Concept Maps: Theory, Methodology, Technology
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USING CONCEPT MAPS AS A RESEARCH TOOL IN SCIENCE EDUCATION RESEARCH

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Abstract. Concept maps were initially developed as a data analysis tool in Novak's research program. In his twelve-year longitudinal study Novak and his research group constructed concept maps to represent changes in children's understanding of science concepts. Since their development, concept maps have been widely used for many purposes and in many different contexts. Concept maps are most well known as metacognitive tools that facilitate student meaningful learning. In our own research programs, we continue to use concept maps in the context for which they were developed -- as a research tool to analyze data. This paper describes our use of concept maps in four research studies. In the first, concept maps were used as a tool for analyzing interview data of students' understanding of ecological processes over a six-year period. In the second, concept maps are being used to compare individual students' understandings of the transformation of matter with students' shared understandings. In the third study, concept maps were used as a research tool by a team of research scientists. They were found to help some members of the team to identify research questions that guided their individual research project. The fourth study, is using concept maps to investigate the development of students' conceptual understanding of science in environmental problem solving-based courses at colleges and universities across the U.S.

1 Introduction

Gowin's and Novak's early work on the nature of knowledge and learning explored factors that influence students' understanding of science and the acquisition of concept meanings (Novak, 1998; Novak & Gowin, 1984). Together their research programs led to the development of two metacognitive tools – Vee diagrams and concept maps. Gowin developed his Vee heuristic to help students studying science make explicit twelve elements essential to constructing scientific knowledge (Gowin, 1981; Novak & Gowin, 1984). Concept mapping grew out of Novak's research program when a tool was needed to represent changes in children's understanding of science concepts over a twelve-year period. This data analysis tool would have to have both simplicity and high specificity (Novak & Musonda, 1991). A concept map visually represents knowledge as a hierarchical framework of concepts and concept relationships. Concept maps are rooted, in part, in epistemological ideas expressed in Gowin's Vee, wherein concept meanings are constructed through human perceptions and interactions with objects and events in the world.

Since their development, concept maps have been widely used for many purposes and in many different contexts. They are most well known to science education researchers and teachers as a metacognitive tool that helps students understand the science they study. Concept maps have also been shown to be useful for (a) providing a summary of a person's existing knowledge, (b) identifying misconceptions, (c) revealing gaps in understanding, (d) promoting reflective thinking, (e) designing curricula and instructional materials, (f) assessing student learning, (g) evaluating program effectiveness, (h) facilitating communication and arriving at shared understandings among members of groups, (i) understanding the processes by which scientists construct new knowledge, and (j) studying problems in epistemological foundations and assumptions (Mintzes, Wandersee & Novak, 1999 & 2000; Novak, 1998; Novak & Gowin, 1984).

Though concept maps have come to be used for many different purposes, we continue to use them in the manner for which they were initially developed, that as a research tool. This paper describes our use of concept maps in our respective research programs. We present narratives of the paths we each took to coming to use concept maps as a research tool. Then we present examples of concept maps drawn from our research.

2 Concept Maps As Research Tools: Contexts and Applications

2.1 A Longitudinal Study of Students' Understanding of Ecological Processes

Over a period of many years teaching biology, I found that students at different ages had difficulties describing, in their own words, how biomass builds up and breaks down. They also had difficulty in describing where matter comes from and where it goes. I have also found students, when discussing general environmental issues, to have limited knowledge about concepts concerning transformations of matter, such as decomposition and combustion. Could their lack of knowledge be due to the fact that teaching has not been based on students' thinking about ecological phenomena? In order to create teaching situations during which students´ ideas about natural phenomena can be challenged, educators must understand how students' thinking about different phenomena develops over time. Therefore, I conducted a longitudinal study of the development of 24 students' understanding of ecological processes from the age of 9 to 15. These ecological processes comprised dealing with conditions for growth, decomposition in nature, and the role of the flower in plant reproduction (Helldén, 1995; Helldén,1999; Helldén, 2004).

