Developing global competences by extended chemistry concept maps

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ABSTRACT This work focuses on a possible teaching approach to promote chemistry learning for students during the first two years of technical high school in Italy (age 14–15). Critical thinking skills can be developed by integrating two different curriculum designs, converging in a novel didactic approach, a modified version of the Systemic Approach to Teaching and Learning (SATL). Interdisciplinary topics help to promote students' interest and motivation because of their applications in real situations, concerning in particular ethics and environmental issues. This method gives the right importance to a stimulating educational context where critical thinking skills are highly encouraged.

This article shows a possible way of teaching chemistry during the first two years of technical high school in Italy (age 14–15) in the framework of a novel systemic approach. In order to improve students' outcomes, the method brings out the importance of interdisciplinary topics related in particular to environmental and ethical issues such as health worker protection, animal testing, climate change and biogas production. This approach was based on a revision of an existing method; such revision required a fusion of two different curriculum designs among the various models listed below.

Curriculum design

The teaching of a subject can be planned according to various approaches that can be divided into five main models (Tessaro, 2002) depending on the curriculum design choice:

1. **Design by objectives**. This model is typical of traditional teaching: the student responds to the stimuli provided by the teacher in a linear and definite way. The approach is characterised by a certain rigidity in that the results obtained by the student are the main issue, regardless of the learning processes that take place in order to achieve the results.
2. **Design by content**. This approach focuses on content transmission rather than on content elaboration. According to this model, the student learns the basic content of the subject carefully selected by the teacher. The danger of this type of design lies in the static idea of the nature of knowledge; the storing of the content is preferred to the correct identification of possible mutual connections.
3. **Design by concepts**. Unlike the design by objectives model, this approach consists of a network structure, made explicit by the construction of concept maps. It is a model relying on the arrangement of knowledge within the subject. The teacher prepares the concept maps, while the student assimilates the concepts, identifying the connections between them. This approach allows the teacher to mediate between the disciplinary structure and the cognitive system of the student.
4. **Design by situations**. This type of design is based upon the student's experience. There is no clear distinction between teacher and learner. The teacher presents a situation that the student has to analyse when trying to identify possible problematic factors. This approach is very attentive to the learner, who is dealing with difficult subjects and developing a complex vision; however, it might be a distracting method, hindering the focus on the learning goals.
5. **Design by competences**. This last model focuses on the development of the student's expertise. The teacher prepares learning resources that foster thinking, reasoning and conceptual production. Consequently, the student tries to apply the content of teaching to real situations, increasing his or her critical thinking skills.

Didactic approach

Curriculum design models 1 and 2 have the disadvantage of not focusing on the learning processes; model 4 is not suitable for a course highly restricted in terms of hours of lessons per day and laboratory experiments, as the first two years of the chemistry course for technical high school Italian students is. The chemistry course represents for many students the only opportunity for fundamental chemistry learning because the majority of them will specialise in non-chemical fields (such as mechanical, electronic or computer science). Therefore, there is the need to teach a large amount of content within a two-year course, pursuing two goals at the same time:

- highlighting the peculiar conceptual structure of chemistry;
- developing critical thinking.

The former goal can be achieved by a design using model 3, the latter goal using model 5.

Model 3, which is focused on gathering and assembling knowledge, suits the systemic nature of chemistry in a non-reductionist perspective. This is very important for technical students, who are (or will be) quite familiar with the concept of a 'mechanical system', whose nature is different from that of a 'chemical system':

Consider a physical entity, separate from its environment, with time-dependent characteristics. The complete separation of this part of [the] *world, the assumption of* [an] *absolutely isolated system, is impossible of course, but this approximation is usually used in mechanics* [and thermodynamics].

