Educational Research Vol. 42 No. 1 Spring 2000 43–57

How a qualitative approach to concept map analysis can be used to aid learning by illustrating patterns of conceptual development

Ian M. Kinchin and David B. Hay, School of Educational Studies, University of Surrey, Guildford, Surrey GU2 5XH, **and Alan Adams,** The Towers School, Faversham Road, Ashford, Kent TN24 9LY

Summary

This paper describes a qualitative approach to analysing students' concept maps. The classification highlights three major patterns which are referred to as 'spoke', 'chain' and 'net' structures. Examples are given from Year 8 science classes. The patterns are interpreted as being indicators of progressive levels of understanding. It is proposed that identification of these differences may help the classroom teacher to focus teaching for more effective learning and may be used as a basis for structuring groups in collaborative settings. This approach to analysing concept maps is of value because it suggests teaching approaches that help students integrate new knowledge and build upon their existing naïve concepts. We also refer to the teacher's scheme of work and to the National Curriculum for science in order to consider their influence in the construction of understanding. These ideas have been deliberately offered for early publication to encourage debate and generate feedback. Further work is in progress to better understand how students with different conceptual structures can be most appropriately helped to achieve learning development.

Keywords: concept mapping, collaborative learning, constructivism, differentiation, meaningful learning, science education

Introduction

In this paper, we attempt to address a perceived need for a mechanism to make the benefits of concept mapping more accessible to the classroom teacher. If it

Address for correspondence: Ian M. Kinchin, School of Educational Studies, University of Surrey, Guildford, Surrey GU2 5XH, UK.
E-mail: I.Kinchin@surrey.ac.uk; kinchi@globalnet.co.uk

is to be widely used, such an approach must present tangible benefits by enhancing communication between the teacher and the students, but it must also be quick and easy to administer. By complementing existing best practice (such as collaborative learning strategies), concept mapping will be seen potentially to have a very powerful role in promoting meaningful learning and providing the teacher with a valuable insight into the mental models of students. This will enable teaching to be more precisely focused on the students' needs and so make more effective use of class time. Here we report on a qualitative approach to concept map analysis. This differs from previously published reports which have focused on quantitative scoring schemes. The method is simple and quick to carry out. The results of a classroom-based exercise described here appear to provide a simple framework for interpretive analysis.

Concept mapping

Concept mapping (as developed by Novak, 1990, 1996, 1998) has been shown to be a classroom technique that can enhance learning in the sciences (e.g. Horton *et al.*, 1993; Lawless, Smee and O'Shea, 1998). Recently it has been suggested that the most appropriate time for introducing mapping may be early in the students' educational careers, before preferred study habits have been firmly established. Where mapping is introduced at a later stage, it is essential that the possible benefits to the learner are made explicit to the students if they are to adopt the technique as a part of their typical study strategy (Santhanam, Leach and Dawson, 1998). In particular, concept mapping can be a helpful metacognitive tool, promoting understanding in which new material interacts with the students' existing cognitive structure. The interaction of new and existing knowledge is made easier if the existing knowledge is made explicit to both teacher and student. This is described as 'meaningful learning'. The construction of a concept map is intended to reveal the perceptions of the map's author, rather than a reproduction of memorized facts (Jonassen *et al.*, 1997). The structure of a map is, therefore, unique to its author, reflecting his/her experiences, beliefs and biases in addition to his/her understanding of a topic. The ability to construct a concept map also illustrates two essential properties of understanding, the representation and the organization of ideas (Halford, 1993).

Regarding representation, Halford (*ibid.*, p. 7) states that 'to understand a concept entails having an internal representation or mental model that reflects the structure of that concept'. A concept map is an attempt to make explicit such a model, so that it can be reviewed with others. Johnson-Laird (1983, p. 165) has suggested that there are three kinds of representations, 'propositional representations which are strings of symbols that correspond to natural language, mental models which are structural analogies of the world, and images which are the perceptual correlates of models from a particular point of view'. This view has been criticized by Halford (1993, p. 23), who proposed that mental models 'may consist of any combination of propositional and imaginal representations'. A concept map can, therefore, be seen as a portrayal of a mental model. Organization of knowledge can assist memory search and so aid recall. It should facilitate learning by making the material to be learned more predictable and so reducing the learning effort required (*ibid.*, p. 7). The construction of concept maps is an excellent way of helping to organize knowledge and so help understanding. In combination, these comments reflect Wandersee's assertion that 'to map is to know' (Wandersee, 1990, p. 923).

Discussion of a possible theoretical model, exploring the mental activities in which students are engaged when producing concept maps, has been given by McAleese (1994). The act of concept mapping may promote the development of thinking skills by providing an explicit point of focus for reflection. This process is described by McAleese as 'auto-monitoring'. A key aspect of this is considered to be the visualization of the 'learning arena' as portrayed by the map, a view echoed by Shambaugh (1995).

The use of concept mapping is often linked to the 'constructivist' view of learning as a concept map makes a good starting-point for constructivist teaching. There are many views that are grouped together under the constructivist heading. In outline, it has been usefully summarized by Novak (1993) as being based in the belief that from birth to senescence or death, individuals construct and reconstruct the meaning of events and objects they observe. For the constructivist, knowledge is created rather than discovered. Even those who have been critical of the constructivist stance have acknowledged its success in generating a significant body of empirical data which has contributed to our knowledge and understanding of difficulties in the learning of science, enabling the development of some innovative teaching methods and creating a greater awareness of the central importance of the learner (e.g. Osborne, 1996). Other commentators have responded to criticisms of constructivism and concluded that there is no fundamental conflict between 'constructivists' and 'traditional scientists' (e.g. Refinetti, 1997; Staver, 1998), with many of the areas of disagreement arising from a lack of mutual understanding. Reports in the literature describe the advantages of a constructivist approach to teaching biology, including improvements to test results, student attitudes and student enjoyment of the subject (e.g. Yager, 1995; Lord, 1997). Constructivism emphasizes that science is a creative human endeavour which is historically and culturally conditioned and that its knowledge claims are not absolute.