I, like many other science education researchers, have found that clinical interviews can give in depth information on students' thinking about natural phenomena (Duit, Treagust & Mansfield, 1996). I interviewed the students on eleven occasions about the three ecological processes. During the interviews I made it clear to them that I was interested in their thoughts per se, not whether their responses were right or wrong. To show the students that I was primarily interested in their thinking, I usually started the first interview question with the words: "What do you think ....?" The interviews were carried out at a small, Swedish primary school and later at a larger lower secondary school with more subject-oriented teaching. Over the course of my study I interviewed the same twenty-four students concerning ecological processes from grade 2 (9 y), with additional students being included to form a stable population of twenty-nine students from grade 4 (11 y) to grade 8 (15 y). The timing of the interviews was complex, but generally occurred in cycles of 1-2 years for each ecological phenomenon. All of the students belonged to the same class for all that time, an unusual feature that reflects the stability of the population in this area in Sweden.

All of the interviews were audiotaped and transcribed verbatim before analysis started. There was a great deal of material to transcribe and analyze. I was not satisfied with the Piaget-inspired analysis that I had been introduced to. After reading *A Theory of Education* by Novak (1977) I became interested in Ausubel's theory of meaningful learning. I met Professor Novak at the Third International Misconception Seminar in Science and Math at Cornell University in 1993. He invited me to spend a semester at Cornell in order work with my interview data. When I came to Cornell in August 1995, I brought all of my interview tapes and transcripts with me but I had not yet found a solid theoretical foundation for my analysis of the interviews. I became involved in fruitful discussions during seminars with Professor Novak's research group. As a result of these discussions, I realised that the development of the students' understandings could be usefully described as a progressive differentiation through which new concepts are subsumed under concepts that already exist in the learner's thinking (Ausubel, Novak, & Hanesian, 1978).

As I began my in-depth analysis of interview data I was faced with the problem of the large amount of interview transcripts that I had to analyze. At this stage I began to construct concept maps of the interviews similar to the methods used by Novak's research group in their twelve year longitudinal study of students' understanding of the particulate nature of matter (Novak & Musonda, 1991). I read the interview transcripts carefully again and again, and I marked the concepts that the students used in responding to my interview questions. I then built a hierarchy according to the students' expressions, starting with the concepts we discussed, for example the needs of plants' placed in a sealed transparent box. By comparing concept maps of the same student at different ages, I could develop an explicit picture of the student's conceptual development. The concept maps visually represented the pathways used by the students to describe and explain the ecological phenomena. Thus I could see how the students developed their understandings by subsuming new concepts under those already present in their cognitive structure.

In Figures 1-3, we can follow how one student, Oscar, developed his understanding about conditions for growth of plants placed in a sealed transparent plastic box. Oscar did not mention anything about water at 10 years of age. When he was 13 he realized that the plant needs water and thought it came from the soil. At 15 years of age he expressed a more complete picture and had subsumed the concepts of evaporation and condensation under the concept of water. We can also follow how Oscar changed his ideas about oxygen. In Figure 1 we can see how he claimed that the plant needed oxygen and that the oxygen would disappear. At 13 years of age he suggested that the plant got its oxygen from the soil. When Oscar was 15 he did not at all talk about any need for oxygen but argued that oxygen was a result of the superordinate concept photosynthesis.

In all of the interviews about conditions for growth, Oscar said that there must be invertebrates like earthworms in the soil. When he was 15 years of age he claimed that the plants in the box had to breathe in