Chemistry works on two levels: the macroscopic [observation] *of pure substances (elements and compounds) and the microscopic* [developing explanations in terms] *of atoms and molecules.* [In contrast with] *physics, both these chemical systems carry out a fundamental role in this discipline, shaping, therefore, chemistry as the first true systemic science and proposing this discipline as a particular way of looking* [at] *the material world (inanimate and animate)* [from] *a non-reductionist and pluralist perspective. In fact, even before considering the system concept in biology, the general vision that comes from* [the] *material world is articulated in a reductionist and a systemic approach, in a 'simple' physical perspective and a 'complex' chemical one. From the cultural and philosophical point of view, the specific characteristic of the chemical approach is a qualitative*[ly] *rich world: its entities (molecules and compounds), millions* [of them], *are different* [from] *each other, different enough to deserve a specific name. This characteristic makes* [a] *chemical approach capable of explaining the complex macroscopic inanimate world, full of objects with different qualities, and, the still more complex, living world. Even* [from a] *strictly scientific point of view, the complexity levels of molecules and of chemical compounds have a particular characteristic: they are the step before the bifurcation between the inanimate and animate world.* (Villani, 2014)

The role as a junction between the animate and inanimate world makes chemistry a '*central science*' (Balaban and Klein, 2006), whose range of influence affects the natural environment as well as health, socio-economic and ethical issues.

In this context, chemistry education may play a key role in helping students to develop thinking skills such as analysis, categorisation and evaluation of phenomena (Richard and Elder, 2006). Chemistry is strongly involved in everyone's lives and touches almost every aspect of our world. Understanding of the scientific method confers on students the 'scientific attitude', which gives them a better chance of reaching the right decision about both personal questions and what affects others in a global community (Marinacci, 1995). Thus, in classrooms that emphasise critical thinking, i.e. linking new ideas to the students' background knowledge, providing opportunities for students to make sense of data and solving new problems from various perspectives, it is possible to stimulate students' thinking skills and their learning (Krajcik and Sutherland, 2010).

Specifically, problem-solving skills (in particular related to resolving stoichiometric exercises) are improved by model 3, which facilitates the connections between various basic concepts; on the other hand, the model based on competences (model 5) facilitates the insertion of the basic concepts in a larger context, developing critical thinking skills in order to evaluate real complex situations. Problem-solving and critical thinking skills require different assessment methods as explained later.

An opportunity for synthesis between the conceptual model and the model structured by competences is provided by a modified version of the existing method called the 'Systemic Approach to Teaching and Learning' (SATL), an evolution of the concept mapping characteristic of model 3 (Fahmy and Lagowski, 2002). Using models 1 and 2, the meaningful concepts are presented separately from each other; these models aim to enhance the storing of content without any special attention to their mutual connections. In this way, the knowledge of notions is encouraged and memory skills are enhanced to the detriment of global thinking ability. In contrast, by the SATL it is possible to transfer the concept of globalisation into the education system, allowing the development of the competences in accordance with model 5:

Thus, the future of science education must reflect a flexibility to adapt to rapidly changing world needs. It is our thesis that a systemic view of science with regard to principles and their internal (to science) interactions as well as the interactions with human needs will best serve the future world society. Through the use of a systemic approach, we believe it is possible to teach people in all areas of human activity; economic, political, ethical, scientific; to practice a more global view of the core science relationships and of the importance of science to such activities. (Cardellini, 2010)

Usually, the classic SATL chemistry concept maps show relationships between disciplinary concepts only; in any case, links with global topics are not graphically recognisable in a clear way. This work shows that it is possible to plan a new systemic way of teaching starting from the SATL, pointing out either the connections 'internal' to the discipline or the 'external' ones related to the interactions with the surrounding environment in a global systemic perspective. Therefore, a new SATL version can be planned by a synthesis between model 3 – highlighting 'internal' connections – and model 5 – highlighting connections with 'external' content (Figure 1). This operation can be done in various ways, for instance by integrating green chemistry topics, and this is extremely effective at increasing interest and for improving students' learning in chemistry.

Interdisciplinary topics

Chemistry teaching can focus on the interplay of science, technology and society with local issues, public policy making and global factors. Some possible topics include, for example, population growth, economic development, human rights and animal rights. All the issues involved pose challenges that need to become part of the chemistry curriculum, connecting chemistry learning to the broader goals of education, especially ethical questions. Today this integrated approach is not usually present in secondary education, so students' critical thinking skills are not adequately cultivated.

