Concept Mapping: Connecting Educators
Proc. of the Third Int. Conference on Concept Mapping
A. J. Cañas, P. Reiska, M. Åhlberg & J. D. Novak, Eds.
Tallinn, Estonia & Helsinki, Finland 2008

# PHYSICS CONCEPTS AND LAWS AS NETWORK-STRUCTURES: COMPARISONS OF STRUCTURAL FEATURES IN EXPERTS' AND NOVICES' CONCEPT MAPS

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**Abstract**. A characteristic feature of physics knowledge is the high degree of coherence and connectedness of its concepts. To large degree physics concepts and laws can be viewed as organized, network-like structures. Consequently, learning can also be seen as the working with and the building of the conceptual networks. It is argued here that a useful viewpoint on learning physics conceptual structure can be developed on the basis that physics concepts can be seen as networks, where the formation of such structures is guided by the meaning coherence of concepts, related to the deductive coherence of concepts themselves and their explanatory coherence with respect to experiments. From this viewpoint, we compare here how experts and novices represent their physics knowledge by drawing concept maps of such networks. By analyzing the topological structure of the concept maps it is shown that experts' maps are characterized by conceptual coherence and hierarchies inbuilt in the network-structures. In novices' concept maps similar features are found in the best cases, but many novices produce maps with poor coherence and a lack of organizing hierarchy. Finally, applications and advantages of the viewpoint emphasizing networked structure of concepts in physics teacher education are discussed.

## 1 Introduction

Experts' abilities to think and solve problems depend strongly on a rich body of knowledge about the subject matter. The "usable knowledge" of expert is easily recovered and applied, because it is not the same as a list of disconnected facts, instead it is connected to and organised around the most important concepts of the subject (Bransford et al. 2000, Mestre 2001). In education the goal is first and foremost tutoring students to achieve and master knowledge, which is well organised and which has inherent hierarchy. Hierarchically organised knowledge structures make both the deployment of knowledge and the integration of new knowledge as a part of the network easier (cf Novak & Gowin 1984; Mestre 2001). Therefore, instructional strategies that help students to create a hierarchy are advantageous to learning (Trowbridge & Wandersee 1989).

Experts view physics concepts as an entangled web, which links concepts to other concepts, as well as embeds the basic laws of the structure to these concepts. The basic laws are here taken as basic models, which frame certain phenomena so, that phenomena become identified and defined in terms of pertinent concepts. For example, phenomena which belong within Newtonian mechanics are framed out of all possible phenomena by application of the basic law $\mathbf{F}=d\mathbf{p}/dt$ (Newton's II law), where all acceptable forces $\mathbf{F}$ need to be defined in terms of additional auxiliary models of forces, as well as linear momentum $\mathbf{p}$ being expressed in terms of kinetic models in order to be tractable or even recognizable. Finally, force and linear momentum need to be embedded in a common system of coordinates. In such conceptual systems concepts are far from being independent; instead, they are fundamentally entangled and can be used only with an understanding of their interdependency. In framing out and recognizing phenomena, which can be described and understood in terms of such conceptual systems requires a set of concepts and laws, which are coherent enough to allow coherent explanations, coherent deductions, and coherent analogies within the system (Thagard 1992, 2000). Following the coherentists views (Thagard 2000) we can say that seeking such *meaning coherence* is the guiding principle in constructing acceptable and usable scientific theories, and when found, it gives the satisfaction of understanding.