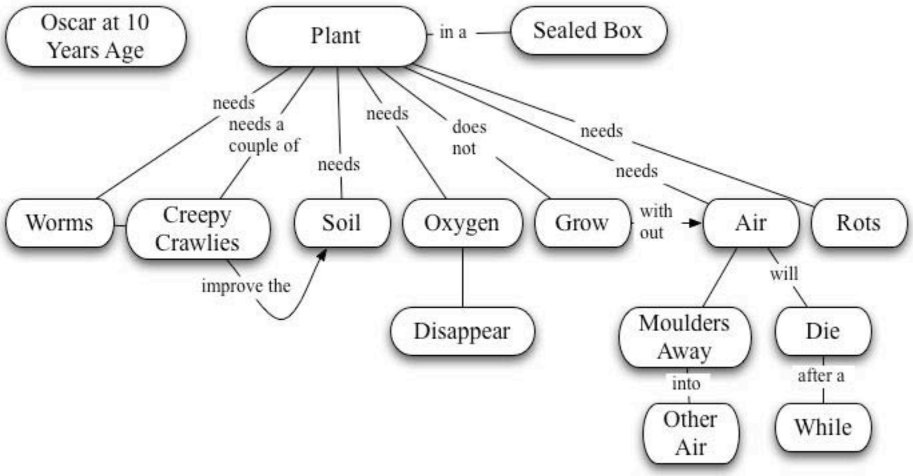

Figure 1. Concept map developed from an interview with Oscar at 10 years of age about conditions for life needed by plants placed in a sealed transparent box.

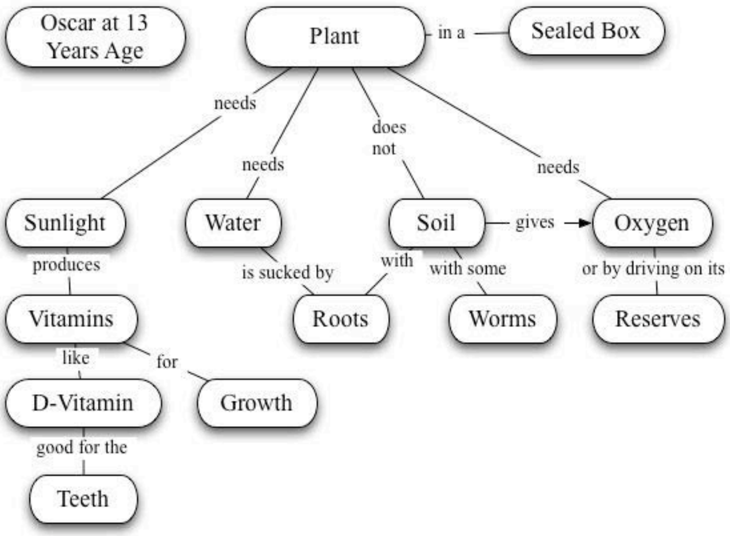

Figure 2. Concept map developed from an interview with Oscar at 13 years of age about conditions for life needed by plants placed in a sealed transparent box.