The development of such constructed and reconstructed knowledge can be represented graphically using concept maps. Teaching that helps this reconstruction process will lead to meaningful learning. The action of mapping is also thought to help the process by revealing to the student connections that had not been recognized previously and by acting as a focus for communication between student and teacher. This is illustrated by Novak and Gowin's statement that, 'students and teachers constructing concept maps often remark that they recognise new relationships and hence new meanings or, at least, meanings they did not consciously hold before making the map' (1984, p. 17).

An important function of the map is to help make the overall framework of the concept explicit. This is particularly important for complex topics where students display a fragmentary understanding of a topic and are frequently unable to integrate all the components to form a meaningful overview (e.g. Stavy, Eisen and Yaakobi, 1987). Identifying these fragments of understanding, termed 'anchoring conceptions' by Clement, Zietsman and Brown (1989), is vital as these must form the foundations for future meaningful learning.

Evaluating concept maps

Differentiation between concept maps has often been undertaken quantitatively, based on the scoring protocol devised by Novak and Gowin (1984). Subsequent authors have made minor modifications (such as the relative weightings of the scoring components), but all tend towards an aggregate score of factors including the number of valid links presented; the degree of cross-linkage indicated; the amount of branching; and the hierarchical structure (e.g. Dorough and Rye, 1997). This has sometimes been done in comparison with an 'expert map' (e.g. Herl, Baker and Neimi, 1996). This aggregation of scoring elements creates a blurring of what the overall score actually reveals.

The scoring of only 'valid links' also misses the point that 'invalid' links may have a value to the student by supporting more valid links (sometimes temporarily) and so contributing to the overall knowledge structure that he or she is using as a basis for further learning. The usual emphasis on 'valid links' seems to contradict the constructivist philosophy underlying the use of concept maps by failing to recognize the significance of students' perspectives. The invalid links in a student's map may reveal much about the thought processes that lead a student along a particular path of understanding. The definition of a 'valid link' can also cause problems as a link may be 'valid' in terms of providing a factually correct statement, but may be inappropriate when considered in the context of the core concept under discussion. Problems in the consistency of scoring schemes, and other limitations of concept mapping have been highlighted in the literature (e.g. Jonassen *et al.*, 1997; Liu and Hinchey, 1996; Ruiz-Primo and Shavelson, 1996).

This suggests that a more informative assessment of concept maps is required that could be used to bring benefits to the students' learning experience while not placing unrealistic demands on the classroom teacher. To satisfy these requirements, a more qualitative description may be appropriate. The comment was made by Stuart (1985, p. 80) that 'to continue to rely on numerical scores . . . is to risk missing . . . diagnostic data used to help the pupil'. Such a numerical description only seems necessary if the map is to be used for summative assessment. Emphasis on quantitative evaluation in the literature seems to reflect the use of concept mapping as a research tool, rather than a formative teaching tool. We are suggesting here that concept maps should be viewed as a qualitative instrument to aid the process of meaningful learning in the classroom.

Qualitative classification of concept maps

The classification described below was originally recognized when reviewing reproduction in flowering plants with a group of Year 8 pupils. This topic has, therefore, been used to provide examples for discussion here. Subsequent studies with students of varying ages (including postgraduate students), and considering different topics in the biological sciences, have revealed the same basic types of map structure. Illustrations of the three types, denoted as 'spoke', 'chain' and 'net', are given in Figure 1(a)–(c) respectively.

As 'invalid links' are seen as being of equal importance to 'valid links' (in terms of teacher-awareness), the time-consuming (and sometimes arbitrary) process of assessing the validity of links is avoided. The simplicity of this classification scheme makes it more likely that it could be adopted for classroom use and yet it fulfils the criteria for an effective qualitative scheme outlined by Kinchin (1998). The scheme differentiates maps in terms of their complexity; resilience in accommodating additions; the establishment of a context for the key concepts; degree of appreciation of a wider viewpoint and its relationship with the 'expert' view. This is summarized in Table 1.

Implicit in this classification is the development of increasing integration of a conceptual framework from spoke structures towards net structures. The structure