Learning is also working with and building of the network. In learning, the conceptual systems are, however, acquired rather through instruction than research. When a conceptual system is constructed or acquired one must "*first through instruction and use build up an integrated set of concepts and rules, and second through argument to come to see its explanatory coherence*" (Thagard 1992). It should be noted, that then the explanatory coherence of most importance is the coherence of concepts with respect to experiments. Within the network view such conceptual structures can be represented as concept maps, where connections between concepts are formed through the requirement of meaning coherence consisting of deductive and explanatory coherence. In this study, we have examined the structural features of such concept maps drawn by experts in physics and by novices (students). The structural features are analysed by using graph theoretical methods to find characteristic topological features of the maps and the hierarchical structure of the maps. It is shown that experts' maps are characterized by conceptual coherence and hierarchies, which are inbuilt in the network-structures. In novices' concept maps similar features are found only in best cases. Many novices produce maps with partial coherence and severely fractured organizing hierarchy; in some cases there is no structure at all. The notion, that structural features of the concept maps are so closely connected to expertise has interesting implications for physics education. Finally, we discuss the applications and advantages of the viewpoint emphasizing the networked structure of concepts in physics teacher education.

## 2 Coherent knowledge structures in physics: Networks of concepts

In physics the structure of knowledge has a certain hierarchy built in it, although the hierarchy is not necessarily a strict one. Traditionally the organisation of knowledge in physics its laws - relations between concepts - is also seen as hierarchical; the uppermost level contains the major principles, and the lower level laws are subordinated to these more general principles (cf. Duhem 1954, Campbell 1920). In more recent views, this idea of hierarchy and connectedness is inherited by the model structures, which are thought to form the basic knowledge structures of physics (Giere 1999).

### *2.1 Coherence of knowledge*

In the coherentist account of knowledge (see e.g. Thagard 1992, 2000) explanatory coherence is central for the epistemic justification of knowledge. Explanatory coherence is obtained when hypothesis and propositions are made to cohere what they explain, also those hypotheses that together explain something, cohere Such coherence is obtained as constraint satisfaction (Thagard 1992). The concept- and theory-structures get their epistemological credentials mainly from their explanatory coherence. In conceptual systems there are usually different possibilities for the use of concepts and models to understand certain target phenomena. In this it is possible to find different mappings between a source and target, and the found coherences in mapping hypotheses. This is referred to as analogical coherence. Analogical coherence, when achieved, enhances explanatory coherence. Finally, there is deductive coherence, where the cohering elements are mathematical propositions, axioms and theorems. Deductive coherence has a close resemblance to explanatory coherence, because some explanations are deductive (but not all). The coherentist account of knowledge leads naturally to the idea that the connections between concepts and the nature of the principles linking the concepts is of central importance in establishing the meaning of the conceptual system. Thus, attempt to establish coherence is the driving force behind the evolution and modification of conceptual systems (Thagard 1992, 2000).

### *2.2 Conceptual hierarchy as network*

Based on the coherentist view of knowledge, Thagard suggests that concepts are complex network-like structures, where a special role is given to interrelations between concepts. This viewpoint emphasises concepts as parts of ordered knowledge structures or networks; they cannot be defined semantically or in isolation of other concepts; '*rules connected to concept are parts of them as well concepts are part of the rules*' (Thagard 1992). These kinds of systems can be analysed as a network of nodes where each node corresponds to a concept and each link corresponds to a relationship between concepts (Thagard 1992, diSessa & Sherin 1998). A conceptual change can then be seen as adding or deleting new nodes or creating new links between the nodes. Within these structures it is possible to distinguish part and kind hierarchies, which organize the whole system. Most notable changes involve changes in the hierarchies, and this change is associated with the restructuring of the links. According to Thagard, the most important feature of the hierarchies is that they not only organize the structures, but they create and define ontologies by specifying the constituents of world and their relation to each other. This entangled web of concepts and rules also makes it possible to apply concepts in different situations for providing explanations and making predictions. The meaning of concept emerges not only when learning the definitions and rules but also in the ways of applying the concepts and rules when solving various problems (Thagard 1992).