The foundation of global competences is a disciplinary and interdisciplinary understanding of the world. A subject such as chemistry provides a powerful lens through which the world can be interpreted. Nevertheless, understanding a subject involves understanding not only key disciplinary concepts but also how such concepts are produced with the aid of disciplinary methods and how they can be applied. Disciplinary understanding is thus an essential component of global competence as it represents the starting point for the interdisciplinary approach. For this reason, global competence is best developed *within* disciplinary courses. Students do not develop global competence after they gain fundamental disciplinary knowledge and skills but rather *while* they are gaining such knowledge and skills. They are induced into reflecting about the nature and the limits of their own understanding (Boix Mansilla and Jackson, 2011). In this way, the central role of chemistry becomes increasingly clear.

Course design

According to the classic SATL, 'systemic' means an arrangement of concepts or issues affecting interacting systems in which all the relationships between concepts and issues are made explicit to the learner using a concept map-like representation. The approach means to create a more-or-less dynamic system of an evolving 'closed system of concepts' – a concept cluster (Fahmy and Lagowski, 2003). In this presentation, 'systemic' refers not only to the particular arrangements of concepts but also to the nature of the global discipline, with particular regard to the influence of chemistry on the surrounding environment and to the relationship with other fields of knowledge. In this case, the systemic nature is not only represented by closed systems; maps are actually open, because they are composed of:

- an internal cluster including chemistry core concepts, aimed at problem-solving skills development (Cardellini, 2009);

- an external part made up of a variable number of branches connecting the inner part with various kinds of issues (related to sustainability, health protection, safety, ethical questions, etc.), aimed at critical thinking development.

Another change to the original SATL lies in the choice of content for the map design: a classic SATL concept map design aims to analyse a very specific subject in depth by its accurate subdivision into many particular aspects, whereas in this new approach:

- maps include concepts that are neither too general nor too specific, in order to allow links with the interdisciplinary topics to be developed;
- links among the concepts internal to the discipline are two-way, so they are always represented by double arrows, whereas links with external concepts are one-way only because they represent the shifting away from the fundamental concepts to the global issues;
- the meanings of each link can be provided by the teacher or expressed by the student as a useful exercise. Because the concepts are not too specific, often there is not a single interpretation of their connections: they can be read in both senses (in the case of double arrows) or expressed with different shades of meaning according to the reader.