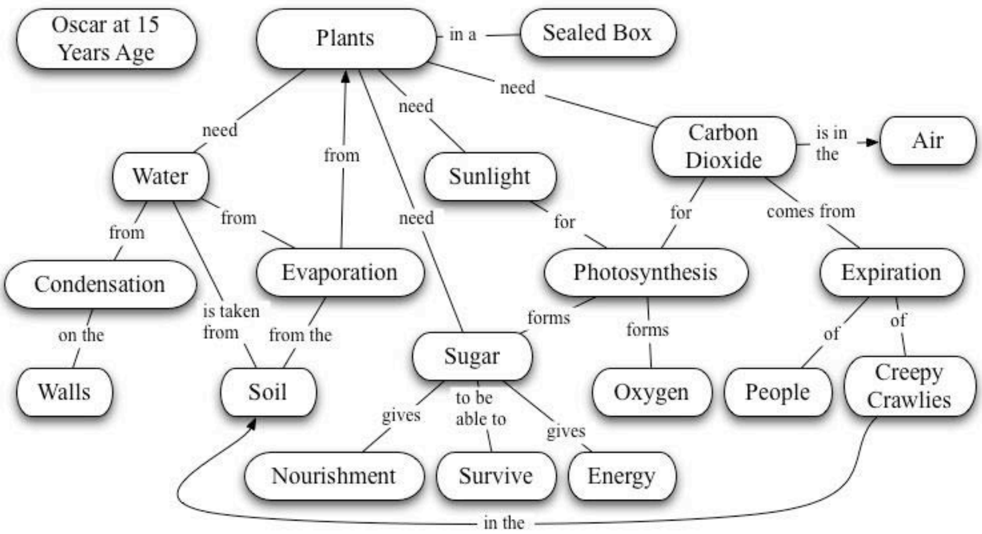

Figure 3. Concept map developed from an interview with Oscar at 15 years of age about conditions for life needed by plants placed in a sealed transparent box.

carbon dioxide, but he had problems explaining from where it came. After a while he said, *"Ah, there must be soil invertebrates in the soil, and they release carbon dioxide that the plants can use."* An integrative reconciliation had occurred. His idea since five years about the need of invertebrates was attached to the need of carbon dioxide for photosynthesis. A new relationship was established in his cognitive structure. By comparing concept maps from interviews at different ages it has been possible to identify personal key ideas that appeared in the interviews through the years like Oscar's mention of soil invertebrates.

2.2 Students' Shared Understandings of the Transformation of Matter

Our most current recent research in Kristianstad is a longitudinal study of the development of students' understanding, from age 7 to 16, about transformations of matter in three different contexts: (1) decomposition of leaves on the ground; (2) a burning candle; and (3) condensation inside a glass-jar (Holgersson & Löfgren, 2004). The students were interviewed individually every year about these examples of transformations of matter. We also wanted to know how the students shared their understandings with other students. Therefore, we decided to let the students first make a concept map of their own. After we had copied the individual concept maps, we let the students discuss with each other the ideas represented in their concept maps. Figures 4 and 5 are examples of two student's individual concept maps on what happens to a burning candle. Figure 6 is a collaborative map on the same topic constructed by three students. These 10-year-old students were familiar with concept mapping and we asked them to construct maps using the following concepts: heat, flame, fire, molecule, but they were permitted to use as many other concepts as they wanted.

We can see in the following concept maps that there are contributions from the individual maps to the construction of the common concept map. There were only a couple of concepts that they had not in common according to the individual concept maps. The concept map that they have done together contains more connections between the concept of molecule and other concepts than the individual concept maps. It also shows the problems have to understand the difference between matter and energy (heat). The discussions during the construction of their map challenge them to talk about the colours of the flame. The concept maps from different groups of students with their shared understanding became an important resource for the design of the next step in our research project. It also became obvious that concept maps with shared understanding can be successfully used in schools.

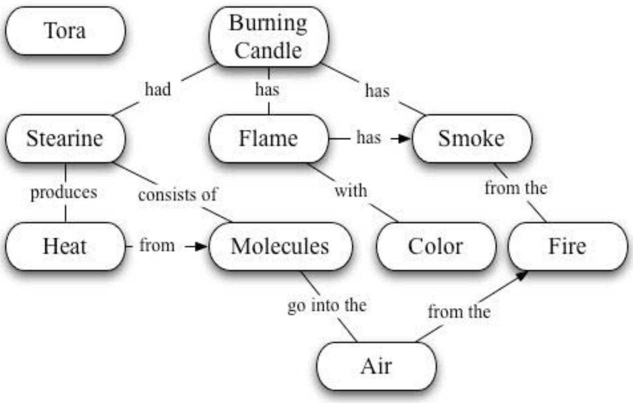

Figure 4. Tora's individual concept map for a burning candle.

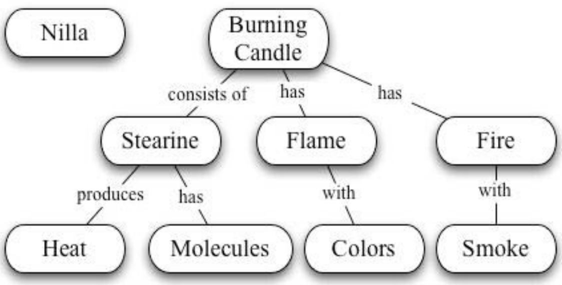

Figure 5. Nilla's individual concept map for a burning candle.