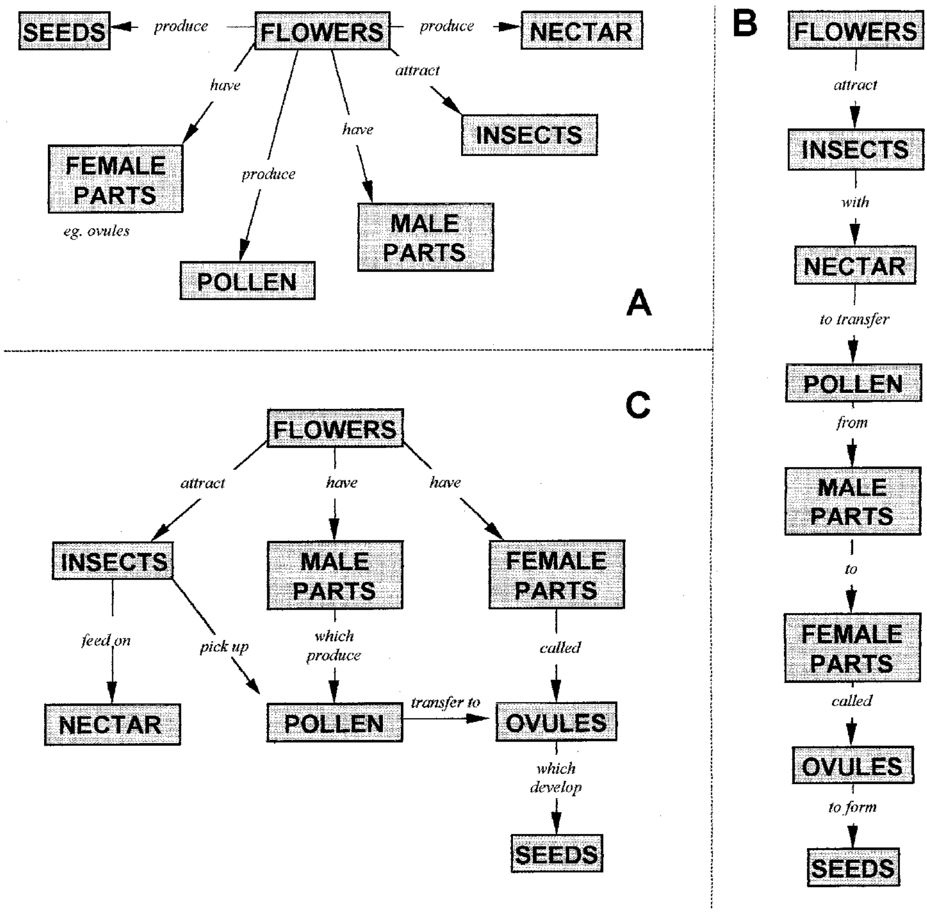

FIGURE 1 The three main concept map structures identified during the study
(a) Spoke – a radial structure in which all the related aspects of the topic are linked directly to the core concept, but are not directly linked to each other.
(b) Chain – a linear sequence of understanding in which each concept is only linked to those immediately above and below. Though a logical sequence exists from beginning to end, the implied hierarchical nature of many of the links is not valid.
(c) Net – a highly integrated and hierarchical network demonstrating a deep understanding of the topic

of the framework held by a student will have implications for the mechanism of further meaningful learning. If a pupil holds a spoke structure (Figure 1(a)), then the addition of new knowledge will not cause any disturbance to the existing framework. It can simply be added in with a link to the core concept, but without any links to associated concepts. The result would be that the knowledge can be assimilated quickly, but only be accessed by reference to the core concept and not by reference to one or other of the associated concepts. For the pupil with a chain structure (Figure 1(b)), the addition of new knowledge will be easy if there is an obvious break in (or premature end to) the sequence, but may be problematic if a workable sequence is already in place as the additional concept may appear superfluous. Alternatively, the addition of a concept near the beginning of the sequence

TABLE 1 Concept map analysis

	Map type		
	Spoke	*Chain*	*Net*
Hierarchy	One level only	Many levels, but often incorrect – e.g. 'female parts' are shown as subordinate to 'male parts' in Figure 2(b)	Several justifiable levels
Processes	Simple association with no understanding of processes or interactions	Shown as a temporal sequence with no complex interactions or feedback	Described as complex interactions at different conceptual levels
Complexity	So little integration that concepts can be added without consequences for 'map integrity'	Map integrity cannot cope with additions, particularly near the beginning of the sequence	Map integrity is high. Adding one or more concepts has minor consequences as 'other routes' through the map are available
Conceptual development	Shows little or no 'world view'. Addition or loss of a link has little effect on the overview	Integrated into a narrow 'world view', suggesting an isolated conceptual understanding. Loss of a link can lose meaning of the whole chain	Can support reorganization to emphasize different components to appreciate a 'larger world view' or to compensate for a 'missing' link
Represents	National Curriculum structure	Lesson sequence	Meaningful learning

may be so disruptive to the knowledge structure lower down that incorporation of the new knowledge is rejected. Additionally, understanding of a concept in the middle of the sequence may be difficult without travelling from the beginning. For the student with a net framework (Figure 1(c)), access to a particular concept may be achieved by a number of routes, making the knowledge more flexible. However, this requires understanding of the associated concepts beyond their link with the core concept and so implies a wider understanding.

The occurrence of the types of map illustrated may be partially explained by the students' interpretation of the styles of 'expert' views to which they are subjected. Consideration of the layout of National Curriculum orders for Science (GB. DFE, 1995), where a core concept is followed by a listing of related concepts to be taught, suggests a spoke arrangement of knowledge. The links between subordinate concepts are not made explicit. While the teacher will be aware of this documentation, the pupils' direct interface with the published curriculum will be through the scheme of work that is followed in class, along with the accompanying textbooks, handouts and tests. These will tend to transform the spoke arrangement of the National Curriculum into a chain arrangement of

