teacher was to give the students, after studying this topic, the possibility of demonstrating the meaningfulness of what they had learned. Starting from the concept stimulus "thermodynamics",

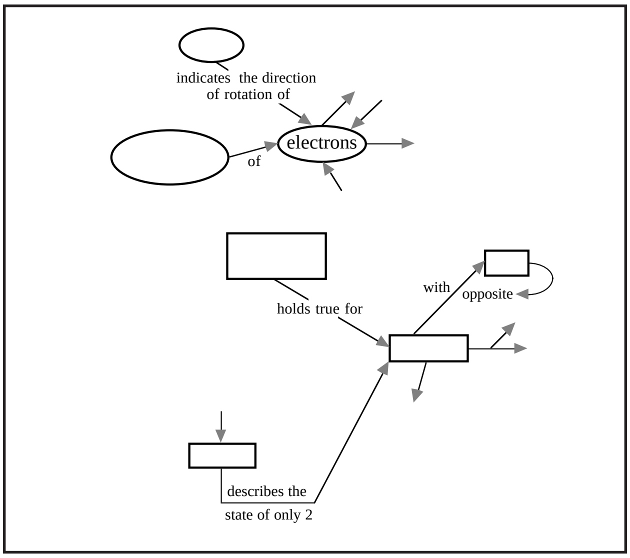

Figure 5. Cognitive Event in (CEin), occurs when a concept label, in this case “orbital”, enters the conceptual framework.

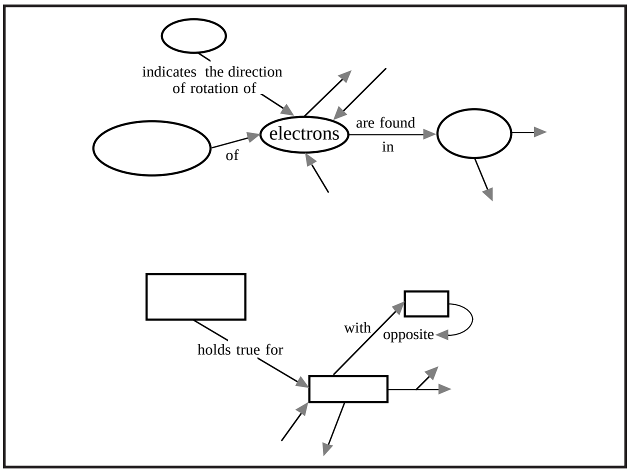

Figure 6. Cognitive Event out (CEout) occurs when a concept label, in this case “orbit”, of the first map is excluded from the second one.

the students were assigned the following task for the first map: the ten terms that they considered most important for representing the basics of thermodynamics were to be chosen and a CM constructed from them. The maps were collected by the teacher, who kept them for a fortnight, during which time the subject was discussed in class. The maps were then given back, and each student had the opportunity to restructure his own map accordingly. The three cognitive events (CEfix, CEin, CEout) can be identified in all the maps. In Figure 7 the first and second maps of one of the students are reported.

Initially, it seems very difficult to link the changes between the two maps to the cognitive events cited before. Since the maps are of the type “concept stimulus”, any term considered suitable is accepted. In the maps reported, all the concepts labels have been changed between the first and second maps. But, have they really?

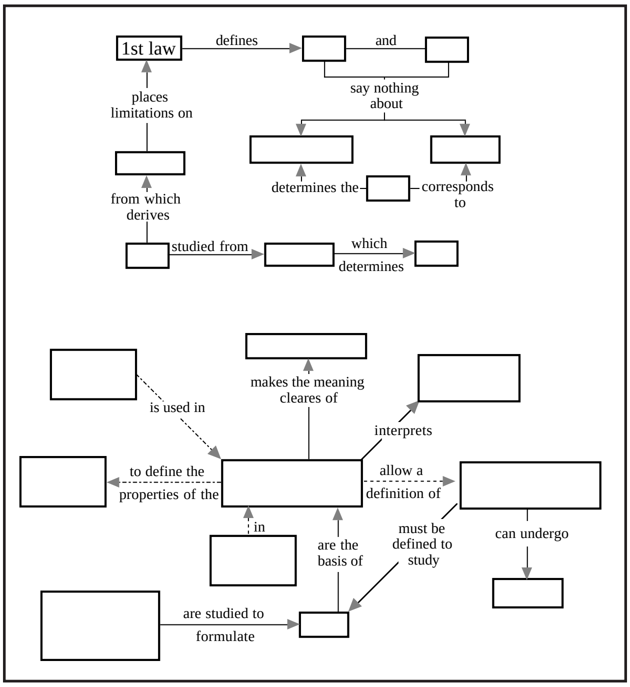

Figure 7. Thermodynamics: an example of two successive maps constructed by the same student.