In the formation of the conceptual network the rules of formation or the rules used to attach new concepts and laws in the network acquire a crucial role. This is largely a methodological question and should not be overlooked, because in physics certain methodological principles need to be acknowledged in order to justify the knowledge. One central method of physics is to integrate new concepts in the framework through experiments, where the concept is operationalised and made measurable through the pre-existing concepts in the network. These experiments are quantifying experiments where quality is transformed to quantity (c.f. Duhem 1954). Quantifying experiments also form new relations between quantities in network and thus new experimental laws (Duhem 1954, Campbell 1920). It is through these quantifying experiments that the hierarchy of network is constructed. Therefore such experiments acquire an important methodological and epistemic role in physics education and they actually contribute to constructing the meaning of concepts (Koponen & Mäntylä 2006). This view, which puts weight on the logic and methodology of physics knowledge formation also forces an unavoidable hierarchy on physics knowledge. Such a hierarchy is quite often taken to be an unquestionable and characteristic feature of physics knowledge (see. e.g. Thagard 1992, Giere 1999).

## 3 Constructing the concept networks

Learning is also working with and building networks. It becomes a continuous conceptual change where new systems are obtained by addition and deletion of nodes, agglomeration of branches of the network, or restructurisation of the network as a whole (Thagard 1992, diSessa & Sherin 1998). The elements and rules, which are used to construct the networks are summarized below as the *nodes* and *edges* the network is made of.

**Nodes.** The structural elements, which are nodes of the network can be:

1. Concepts or quantity.
2. Laws, i.e. particular laws or law-like relations.
3. Fundamental principles.

Of these elements, laws could be taken as particular experimental laws or law-like predictions in specific situations (derived from theory). Fundamental principles are the highest-level principles or axioms of theory.

**Edges.** The rules to make connections create edges. Each edge is a well-defined procedure and can be:

4. A Logical procedure, which are definitions or logical deductions.
5. An experimental procedure, which is operational definition or demonstration.

These procedures are represented as links connecting concept and create edges (links) on the representation. Adopting these rules for the construction of the graphs restricts the possibilities of what kinds of knowledge can be represented in these graphs. However, the experts agreed that although this is a restriction, it is not too severe and does not prevent us from displaying essential and useful information in the graphs. In addition, it should be noted that the adoption of any rules for the construction of structures always forces on these structures a certain order or even hierarchy. However, if the rules are not alien to the knowledge we want to represents, such structures and hierarchies may well be truthful enough for the structure of knowledge we want to reveal. The most severe restriction of these representations is that our conceptual structures will be limited to laboratory phenomena and experiments. Such structures will at best have explanatory coherence only for those experiments, which are included as procedures. However, without extending the conceptual framework to provide explanations for real phenomena, we cannot actually show how the explanatory coherence on a larger scale is acquired. In addition, the logical procedures provide the deductive coherence. In what follows, we will use the term *meaning coherence* to describe this combination of explanatory coherence, which is restricted to laboratory experiments and deductive coherence.

## 4 Applications of network-view: Expert's and novice's knowledge structures compared

Three experts, who are physics instructors, were given the task to represent connections between concepts of electrostatics. The experts were familiarized with idea of representing the concepts and laws as a connected network-like structure. In effect, they were asked to produce a concept map collaboratively of the pertinent knowledge elements. In order to have representations which could be evaluated and analysed as unambiguously as possible, the experts were introduced to the use of rules for connections (links or edges) and rules to make distinction between different entities in map. Because the experts were familiar with the idea of concept mapping and had used it in their teaching to some degree before, the methods and ideas for drawing such representations was familiar to them. In what follows, it is important to note that although the rules adopted to construct the maps are restrictive, they do not prevent the display of relevant physics knowledge. This means representing that part of the expert's knowledge, which has the meaning coherence allowed by logical and experimental procedures coded in the edges. Novices' maps are then compared against the expert map, and then similarities between the expert map structures can immediately be taken hallmarks of good content, and severe deviations as hallmarks of deficient content. In this way, structures and comparison of structures also give us information about the quality of the content. Of course, more detailed content analysis, which is independent of the structure, would give more information about the quality of knowledge represented by the maps. However, at present we are concentrating only on the structural aspects only.