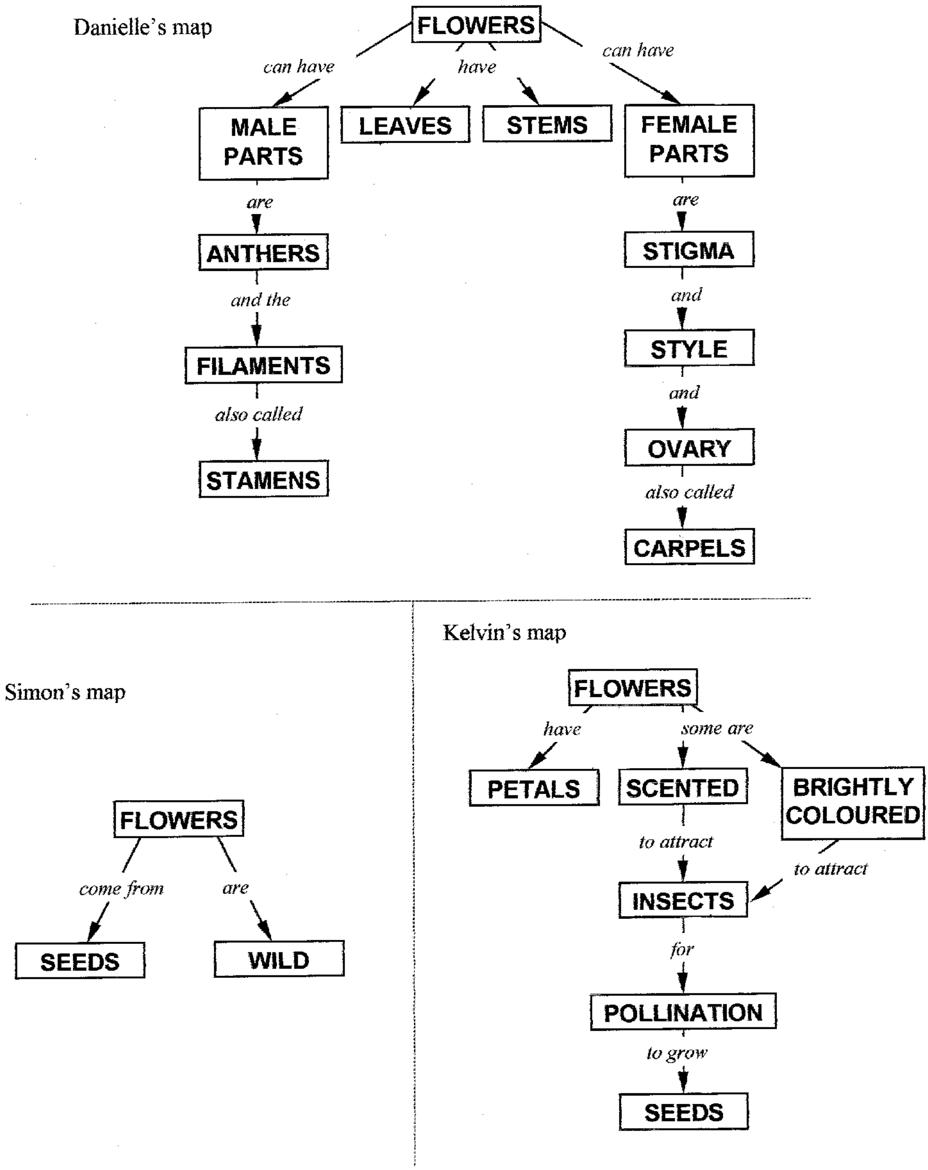

FIGURE 2 Examples of concept maps produced by Year 8 pupils on the subject of reproduction in flowering plants

a lesson sequence. This is reflected in the maps shown in Figure 2, which were produced by Year 8 pupils on completion of a series of lessons on reproduction in flowers. Three of those pupils are referred to here as Kelvin, Danielle and Simon.

Kelvin's map is dominated by a chain showing an appreciation that flowers need to attract insects for pollination, suggesting a focus on one particular section of a lesson sequence. Danielle's map is characterized by two chains showing an appreciation of the male parts of flowers and a separate appreciation of the female parts of flowers. These are shown as distinct sequences of understanding with the lack of overlap emphasized by the positioning of the chains so far apart in her map. While the interrelationship between male and female may seem obvious to the teacher, Danielle has failed to make this connection and so has missed out on one of the key points of reproduction. Martin (1994, p. 15) has noted how often 'teachers teach one of the vertical hierarchies of the map, then the next one, then the next one, and so on, sequentially, failing to relate the parts to each other and failing to demonstrate the interrelationships that need to be linked'. This suggests that curriculum documents and schemes of work need to concentrate on links between concepts as much as on the concepts themselves, as without appropriate links the concepts lose meaning. This will help students to put their understanding into a context that makes it more meaningful by creating potential for interaction with existing knowledge. Teachers may find it useful to include concept maps in their schemes of work to remind themselves of important links which need to be made explicit to their students and to help sequence teaching materials more effectively, as demonstrated by Cliburn (1986). It can be seen from Danielle's and Kelvin's maps that when such links are not emphasized, different students will take different elements from a teaching sequence upon which to base their individual knowledge structures.

In comparison to Danielle and Kelvin, who both have well-developed knowledge structures covering certain components of the topic, Simon's map suggests that he has really failed to internalize the details of reproduction in flowering parts in terms of sexuality or in terms of the relationship between flowers and insects. Such a simple map does not contain enough information to have its structure categorized as spoke, chain or net. It is, therefore, designated as a 'simple' structure, which demonstrates no development from typical pre-instructional understanding of this topic that would be expected of a much younger student (e.g. Hickling and Gelman, 1995).

Optimizing collaborative learning groups

For concept mapping to become a normal part of classroom teaching, it has to be able to complement other favoured strategies. This can be shown to be the case with the example of collaborative learning. The increased popularity of collaborative groupwork as an instructional strategy in the sciences has been described recently by Jones and Carter (1998). They view this growth as a parallel to a perceived shift in the focus of educators from an individual (Piagetian) perspective towards a wider social (Vygotskian) perspective. Implications of this have been explored by Scott (1996), Howe (1996) and Hodson and Hodson (1998). This move towards a social development of understanding recognizes the central importance of the use of appropriate language by students in a scientific context. Various initiatives have promoted the active use of scientific language through pupil–pupil interaction and pupil–text interaction (e.g. Henderson and Wellington, 1998) as an attempt to reduce reliance on passive learning.