The labels “1st law”, “2nd law”, and “3rd law” in the first map have been changed into “laws” in the second one; the labels “ΔU”, “ΔH”, “ΔG, “ΔS” in the first map are summarized in the term “state functions” in the second one. This can also be seen for the labels “chemical thermodynamics” and “chemical phenomena” in the second map, which derive from the terms “affinity” (understood as chemical affinity) and “spontaneity” (spontaneity of a reaction) in the first map.

The vastness of the topic caused some difficulty for the students, who resorted to more general concepts only in the second map, thus summarizing the large variety of terms used in the domain of thermodynamics. It must be remembered that the way of giving the students the concept labels directly influences the types of cognitive events to be found in the CMs they develop. “Noted terms” maps never show “in” or “out” cognitive events, while “guided choice terms” or “concept stimulus” maps normally show all three events. These obviously do not represent the complexity of a human’s mental processes: they are extreme cases, which should be looked for in students’ CMs, as they are signs of meaningful learning.

Moreover, a concept map is an idiosyncratic representation of a domain specific knowledge. Consequently, the maps reproduced are not representative or typical of our students. A CM strictly reflects the conceptual organization of the single student who has produced it, giving evidence to a specific level of conceptual understanding.

Conclusions

It is now four years since we introduced concept maps into our chemistry courses, as participants in an action-research project concerning the improvement of chemical education in secondary schools. At the beginning, we tried to use them as assessment devices: scores were assigned to postinstruction maps for the number and correctness of the relationships portrayed, for the levels of hierarchy, and for cross-linking. We also tried to assign scores for the convergence of the students' maps to teacher-constructed maps. But we soon had to recognize that students' CMs are highly idiosyncratic representations of a domain-specific knowledge, and the interindividual differences displayed among them were far more striking than the similarities. Taking into account the critical opinions on the scoring of concept maps (*5*), this observation led us to shift emphasis and focus on changes in content and organization of CMs over time, and on helping the students to become aware of and criticize their own frames and those of the others. Such use is consistent with a constructivist theory of learning, which is the foundation of our teaching strategy, viewing knowledge as being actively constructed by the learner.

During the four years of practical experience in using CMs, we have grown more and more impressed by the potential of this metacognitive tool to help chemistry teachers and learners to improve teaching and learning. Concept maps are useful for teachers, since they give them information on what students know, showing the concepts already present in their minds (initial concepts), how they are related to one another (context), and how learners reorganize their cognitive structure after a specific teaching activity. In this way, teachers can be aware of the presence of misconceptions that are potential "obstacles" to the construction of new, meaningful knowledge. Moreover, CMs give the teacher the possibility to check the influence of teaching on the cognitive structures of students, since this tool is especially valuable in documenting and exploring the restructuring of conceptual frameworks.

But concept maps are also judged a very useful metacognitive tool by students. In fact, many of those trained to develop CMs in chemistry have spontaneously adopted them to represent knowledge in other disciplines, such as history and Italian, claiming that CMs are powerful helps in meaningful learning of new subject matter.

Concept maps are also currently used in our classes as the starting points for discussions on chemistry topics involving the students and the teacher, who acts as the chairman. Von Glaserfeld (*6*) has emphasized the importance of social interaction in the construction of new meanings, and we have found that by using the CMs we can effectively act both on the interpersonal and the intrapersonal aspects of learning.

As Novak says "concepts map... is no "magic bullet", no "quick fix" for classroom where rote learning predominates" (*7*) and use of the maps can be successful only by adopting a constructivist approach to chemical education. Many teachers object that turning to a constructivist approach and using concept maps is very time-demanding, and their objection is both true and false. It is true if we limit our attention to the beginning of the course, when students have to become acquainted with the idea that they construct their own knowledge and learn to develop concept maps. It is false if we go further along the course, since the meaningful learning of the first fundaments of chemistry (the particulate model and the conceptions of pure substance and chemical reaction) gives the students powerful instruments to construct further meaningful knowledge more easily and more quickly than in traditional teaching.

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Literature Cited

1. Chalmers, A. F. *Science and its Fabrication*; Open University: Buckingham, 1990.
2. Hodson, D. *Sci. Educ.* **1988**, *72 (1),* 19–40.
3. Ausubel, D. P. *Educational Psychology: a cognitive view*; Holt, Rinehart and Winston: New York, 1968.
4. Novak, J. D.; Gowin, D. B. *Learning How to Learn;* Cambridge University: 1984.
5. Stuart, H. A. *Eur. J. Sci. Educ.* **1985**, *7*, 73–81.
6. Von Glaserfeld, E. *Synthese* **1989**, *80*, 121–140.
7. Novak, J. D. *J. Res. Sci. Teach.* **1990**, *27*, 937–949.