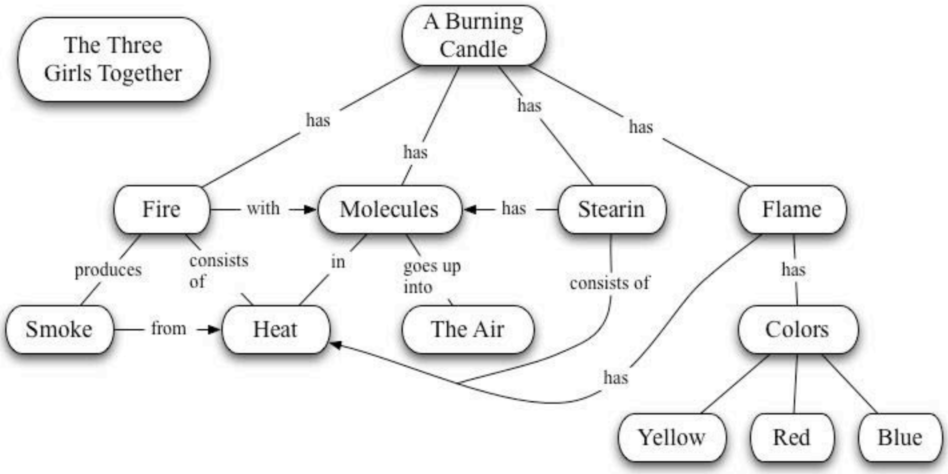

Figure 6. Tora's, Nilla's and Sofie's collaborative concept map for a burning candle.

2.3 The Use of Metacognitive Tools in a Multidimensional Research Project

During my fourth year into my doctoral studies in plant pathology at Cornell University I had the opportunity to enroll in an education course to explore my emerging interest in teaching science. That course, Learning to Learn, was taught by Joe Novak. I had never before heard of constructivism, meaningful learning, concept mapping, nor most of the concepts and principles presented in the course. It was all new to me, however, it was all very exciting. The experiences and knowledge I gained in the course changed my whole outlook on life and the direction I was headed. With Joe's encouragement and support, I left my program in plant pathology and began my doctoral studies in science education under the mentorship of Joe Novak.

My experiences conducting science research together with my developing understanding of human learning led me to my world view that it is essential for scientists to have an understanding of the nature of knowledge and scientific inquiry if they are to be exemplary researchers and teachers. Only then will they be empowered to facilitate their own, and their students', meaningful learning; and only then will they have the creative insight to make quantum leaps in our understanding of objects and events in the natural world. Throughout her research career, Nobel laureate Barbara McClintock demonstrated that personal convictions on the nature of knowledge extend beyond the cognitive domain (Iuli, 1998). For her, research was filled with emotions. She could not divorce herself from this essence of being human. It was clear to her that cognition and affect, thinking and feeling, could not be divorced from one another, no matter how "objective" a person tries to be.

The success of metacognitive tools in educational settings suggested to me that they may help scientists organize and construct knowledge; thereby facilitating their research activities and enhancing their understanding of the events and objects they study (Iuli, 1998). This research study investigated how members of a multidimensional team of research scientists (the USDA Rhizobotany Project) constructed and organized knowledge (Iuli, 1998; Novak & Iuli, 1995).

A fundamental problem of conducting interdisciplinary research, working in collaborative groups, and teaching and learning in classroom environments is communication and arriving at a shared understanding among members of the group. Thus one way in which I used concept maps in my research was as a tool to help members of the Rhizobotany Project arrive at a shared understanding of the overarching goals of their work and how each individual's piece fit within the larger puzzle.