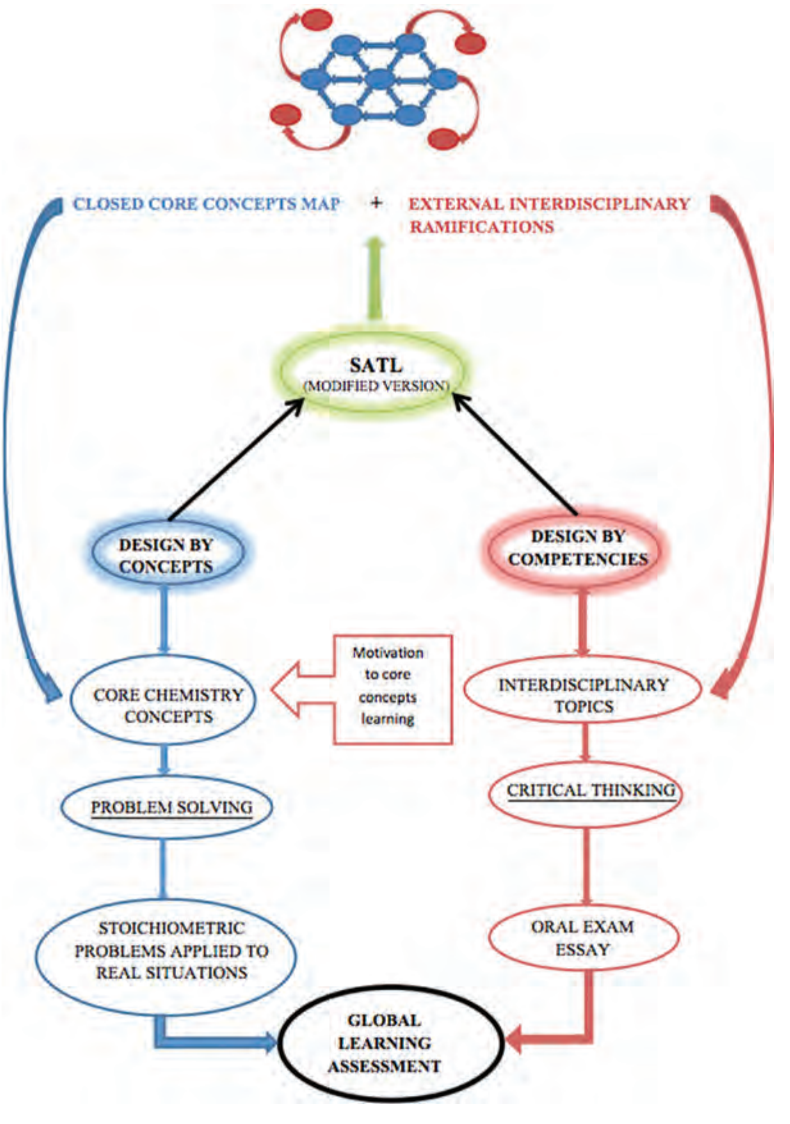


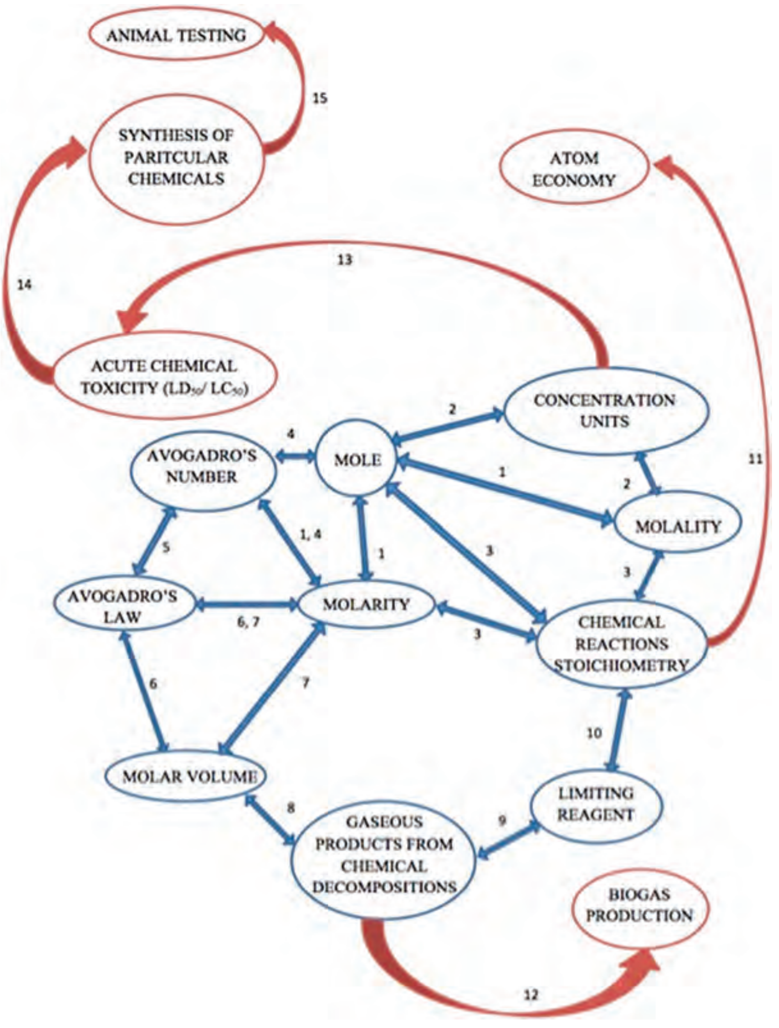
Figure 1 Overview of the didactic approach

Three examples of ‘open maps’ (with a possible links interpretation) are represented in Figures 2–4 (blue double arrows connect basic content between them; red single arrows connect basic content with interdisciplinary topics). The scientific literature shows SATL applications for a large number of disciplines at pre-university and university level. In the chemical field, SATL applications have been successful in particular for organic chemistry topics (Fahmy and Lagowski, 2002), but interdisciplinary connections are mostly overlooked to concentrate on the internal disciplinary links. An SATL modified version as illustrated in this article allows teachers to administer this method giving more importance to interdisciplinary topics.