### *4.1 Structure and meaning coherence of expert's map*

Following the rules outlined above, experts produced a preliminary map, which they then after discussions modified over several stages. The final version which they agreed on and which they thought contained the essential elements of electrostatics is shown in Figure 1. In this representation, following rules for nodes and edges is shown concepts (boxes), laws and principles (boxes with thick borders), definitions (D) and logical deductions (L). In addition, a conceptual (geometrical) model is shown as ellipse, and entity like objects as rounded boxes. Of the procedures, only the operationalising experiments are shown (E), and in most cases the demonstrating experiments are similar ones, but the directions of the arrows are reversed. The detailed content of the experiments is not important here, it is sufficient to know that they are mostly standard student laboratory experiments done in the context of electrostatics. The interesting feature of the expert map is the high connectivity of concepts and the tendency of some concepts to attract edges. However, a more detailed analysis of the maps is difficult without methods to analyse the topology of the maps.

The previous study by Reichherzer and Leake (2006) of the structure of a concept map as it relates to the content of the map have shown that the relevant information of a central concept can be extracted from topological information, even from average measures like the root distance and the connectivity of nodes characterizing the topology (Reichherzer & Leake, 2006). Topological taxonomy has been used also by Cañas et al. (2006) to classify concept maps and to evaluate their quality. However, whereas Reichherzer & Leake use metrics emphasising connectivity of nodes, Cañas et al. pay attention to measures related to branching. In what follows, we propose a topological analysis which simultaneously takes into account node connectivity as well as branching. Moreover, global topological features are in focus, and possibility to transform maps from one layout to a topologically equivalent layout for better recognition of central features.

The topology of the expert map can be examined more closely by using the methods of graph theory. The steps followed to analyze the structure are:

- coding the map to a connectivity matrix
- using the matrix to redraw the map as a hierarchically ordered tree

The coding of the map nodes and edges is done by using only the binary values 0 and 1, so that no other qualities but the existence of connection and its direction are coded, but no other qualities. In fact, the information of the directedness is not taken into account, because it is not needed in order to show the primary features of the topology. Of course, in more detailed analysis, when also type of the edges is considered, the directedness of edges is of central importance. However, in this works only the primary features of topology and the possibility to transform the maps in different topological forms and the advantages of these transformations are of interest.