At times during my research there were some exciting moments when I thought that members of the research team saw the global picture of the Rhizobotany Project and the connections among the different areas of research being explored. One of these moments occurred early on in my work with the team. Figure 7 shows a concept map for the multidimensional research efforts of the Rhizobotany Project. This global map was constructed by the team, including myself, following a weekly Project meeting devoted to brainstorming. The project director's opening comments to the research team at the start of the brainstorming session were, "One of the things we are brainstorming for is a first step priority concept map to figure out where we are going next. The work we are going to be doing for the next five years or more is dependent upon the information that [we will discuss today]." Though the team was able to arrive at a shared understanding of the goals and aims of the

Rhizobotany Project, some members of the team, in their own area of work, were unable to keep this global perspective in mind. They were working in, what I called, conceptual isolation.

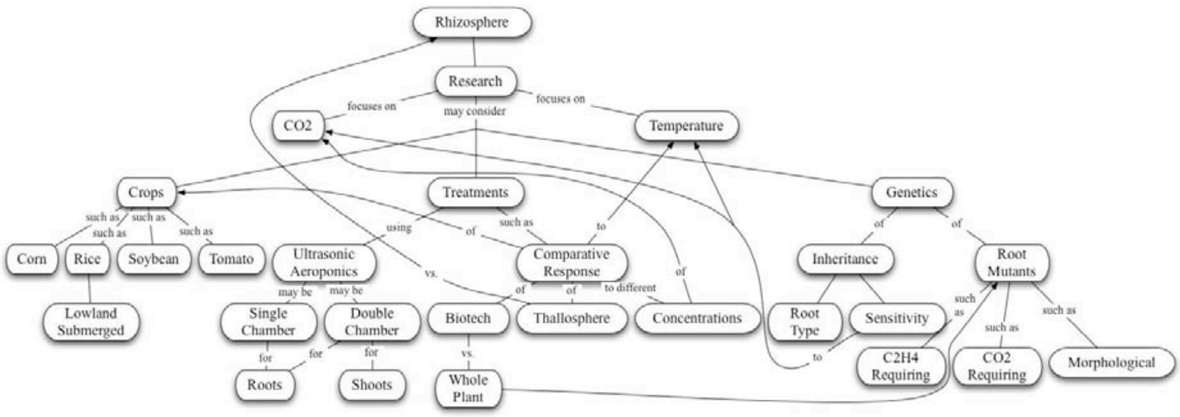

Figure 7. Concept map showing areas of research being conducted by scientists of the Rhizobotany Project.

During the two and one half years of this naturalistic study I found that some members of the team used concept maps to help define their research questions, design experiments, and identify key links between their individual research and that of other members of the team. Figure 8 is an example of one researcher's concept map. Concept maps, such as this one, that Brad constructed from his existing knowledge of plant root-soil interactions served to guide his research on root morphological responses to acid and compacted soil layers. In constructing his map, he was able to articulate questions that helped to guide his research.