Concept maps have to be structured taking into account the issues established within lessons and the type of questions that will be asked during the final examination. Every map has to be prepared at the end of a certain number of lessons dealing with various topics and their relationships with real situations; in particular, the maps have to show where and why a certain concept can be expanded into something that is an application of the concept, showing how to build the curriculum.

Concept maps can be employed in various ways. For example, the teacher prepares them without specifying connections between the topics involved; then students (individually or in groups) write the possible connections on the map and explain them on a separate sheet. This use reveals in more detail how concepts can be connected to each other, and can support deeper learning directly (not just planning it).

Representing concept maps that are actually of help for the teaching–learning process is very demanding work, because chemistry is inherently complex. The type of learning assessment should also consider this complexity.



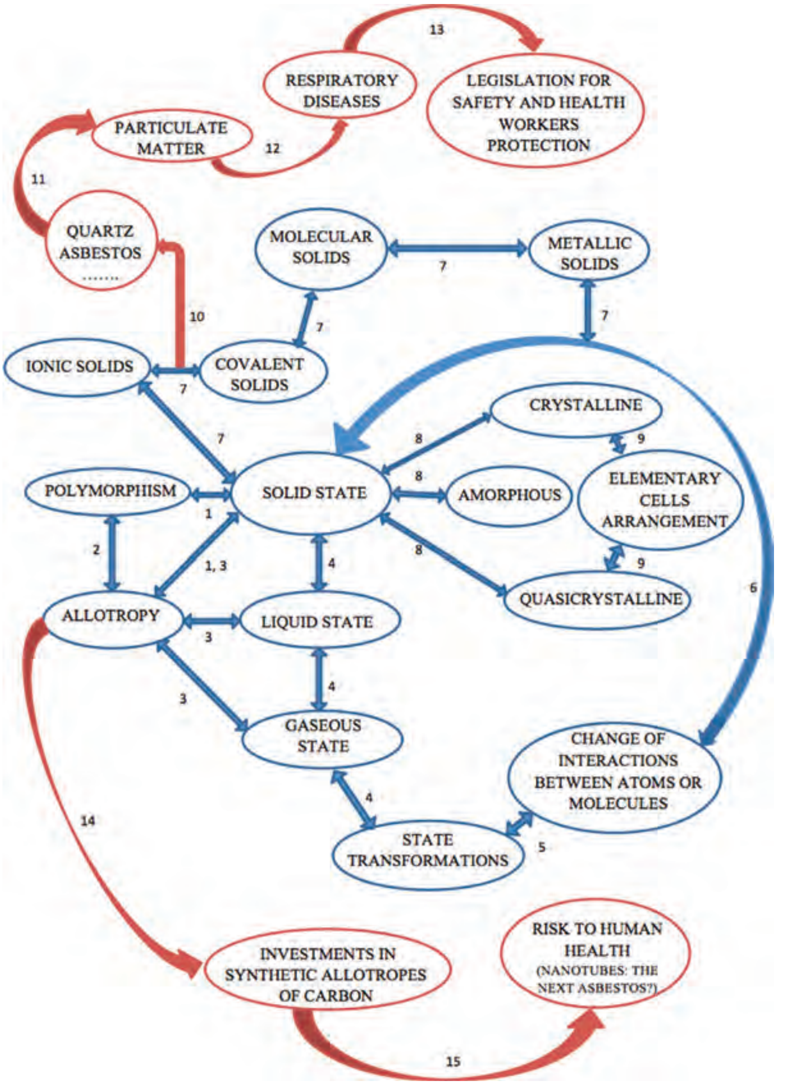
1 The molarity and molality units of measurement are related to the number of moles
2 The mole is used in different concentration units/molality is a concentration unit
3 The mole/molarity/molality is used in chemical reactions stoichiometry
4 One mole contains an Avogadro's number of particles
5 The Avogadro's number was calculated after the formulation of Avogadro's law
6 The molar volume of an ideal gas is a particular volume related to Avogadro's law
7 The molar volume is employed to calculate molarity in the gaseous phase
8 Gaseous products can be calculated as molar volumes
9 The reagents' decomposition determines the limiting reagent
10 The limiting reagent is the substance totally consumed when the chemical reaction is complete
11 Atom economy describes the conversion efficiency of a chemical reaction in terms of atoms involved (green chemistry philosophy concept)
12 Biogas (renewable energy source) refers to a gas mixture produced by the decomposition of organic reagents without oxygen
13 The toxicity of a chemical is related to its concentration in a living organism
14 Chemicals as drugs or cosmetics could have toxic effects
15 Ethical issue: animal testing is used to assess toxicity of particular chemicals