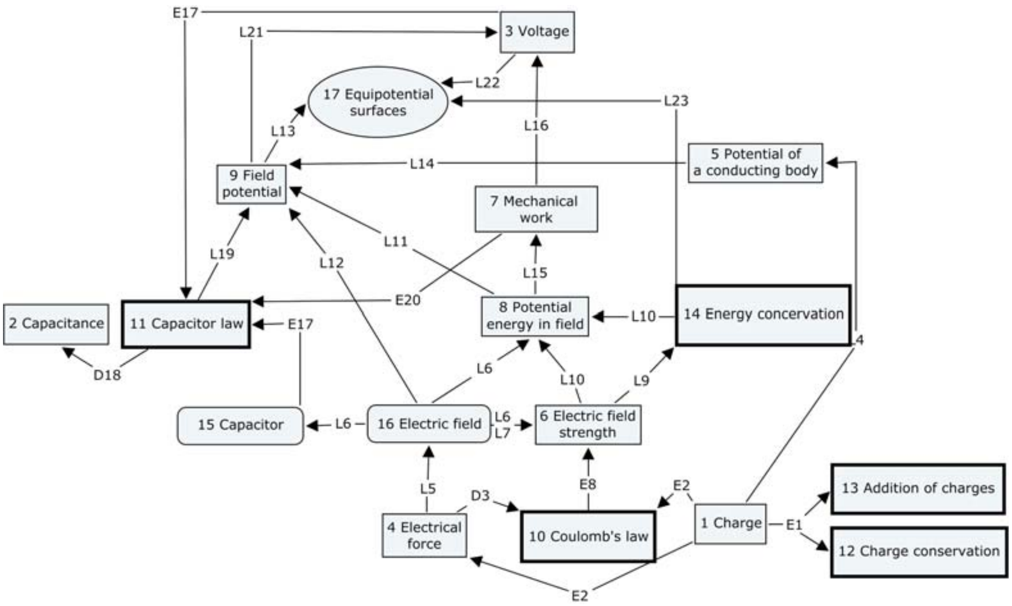


**Figure 1**. The experts' map for the concepts and laws in electrostatics. The map is shows concepts (boxes), laws and principles (boxes with thick borders), definitions (D) and logical deductions (L), and operationalising experiments (E). Conceptual (geometrical) model is shown as an ellipse, and entity like objects as rounded boxes.

The redrawing and transformation of graphs was done using COMBINATORICA (Pemmaraju & Skiama 2006), which allows using different rules to redraw the maps and to compare their topological features. Using well-defined rules to represent maps removes the ambiguity associated with personal styles for doing the layout of the maps. In addition, the transformation of maps in different forms to detect hierarchical structures hidden in the connections becomes much easier. The advantage of COMBINATORICA is that it is based on well defined and established graph theoretical concepts, and it is freely available.

In analyzing and redrawing the concept maps we used two different graph-embedding methods, which produced webs- and tree-like structures.

**Webs.** Maps are redrawn as undirected structures but so that the "energy" of edges (edges taken as springs with tension) is minimized while "entropy" (nodes are located as far from each other as possible) of the structure is maximized. This reveals how tightly certain concepts are tied together. The coherent map should not then break up into distinct loosely connected branches or chains instead it should resemble a web-like structure.

**Trees.** Maps are redrawn as an ordered hierarchical tree, selecting a certain node as a root. Then nodes and edges are rearranged so that nodes that are equidistant from the root are on the same hierarchical level. The coherence of the structure is now reflected as distinct hierarchical levels, with many interconnections within each level. It should be noted, that a hierarchical tree without intra-level connections is not coherent and meaningful.

The expert map redrawn as a web and tree-like hierarchical structure is shown in Figure 2. From these redrawn maps we can see that the expert map contains hidden hierarchies when a physically relevant concept is chosen as a root concept. This, of course, is as expected, because the map is drawn following physically meaningful rules, where concepts and laws follow either from well defined experimental procedures or from logical procedures. Therefore, it is important to understand, that the organized structure and with a well-defined hierarchy with clearly recognizable hierarchical levels is a direct consequence of physically meaningful and coherent content. The rules build on the structure the meaning coherence and meaning coherence is thus recognized through structural characteristics and through hierarchy.