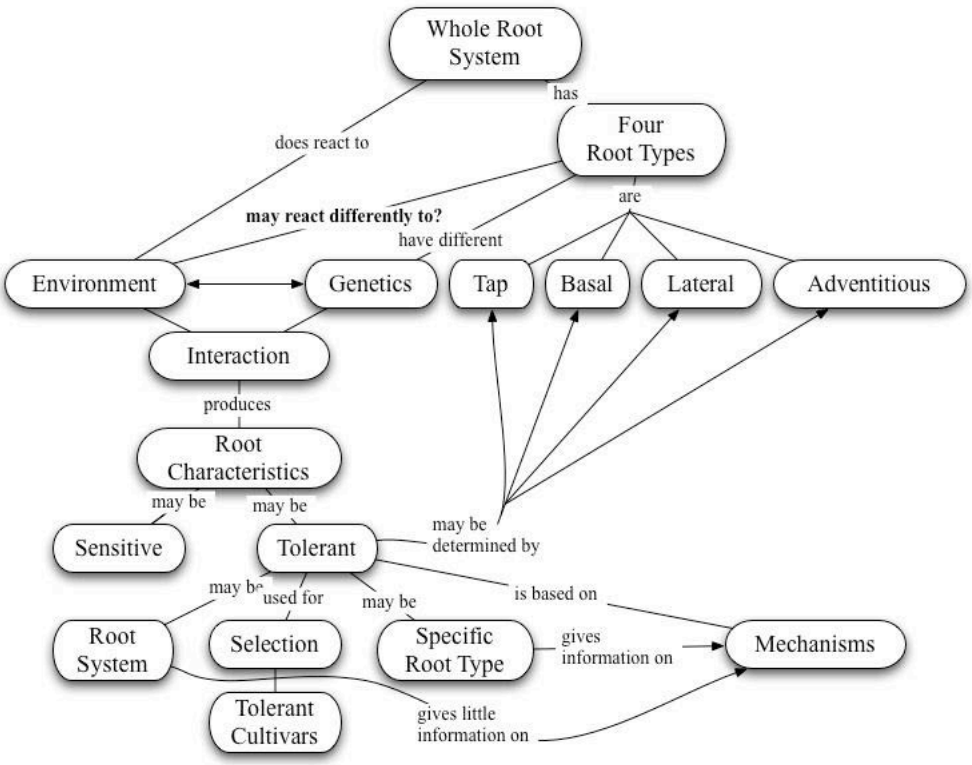

Figure 8. Brad's concept map that he constructed to guide his own research within the context of the Rhizobotany Project.

2.4 Assessing Student Conceptual Development in the NSF-Funded Regional Workshop Project

The National Science Foundation Regional Workshop Project is a national dissemination project that provides training to nearly 400 college and university science faculty across the U.S. in the use of an environmental problem solving (EPS) model to teach university-level science courses. Our current research focuses on investigating the effectiveness of the Regional Workshop Project. Two goals of our research are (1) to evaluate faculties' capacity to adapt the EPS model to their undergraduate science courses and (2) to assess their students' conceptual development of science over the course of a semester in EPS-based courses. Concept maps are our primary research tool for helping course faculty to identify key concepts and concept relationships that they expect students to learn and for assessing student conceptual development in their EPS-based courses.

One year after faculty participate in a Regional Workshop, we interview selected case study faculty about key concepts and concept relationships that they expect their students to learn in their EPS-based course. The interview tapes are transcribed and our research team constructs concept maps of the faculty interviews. These expert-level concept maps are used for two purposes. First, they are used to develop pre-and post-instruction interview guides for student interviews, Second, the expert-level maps serve as a benchmark against which concept maps constructed from student interviews are compared for quality and quantity of understanding.

We select and interview 10 students in each case study faculty's science course. Students are interviewed pre- and post-instruction. The interview tapes are transcribed and we again construct concept maps from the interview transcripts. Data analysis of student concept maps addresses both ipsative comparisons (examining the change in conceptual understanding from the beginning to the end of semester for each student) as well as criterion-referenced comparisons (examining the similarity of the student maps to a faculty "expert" map at the beginning and end of semester). We closely examine maps for accuracy by calculating the percentage of correct propositions in the faculty map that are also present in the student map. The percentages of correct propositions in the student map are compared at the beginning and end of semester to indicate a measure of growth in conceptual understanding.

Figure 9 is a concept map constructed from a faculty interview. In addition to helping the faculty clearly identify what it is s/he expects students to learn in their course, such expert-level maps are used as benchmark against which to compare pre- and post- instruction student maps.