Within collaborative classroom settings, it is not at all clear that the decisions on group structure are often made on sound educational criteria, rather than purely social or organizational reasons, such as simply letting friendship groups work together. Studies have shown that closely related factors variously termed 'achievement levels', 'ability' or 'status' of students will influence learning opportunities within collaborative groups (e.g. Bianchini, 1997; Hirokawa and Johnston, 1989; Rafal, 1996; Webb, 1989). Some studies have deliberately arranged students in mixed-ability groups as it was believed that this provides better learning opportunities for all students (e.g. Mueller, 1997). However, if the ability range within a group is too wide, it is suggested by Blumenfeld *et al.* (1996) that, in particular, middle-ability students will benefit less. Rafal (1996, p. 291) also reminds us that 'small groups occur in a larger social and academic context, embedded within a history of relations', and so the group should not be viewed in isolation, but seen in the context of the whole class. Therefore, just as some individuals within a group may be perceived by their peers as being of 'high' or 'low' status, some entire groups may also be working under similar labels.

While highlighting differences between students can clearly create problems, it would seem that identifying the diversity of knowledge structures in a non-threatening fashion is critical for the benefits of collaborative learning to be optimized. If differences within a group could be maximized (even within a narrow ability range), it has been suggested that this difference may act as a stimulant for conceptual development. Studies show that more progress takes place when students with different levels of insight work together than when students with the same levels do so (e.g. Mugny and Doise, 1978; Pine and Messer, 1998). The method used by Thorley and Treagust (1987) for differentiation of student pairs was to simply divide their students in two groups: those who 'knew it' and those who 'did not'. They subsequently found this to be unsatisfactory. These problems of optimizing group composition have recently been summarized by Wood and O'Malley (1996, pp. 5–6):

> the elaboration of knowledge and the motivation for reasoning and problem solving are most likely to occur when group members bring different perspectives and expectations to a shared activity. The implication of all this is that teachers should have a detailed knowledge of children's beliefs and expectations and know how to use this knowledge when forming groups designed to facilitate learning in such contexts.

A recognition of different concept map structures may provide a sensitive mechanism for creating such mixed groups without the attached stigma of individual or group labels as 'high' or 'low' achievers, as has been the case with some studies (e.g. Bennett and Cass, 1988). This would allow students with complementary knowledge structures (i.e. each of spoke, chain and net structures) for a particular topic to be best placed to promote each others' learning in a collaborative environment. A student with a 'simple' knowledge structure (e.g. Simon in Figure 2) would benefit from interaction with peers with a more developed structure represented by any of the three categories.

One aim of collaborative activity is to promote conceptual development within groups as a result of interractions that generate student dissatisfaction with their own theories, (i.e. cognitive conflict). For this to happen, some differentiation between potential group members is required to optimize group structure to promote cognitive conflict. The qualitative classification of concept maps, and the complementary grouping of students on this basis, may provide a non-threatening method for achieving this. It should be noted, however, that the knowledge presented by a student will be dynamic in nature, so that a map structure viewed at a given time may be considered ephemeral: continually representing a transitional state towards the next level of understanding. This needs to be reflected in a flexible approach to group structuring.

Diversity of naïve knowledge structures

It has been shown that the ways in which scientific understandings develop tend to follow 'common conceptual trajectories' (Driver *et al.*, 1994). An awareness of these trajectories (gained from surveys into misconceptions) allows certain developmental pathways to be anticipated by the teacher. From this, a careful sequencing of teaching materials to reflect these trajectories should promote meaningful learning. However, such developmental pathways can only be loose generalizations. As Chi, Slotta and De Leeuw (1994, p. 37) have noted, 'even though the false beliefs of a significant minority of students may share similar elements, they are not the same beliefs'. An assumption that all the commonly held misconceptions within a given domain are held by every member of a class would probably be a misconception on the part of the teacher. This would simply substitute one set of assumptions for another and would ignore the diversity of naïve theories that may exist within a group. As students' ideas are likely to evolve at differing rates and in response to differing influences, so each student will develop a unique view of the world. Gaining access to these views and then guiding the student to build upon them seems to be the essence of the constructivist view of learning. However, most studies that have dealt with the development of naïve knowledge structures have considered them as an undifferentiated group (Greca and Moreira,1997). Analysis of naïve concept maps will quickly show this not to be the case, and it has been suggested that a recognition of the diversity of naïve knowledge structures may provide a tool to bring benefits to the students' learning (Kinchin, 1998).

Discovering what each student knows (rather than trying to anticipate it) can be achieved in the classroom using concept maps. This has been shown to be as effective in revealing patterns of understanding and misunderstanding as conducting personal interviews (Edwards and Fraser, 1983), and is more practical as a classroom strategy. In addition to showing *what* knowledge a student holds, concept maps also illustrate *how* that knowledge is arranged in the student's mind. This arrangement of knowledge and the nature of the links between concepts suggest practical implications for the student's future learning. Certain arrangements (corresponding to spoke, chain or net structures) may make it more or less difficult for new ideas to be incorporated into the student's existing framework. An appreciation of this is key if the teacher is to be adequately prepared to organize learning experiences which promote shared meanings.

Monitoring progress

Evaluation of sequences of concept maps will give an illustration of the developmental pathways employed by a student as progress is made from a naïve theory closer towards a shared understanding with the teacher. This may be more sensitive to such developmental changes than traditional testing in which questions often focus on isolated ideas. While some of these ideas may be resistant to change, their interrelationships with other ideas may be more fluid. This is described by Benlloch and Pozo (1996, p. 209): 'Although ideas persist, their meanings change as the conceptual structure (or theory) in which they are embedded changes.' Concept mapping is able to show that an idea is held by a student, and also to contextualize it.