Figure 2 Example of an open map revolving around the mole concept

Learning assessment

Many research works illustrate various possibilities of planning valid and reliable examination items reconciling the complex epistemological nature of chemistry and students' cognitive maturity (Knaus *et al*., 2011). Therefore, the design of well-structured assessment materials provides a more steady measure of the learning. The learning assessment must take into account various factors: the conceptual structure of chemistry, course content, students' age and typology.

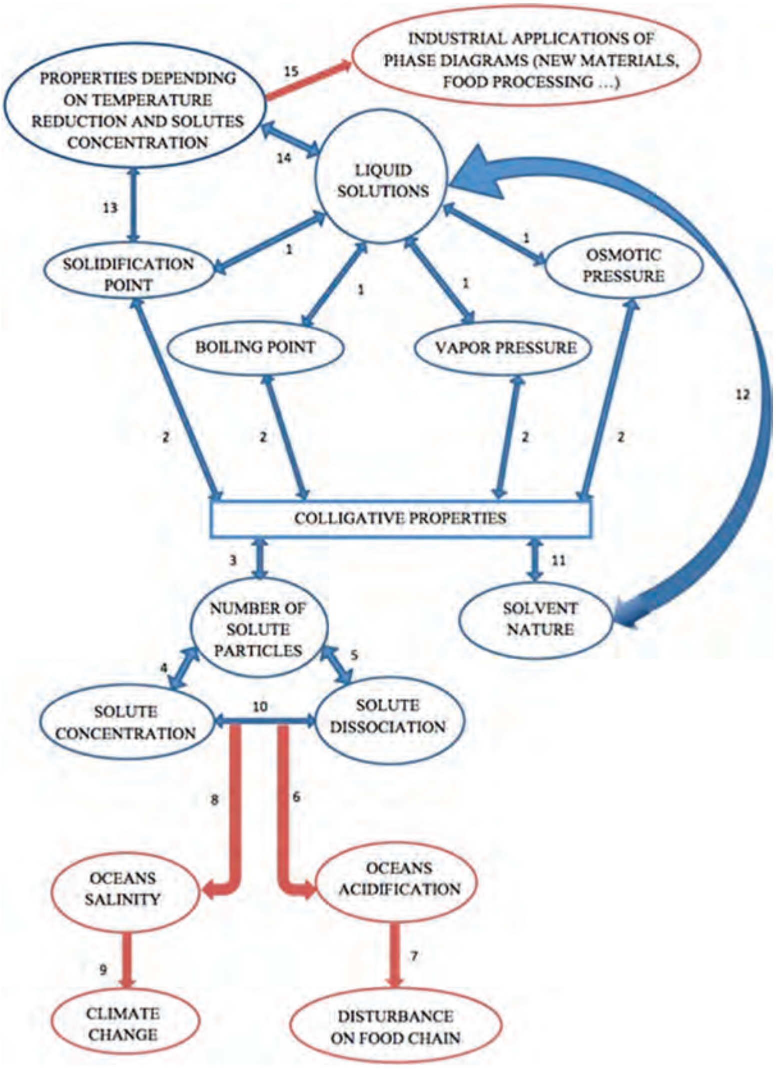
For example, if the goal is to test the knowledge of fundamental chemistry concepts and problem-solving skills, questions about 'external' content (see the parts of the concept maps coloured red) should not be put in the same examination (although it has already been pointed out how useful they can be in order to motivate students with a more complex epistemological vision, as highlighted in Figure 1). The mastery of the external content has to be assessed using various methods suited to verifying critical thinking skills. So, global evaluation of student performance needs at least two complementary assessment forms. The teacher will attach the