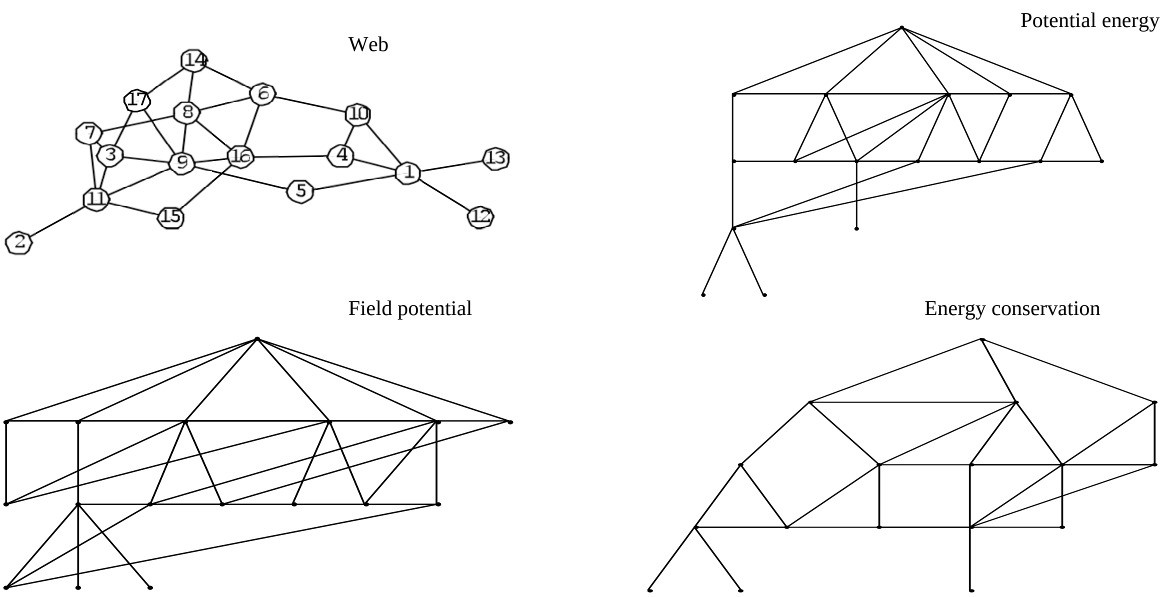


**Figure 2.** Web-structure (upper left) and tree-structures and hidden hierarchies in expert map

*4.2 Structure and coherence in novices' maps*

The students' map are analysed following the same principles as expert's map. The students who produced the maps had studied the standard first year university courses on electricity and magnetism and electromagnetism, but they had not done any advanced studies. Therefore, the student maps are expected to be more like novices maps. The students drew maps for the connections between concepts of electrostatics in a teacher preparation course (third year studies). The students were given a list of concepts and laws that contained all the same concepts and laws as our expert map. On the basis of the list, the students were asked to represent the connections and also to define the nature of the connections, i.e. whether they were experimental procedures or logical procedures. All the students were already familiar with concept mapping and the use of concept maps.

Students produced the maps in groups and we got a total of 20 maps. The maps were analysed using the same methods as used for expert map. First a connectivity matrix was produced, which was used to redraw the webs and trees using COMBINATORICA. On the basis of their structure the maps were classified into three classes according to their structure. In this classification, the overall structure (connected webs, loose webs and chains) and hierarchy was used as the basis of classification. In these three classes, we can see the typical features of student maps.

**Connected webs.** In case of connected webs the topology of redrawn maps as webs is rather similar to that of the expert map. The web seems to be tightly connected and there are no clearly separate branches. Looking more closely at the hierarchies contained in the maps, it becomes evident that there is number of relevant hierarchies, where concepts are coherently connected. One example is shown in Figure 3 (I). In comparison to the expert map we can however see that the hierarchies are not as well defined as in the case of the expert map, and the hierarchies are partially broken. This reveals that not all possible coherent meanings are contained in the map. This kind of map, although not yet as comprehensive and coherent as the expert map, shows already a mature understanding of the structure of a concept web and it allows many coherent meanings to be represented. The map has significant meaning coherence.

**Loose webs.** In some cases student maps have a topology that consists of connected webs as subsets, but the subsets are loosely connected. These kinds of webs shown in Figure 3 (II) we have called loose webs. The fragmentation of map to subsets reveals that some important connections are missing. This deficiency is also seen in tree-like redrawn maps, where hierarchies are now severely broken, as can be in lower panel in the example in Figure 3. In comparison to connected webs, these loose webs thus have significantly less inbuilt meaning coherence inbuilt than connected webs.

**Chains.** In some cases, the structures are not webs, but rather consist of linear branches that resemble chains or weeds, as shown in Figure 3 (III). In these structures, there is very little connectivity. Hierarchies in these cases are trivial branching hierarchies, with no intra-level connections. The missing connections are directly connected to poor relatedness between concepts and weak coherence between concepts. These structures lack the meaning coherence and are not adequate representation of conceptual structure.