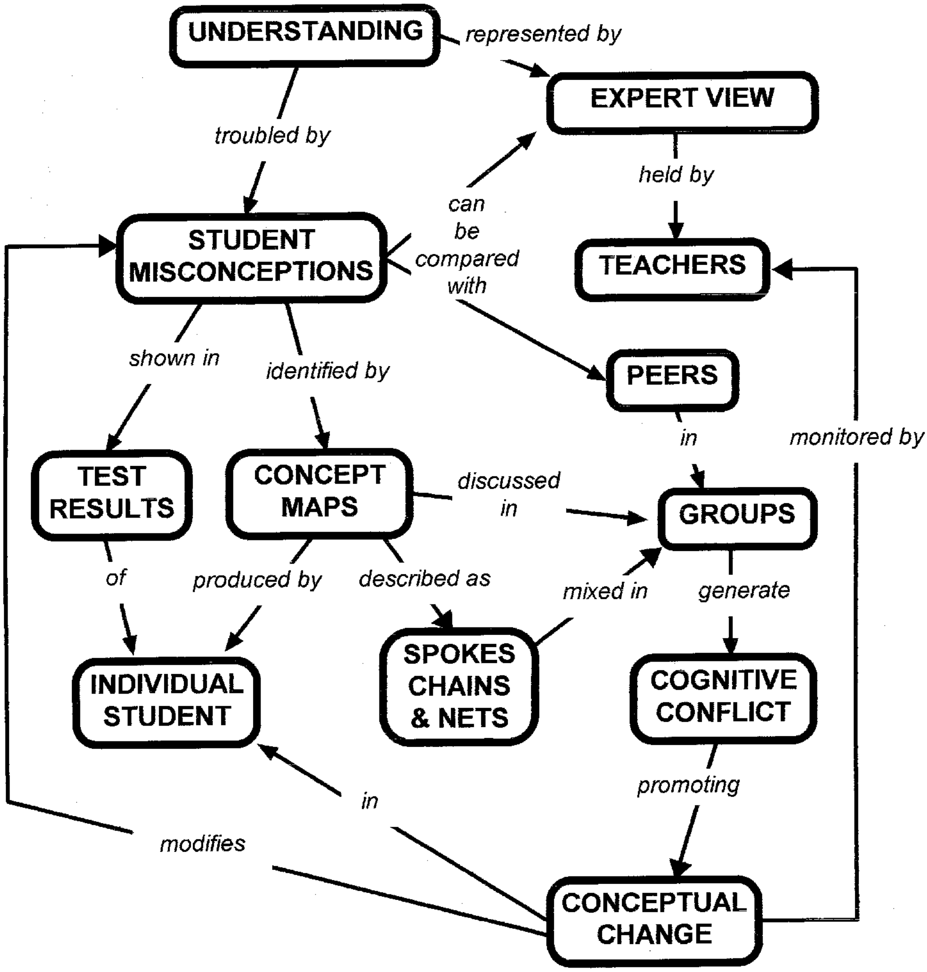

FIGURE 3 A concept map summarizing the application of concept map classification in the promotion of learning in collaborative groups

Analysis of the patterns of concepts and links within a concept map may not only be used to pinpoint existing understanding, but may also give an indicator of a student's readiness to progress in a certain direction. In Vygotskian terms, they can be used to identify the dimensions of a student's zone of proximal development (ZPD)[1] in a particular domain. A comparison of a naïve map with a subsequent collaborative revision may indicate the dimensions of a student's ZPD at a given time (Brown and Ferrara, 1985). Such a mechanism for identifying a student's personal relevance may provide the classroom teacher with a powerful tool which may effectively suggest learning targets and provide a means of monitoring progress by revealing thought processes that generally remain private to the learner (Cohen, 1987). Traditional testing, which typically focuses on the end-result of prior learning, does not expose such developmental thought processes. In such tests, a student may be able to produce the 'right' answer while retaining fundamental misconceptions (e.g. Marek, 1986).

Conclusion

Concept mapping is a flexible tool that may be used to illustrate students' existing understanding and suggest routes for future learning. It can enable the classroom teacher to differentiate between students in a non-threatening manner using a simple classification scheme. This, in turn, may be used to optimize the composition of collaborative groups to promote conceptual change. The development of the students' concept maps encourages participation by reducing the burden on working memory (e.g. Stensvold and Wilson, 1990) and acts as a focus for the group's discussions, as summarized in Figure 3. Eden (1988, p. 7) has expressed this in terms of viewing individually generated maps as 'the "grounded" data for the construction of an aggregated map which could act as a model amenable to analysis which is more importantly a device for facilitating negotiation'.

Higher-order thinking skills, particularly problem-solving, rely on well-organized, domain-specific knowledge. Concept mapping aids the development and representation of such knowledge and is considered to be predictive of different forms of higher-order thinking (e.g. Jonassen *et al.*, 1997). In his brief review of constructivist science education research, written from the perspective of a related discipline, Robertson (1994, p. 25) concluded that 'A goal of interpretive science education research has been to probe [students'] knowledge or understanding in an attempt to make it explicit, so that it can be characterized'. It is clear that concept mapping is a tool that can help to make student understanding explicit. The descriptive mechanism introduced in this article makes a start towards its characterization.

Finally, concept maps produced by teachers, as part of their schemes of work, may be helpful in reinforcing the conceptual links that they need to make explicit to their students if they are to develop an integrated knowledge structure. Further studies will be investigating the utility of the scheme described here by looking at the suggested influence on collaborative groups and possible progression routes from one type of map to another.