1 Polymorphism/allotropy represents different forms of a chemical substance
2 Difference between polymorphism and allotropy (polymorphism refers only to solid state)
3 Allotropy refers to different crystalline forms of an element within the same phase (solid, liquid or gaseous)
4 State transformations are realised by temperature or pressure changes
5 State transformations involve changes related to the force of the interactions between atoms or molecules
6 Solid state presents different interactions between atoms, molecules or ions
7 Ionic, covalent, molecular and metallic solids are characterised by different inter-actions between atoms, molecules or ions
8 A solid substance can be crystalline, quasicrystalline or amorphous
9 Elementary unit cells result in crystalline or quasicrystalline solids depending on their mutual arrangement
10 Some types of solid substances have ionic and/or covalent bonds
11 Processing of quartz, asbestos, etc. can produce noxious particulate matter
12 Particulate matter causes respiratory diseases
13 Ethical issue: in many countries legislation does not protect workers from particulate matter dangers
14 Synthetic allotropes of carbon have economic importance because of their particular properties
15 Ethical issue: economic interests can prevail over risks to human health

Figure 3 Example of an open map revolving around the solid state concept right importance to each form depending on the structure of the course.

Critical thinking skills require assessment methods that allow students to argue about various questions, evaluate real situations, couch their criticism in scientific terms, and express decision-making abilities. Therefore, critical thinking calls for soft skills requiring flexibility in the way the questions can be answered. Such skills can be assessed more effectively by a discursive examination, ranging from an oral dissertation to an essay assignment (Figure 1) related to interdisciplinary topics dealt with during the lessons (the external content of the extended concept maps). The effectiveness of the essay in introductory chemistry courses is supported by a large number of articles, from high school to university level (Grossman, 1997); these articles describe how to design the essay to stimulate students' interest in the role of chemistry in their lives, to help them to make connections between classroom information and the 'real world', to improve their writing skills, and to teach them to use the library and other sources of scientific information.



1 Liquid solutions are characterised by solidification point, boiling point, vapour pressure and osmotic pressure
2 Solidification point/boiling point/vapour pressure/osmotic pressure variation is a colligative property
3 Colligative properties of solutions depend on the number of solute particles in a solution and the nature of the solvent
4 The number of solute particles depends on solute concentration
5 The number of solute particles depends on solute dissociation
6 Acid solute dissociation increases the oceans' acidification
7 Environmental issue: ocean acidification increases cause disturbances to the food chain
8 Saline solutes increase ocean salinity
9 Environmental issue: ocean salinity increases cause climate change
10 The dissociation constant (e.g. for weak acids) is usually written as a quotient of the equilibrium concentrations
11 Colligative properties of solutions depend on the solvent nature
12 All the properties of liquid solutions with the same solute are strongly influenced by the solvent nature
13 The solidification point of multicomponent liquid solutions is a critical value that is not easily predicted
14 Multicomponent liquid solutions exhibit particular temperature- and solutes' concentration-dependent properties
15 Technological implications: multicomponent systems' properties are very important for new materials design and for food processing operations

Figure 4 Example of an open map revolving around the colligative property concept

Conclusion

A stimulating educational context is important to encourage students in thinking and learning actively. Such a context can be realised by a systemic approach allowing either a complex analysis of subject knowledge or constant attention to the role of chemistry in a larger context, to encourage students' interest and involvement. Therefore, to achieve good results, a good strategy consists of integrating different and complementary didactic approaches, followed by different and complementary learning assessments whose effectiveness has been proved by scientific literature data.

Technical high school students represent a target suitable for this strategy because they need to learn chemistry fundamental concepts in a short time without losing sight of connections between them and their role in real situations.

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