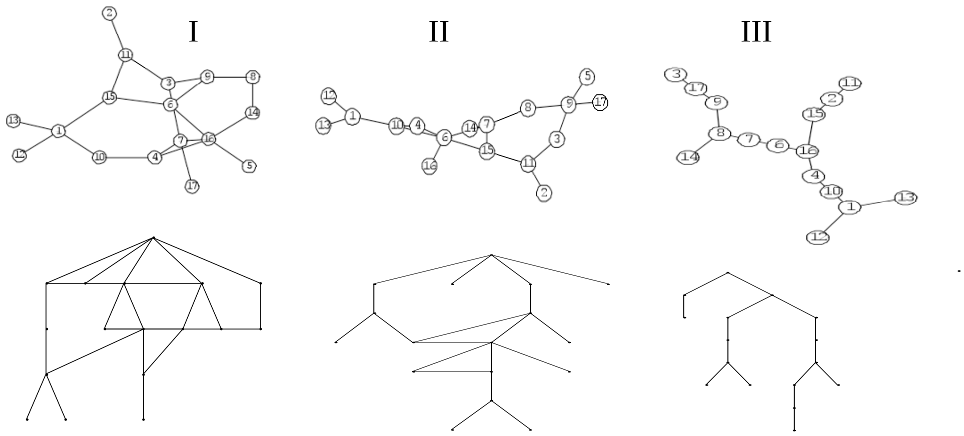


**Figure 4.** Connected webs (I), loose webs (II) and chains (III). An example of a typical tree-structure corresponding each type of map is given in lower panel. Only for connected web hierarchies can be found, for other structures the hierarchies are severely broken.

The classification of structures in connected webs, loose webs and chains brings forward the notion that meaning coherence inbuilt in the structures is reflected on the overall topology. This connection comes from the fact that meaning is constructed through the creation of edges (creation of links), which we required to have a specific meaning: either experimental or logical. In absence of these meanings, it is not possible to establish the connections. This simple notion underlines the importance of attributing a definite meaning to each link. Just drawing a line without specified meaning is void of meaning, not interpretable and ambiguous. It should be noted, that now the attributes attached to edges are not simply verbs or expression making it possible to form a sentence, as in case of ordinary concept maps. Instead, the links represents procedures, which we can perform. Therefore, links contain essential knowledge about the methods of physics concept formation.

The differences in expert's map and novices maps can also be seen by calculating some characteristic measures for the maps. First, we can classify the nodes as hubs, junctions and outliers. **Hubs** are important connecting nodes, which tend to collect edges, and have more than two incoming/outgoing edges. **Junctions** are nodes that have at least one incoming and one outgoing edge to two different nodes, so that the removal of junction will break the network in two pieces. **Outliers** are simply terminal nodes, which have no role in connecting parts of the network. In Table I is listed the relative fraction of hubs, junctions and outliers in the expert’s map shown in Figure 2 and in the novices’ maps shown in Figure 3. In addition, we have calculated the degree of hierarchy as an average number of hierarchical levels per physically meaningful root concept.

| | Expert | Novice I Connected web | Novice II Loose web | Novice III Chain |
|---|---|---|---|---|
| Hubs | 0.7 (12) | 0.6 (9) | 0.4 (7) | 0.2 (3) |
| Junctions | 0.2 (3) | 0.3 (5) | 0.4 (7) | 0.3 (5) |
| Outliers | 0.1 (2) | 0.2 (3) | 0.2 (3) | 0.5 (8) |
| Hierarchy | 4.4 | 2.6 | 1.6 | 1.0 |

**Table I:** Relative fraction of different types of nodes and the degree of hierarchy of the expert’s map and novice’s maps I-III. Total number of each type of nodes is given in parenthesis.

The results in Table I show that there is clear correlation between the connectedness of the map and its degree of hierarchy. By classifying all the novice’s maps we found that in class of connected webs, the hierarchy degree is on the average 2.5, loose webs have 2.0 while chains score only 1.5. So there is a correlation between the topology of networks and their inbuilt hierarchies.