Note

1 The zone of proximal development is defined as: *the distance between the actual development level as determined by independent problem-solving and the level of potential development as determined through problem-solving under adult guidance or in collaboration with more capable peers* (Vygotsky, 1978, p. 86).

References

BENLLOCH, M. and POZO, J. I. (1996). 'What changes in conceptual change?: from ideas to theories.' In: WELFORD, G., OSBORNE, J. and SCOTT, P. (Eds) *Research in Science Education in Europe: Current Issues and Themes*. London: Falmer Press, pp. 200–11.

BENNETT, N. and CASS, A. (1988). 'The effects of group composition on group interactive processes and pupil understanding', *British Educational Research Journal*, **15**, 1, 19–32.

BIANCHINI, J. A. (1997). 'Where knowledge construction, equity, and context intersect:

student learning of science in small groups', *Journal of Research in Science Teaching*, **34**, 10, 1039–65.

BLUMENFELD, P. C., MARX, R. W., SOLOWAY, E. and KRAJCIK, J. (1996). 'Learning with peers: from small group co-operation to collaborative communities', *Educational Researcher*, **25**, 37–40.

BROWN, A. L. and FERRARA, R. A. (1985). 'Diagnosing zones of proximal development.' In: WERTSCH, J. V. (Ed) *Culture, Communication and Cognition: Vygotskian Perspectives*. Cambridge: Cambridge University Press, pp. 273–305.

CHI, M. T. H., SLOTTA, J. D. and DE LEEUW, N. (1994). 'From things to processes: a theory of conceptual change for learning science concepts', *Learning and Instruction*, **4**, 27–43.

CLEMENT, J., ZIETSMAN, A. and BROWN, D. E. (1989). 'Not all preconceptions are misconceptions: finding "anchoring conceptions" for grounding instruction on students' intuitions', *International Journal of Science Education*, **11**, 5, 554–65.

CLIBURN, J. W. (1986). 'Using concept maps to sequence instructional materials', *Journal of College Science Teaching*, **15**, 4, 377–9.

COHEN, D. (1987). 'The use of concept maps to represent unique thought processes: toward more meaningful learning', *Journal of Curriculum and Supervision*, **2**, 3, 285–9.

DOROUGH, D. K. and RYE, J. A. (1997). 'Mapping for understanding', *Science Teacher*, **64**, 1, 36–41.

DRIVER, R., ASOKO, H., LEACH, J., MORTIMER, E. and SCOTT, P. (1994). 'Constructing scientific knowledge in the classroom', *Educational Researcher*, **23**, 7, 5–12.

EDEN, C. (1988). 'Cognitive mapping', *European Journal of Operational Research*, **36**, 1–13.

EDWARDS, J. and FRASER, K. (1983). 'Concept maps as reflectors of conceptual understanding', *Research in Science Education*, **13**, 19–26.

GREAT BRITAIN. DEPARTMENT FOR EDUCATION (1995). *Science in the National Curriculum*. London: HMSO.

GRECA, I. M. and MOREIRA, M. A. (1997). 'The kinds of mental representations – models, propositions and images – used by college physics students regarding the concept of field', *International Journal of Science Education*, **19**, 6, 711–24.

HALFORD, G. S. (1993). *Children's Understanding: The Development of Mental Models*. Hillsdale, NJ: Lawrence Erlbaum.

HENDERSON, J. and WELLINGTON, J. (1998). 'Lowering the language barrier in learning and teaching science', *School Science Review*, **79**, 288, 35–46.

HERL, H. E., BAKER, E. L. and NEIMI, D. (1996). 'Construct validation of an approach to modelling cognitive structure of US history knowledge', *Journal of Educational Research*, **89**, 4, 206–18.

HICKLING, A. K. and GELMAN, S. A. (1995). 'How does your garden grow? Early conceptualisation of seeds and their place in the plant growth cycle', *Child Development*, **66**, 3, 856–76.

HIROKAWA, R. Y. and JOHNSTON, D. D. (1989). 'Toward a general theory of group decision making', *Small Group Behaviour*, **20**, 4, 500–23.

HODSON, D. and HODSON, J. (1998). 'From constructivism to social constructivism: a Vygotskian perspective on teaching and learning sciences', *School Science Review*, **79**, 289, 33–41.

HORTON, P. B., McCONNEY, A. A., GALLO, M., WOODS, A. L., SENN, G. J. and HAMELIN, D. (1993). 'An investigation of the effectiveness of concept mapping as an instructional tool', *Science Education*, **77**, 95–111.

HOWE, A. C. (1996). 'Development of science concepts within a Vygotskian framework', *Science Education*, **80**, 1, 35–51.

JOHNSON-LAIRD, P. N. (1983). *Mental Models*. Cambridge: Cambridge University Press.

JONASSEN, D. H., REEVES, T., HONG, N., HARVEY, D. and PETERS, K. (1997).

'Concept mapping as cognitive learning and assessment tools', *Journal of Interactive Learning Research*, **8**, 3–4, 289–308.

JONES, M. G. and CARTER, G. (1998). 'Small groups and shared constructions.' In: MINTZES, J. J., WANDERSEE, J. H. and NOVAK, J. D. (Eds) *Teaching Science for Understanding: A Human Constructivist View.* San Diego, Calif.: Academic Press, pp. 261–79.