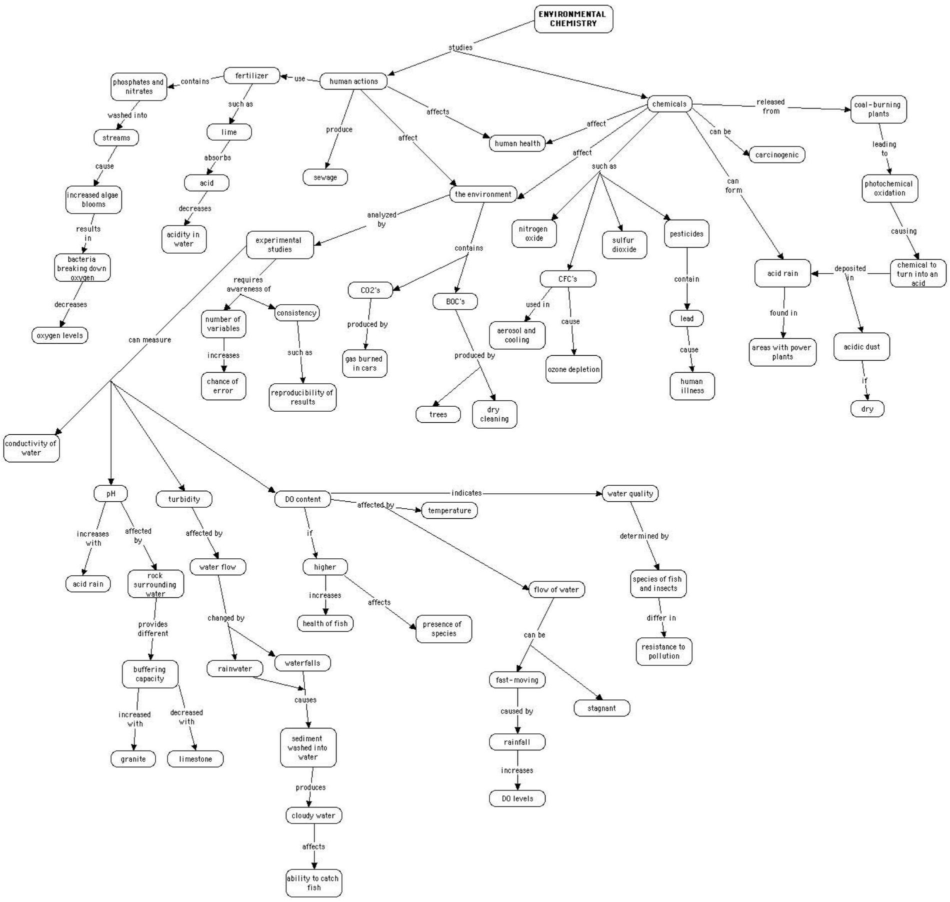

Figure 9. Concept map constructed from faculty interview. This concept map is used to develop the pre- and post-instruction student interview guides and as a benchmark for comparing concept maps of student interviews.

3 Summary

In our own research programs we continue to use concept maps primarily as a research tool – the very purpose for which they were initially developed. We have presented brief descriptions along with example concept maps from four of our research studies. In the first, *A Longitudinal Study of Students' Understanding of Ecological Processes,* concept maps were used to track the development of students' understanding of ecological processes from age 9 to 15. Concept maps were used to analyze interview data over this six-year period. In the second, *Students' Shared Understandings of the Transformation of Matter*, concept maps were used to compare individual students' understandings of concepts relating to the transformation of matter with students' shared understandings. Students first constructed individual concept maps. After viewing and discussing one another's' maps, students constructed a collaborative map that reflected their shared understandings. Comparison of individual and collaborative maps showed that students had difficulty differentiating "matter" and "energy".

In the study, *The Use of Metacognitive Tools in a Multidimensional Research Project*, concept maps were used as a research tool by a team of research scientists. They were shown to help the research team construct a global blueprint of their research efforts. They also helped some members of the team to identify research questions that guided their individual research project. The fourth study, *Assessing Student Conceptual Development in the NSF-Funded Regional Workshop Project,* uses concept maps to investigate the development of students' conceptual understanding of science in environmental problem solving-based courses at colleges and universities across the U.S.. Individual student concept maps, constructed from pre- and post-instruction interviews, are compared to one another for growth in quality and quantity of understanding. They are also compared with faculty concept maps for scientific accuracy and depth of understanding.

4 Acknowledgements

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