## 5 Discussion and conclusions

The notion that there is a clear connection between the contents of the maps and their structures may seem rather trivial and just agree with our most obvious expectations. However, if we ask how a good structure can be recognized, and on what aspects we need to pay attention to, the situation is not so simple. An often used criterion in traditional analyses of concept maps an often used criterion is the number of cross links and the requirement that links have some verbs or attributes attached to them (see e.g. Slotte & Lonka 1999 and references therein). In our case, these requirements are simply insufficient and could not lead to meaningful evaluation of the maps. On the contrary, just increasing the cross links would not improve the meaning coherence, if there are no reasonable and physically sound procedures for the creation of links. It is essential to note, that in our case nodes are not connected on basis of associations but rather on basis of well defined procedures. Similarly, the requirement that edges make the connected nodes as propositions, which can be verbalized (Ruiz-Primo & Shavelson 1996), is not appropriate for our purposes of representing physics concepts and laws, because it would mean diminishing the meaning content of the link.

The analysis we have done here suggests that if we have rules to create edges and the rules which are based on procedures, we will have representations, where content and structural aspects are strongly coupled. The structural and topological characteristics of maps have a resolving power, so that three qualitatively different types of networks can be distinguished from novices’ maps, and these can be compared with an expert’s map. It is found, that the topological connectedness and richness of hierarchical structures organized by physically meaningful root concept are hallmarks of rich meaning content. The hierarchy, on the other hand, is seen to be connected to the general topology and appears only in structures that are connected webs. These notions can be easily embedded and made understandable within the framework of the coherentist view of knowledge, as advocated by Thagard (1992, 2000). In this view, knowledge and concept and principles associated with the knowledge obtain their credibility, reliability and truth from the coherence of the structures. In that explanatory coherence is of central epistemic importance, because it connects the structures to reality. In our case, the networks contain explanatory coherence in a restricted sense; only with respect to experiments and experimental procedures (the standard student experiments used in teaching) connected to the links and in addition deductive coherence connected to logical procedures. Together these coherent features provide the map what we have here called meaning coherence.

However, the meaning coherence defined in that way is much reduced form of all possible forms of coherence (c.f. Thagard 2000) found in scientific knowledge. In the present case we have deliberately restricted the scope of explanatory coherence in order to make the structures here more tractable and yielding to detailed analysis. In future, of course, in order to extend the conceptual structures to cover broader areas of phenomena and not only laboratory experiments and laboratory phenomena, we should make a similar representation of concepts and laws as applied in giving explanations of real complex phenomena. However, it is evident that such an attempt would be far more demanding than the case studied here. Nevertheless, the analysis given here and the way the connections are build in show there is a direct connection between the topology and hierarchy of the maps and their meaning coherence; maps with good meaning coherence have rich internal hierarchy and well connected topology. The analysis carried out here has taken into account a certain minimal meaning content of edges, and more thorough analysis of meaning content is needed to make further progress. A promising combination is a structural analysis combined with e.g. semantic analysis of content (see e.g. Cañas et al 2006).

An interesting possibility contained in network view is its potential for uses to monitor conceptual development. Within the network view conceptual development takes place through addition and deletion of nodes and edges in the structure, and the driving force behind this is the acquisition of a better meaning coherence of such structures. Thagard (1992) has applied the network-view to understanding the historical conceptual change or historical conceptual revolutions, and it seems that in this case the network view leads to a deepened understanding of how explanatory coherence guides the evolution of the conceptual structures. In Thagard's work the focus is on addition and deletion of nodes and in restructirization of links, both processes being driven by constraint satisfaction for better explanatory coherence. It is quite evident, that similar description also could be possible in learning and in monitoring the learning, and in finding typical features of the conceptual change during learning. The directions seem to open up promising ways to improve traditional physics teaching and instruction, and to develop concept mapping and concept maps which are truly useful representations for expressing physics knowledge, its structure and the relation of structure to methodological procedures. Such an extended view on concept maps escalates the maps from tools of thinking and reasoning in the personal cognitive realm to a more inter-subjective level, where they begin to share more and more structural aspects and contents of physics knowledge itself. In this form they can eventually begin to function as effective learning tools also for learning the real content knowledge of physics in higher education

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