KINCHIN, I. M. (1998). 'Constructivism in the classroom: mapping your way through. Paper presented at the British Educational Research Association Annual Student Conference, The Queen's University of Belfast, 26–27 August; available at: http://www.leeds.ac.uk/educol/documents/000000811.htm

LAWLESS, C., SMEE, P. and O'SHEA, T. (1998). 'Using concept sorting and concept mapping in business and public administration, and in education: an overview', *Educational Research*, **40**, 2, 219–35.

LIU, X. and HINCHEY, M. (1996). 'The internal consistency of a concept mapping scoring scheme and its effect on prediction validity', *International Journal of Science Education*, **18**, 8, 921–37.

LORD, T. R. (1997). 'A comparison between traditional and constructivist teaching in college biology', *Innovative Higher Education*, **21**, 3, 197–216.

McALEESE, R. (1994). 'A theoretical view on concept mapping', *Association for Learning Technology Journal,* **2**, 1, 38–48.

MAREK, E. A. (1986). 'They misunderstand, but they'll pass', *Science Teacher*, **53**, 9, 32–5.

MARTIN, D. J. (1994). 'Concept mapping as an aid to lesson planning: a longitudinal study', *Journal of Elementary Science Education*, **6**, 2, 11–30.

MUELLER, A. (1997). 'Discourse of scientific inquiry in the elementary classroom', *Journal of Elementary Science Education*, **9**, 1, 15–33.

MUGNY, G. and DOISE, W. (1978). 'Socio-cognitive conflict and structure of individual and collective performances', *European Journal of Social Psychology*, **8**, 181–92.

NOVAK, J. D. (1990). 'Concept mapping: a useful tool for science education', *Journal of Research in Science Teaching*, **27**, 10, 937–49.

NOVAK, J. D. (1993). 'Human constructivism: a unification of psychological and epistemological phenomena in meaning making', *International Journal of Personal Construct Psychology*, **6**, 167–93.

NOVAK, J. D. (1996). 'Concept mapping: a tool for improving science teaching and learning.' In: TREAGUST, D. F., DUIT, R. and FRASER, B. J. (Eds) *Improving Teaching and Learning in Science and Mathematics*. London: Teachers College Press, pp. 32–43.

NOVAK, J. D. (1998). *Learning, Creating and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations*. Hillsdale, NJ: Lawrence Erlbaum.

NOVAK, J. D. and GOWIN, D. B. (1984). *Learning How to Learn*. Cambridge: Cambridge University Press.

OSBORNE, J. F. (1996). 'Beyond constructivism', *Science Education*, **80**, 1, 53–82.

PINE, K. J. and MESSER, D. J. (1998). 'Group collaboration effects and the explicitness of children's knowledge', *Cognitive Development*, **13**, 1, 109–26.

RAFAL, C. T. (1996). 'From co-construction to takeovers: science talk in a group of four girls', *Journal of the Learning Sciences*, **5**, 3, 279–93.

REFINETTI, R. (1997). 'Philosophy of science and physiology education', *Advances in Physiology Education*, **17**, 1, 31–5.

ROBERTSON, A. (1994). 'Toward constructivist research in environmental education', *Journal of Environmental Education*, **25**, 2, 21–31.

RUIZ-PRIMO, M. A. and SHAVELSON, R. J. (1996). 'Problems and issues in the use of concept maps in science assessment', *Journal of Research in Science Teaching*, **33**, 6, 569–600.

SANTHANAM, E., LEACH, C. and DAWSON, C. (1998). 'Concept mapping: how should it be introduced, and is there evidence for long term benefit?' *Higher Education*, **35**, 3, 317–28.

SCOTT, P. (1996). 'Social interactions and personal meaning making in secondary science classrooms.' In: WELFORD, G., OSBORNE, J. and SCOTT, P. (Eds) *Research in Science Education: Current Issues and Themes*. London: Falmer Press, pp. 325–36.

SHAMBAUGH, R. N. (1995). 'The cognitive potential of visual constructions', *Journal of Visual Literacy*, **15**, 1, 7–24.

STAVER, J. R. (1998). 'Constructivism: sound theory for explicating the practice of science and science teaching', *Journal of Research in Science Teaching*, **35**, 5, 501–20.

STAVY, R., EISEN, Y. and YAAKOBI, D. (1987). 'How students aged 13–15 understand photosynthesis', *International Journal of Science Education*, **9**, 1, 105–15.

STENSVOLD, M. S. and WILSON, J. T. (1990). 'The interaction of verbal ability with concept mapping in learning from a chemistry laboratory activity', *Science Education*, **74**, 4, 473–80.

STUART, H. (1985). 'Should concept maps be scored numerically?' *European Journal of Science Education*, **7**, 1, 73–81.

THORLEY, N. R. and TREAGUST, D. F. (1987). 'Conflict within dyadic interactions as a stimulant for conceptual change in physics', *International Journal of Science Education*, **9**, 2, 203–16.

VYGOTSKY, L. S. (1978). *Mind in Society* (edited by M. Cole, V. John-Steiner, S. Scribner and E. Souberman). Cambridge, Mass.: Harvard University Press.

WANDERSEE, J. H. (1990). 'Concept mapping and the cartography of cognition', *Journal of Research in Science Teaching*, **27**, 10, 932–6.

WEBB, N. M. (1989). 'Peer interaction and learning in small groups', *International Journal of Educational Research*, **13**, 21–39.

WOOD, D. and O'MALLEY, C. (1996). 'Collaborative learning between peers: an overview', *Educational Psychology in Practice*, **11**, 4, 4–9.

YAGER, R. E. (1995). 'Constructivism and the learning of science.' In: GLYNN, S. M. and DUIT, R. (Eds) *Learning Science in the Schools: Research Reforming Practice*. Mahwah, NJ: Lawrence Erlbaum, pp. 35–58.