The Interrogative Model of Inquiry and Computer-Supported Collaborative Learning

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Abstract. The purpose of the study was to examine how the Interrogative Model of Inquiry (I-Model), developed by Jaakko Hintikka and Matti Sintonen for the purposes of epistemology and philosophy of science, could be applied to analyze elementary school students' process of inquiry in computer-supported learning. We review the basic assumptions of I-Model, report results of empirical investigation of the model in the context of computer-supported collaborative learning, and discuss pedagogical implications of the model. The results of the study furnished evidence that elementary school students were able to transform initially vague explanation-seeking question to a series of more specific subordinate questions while pursuing their knowledge-seeking inquiry. The evidence presented indicates that, in an appropriate environment, it is entirely possible for young students, with computer-support for collaborative learning, to engage in sophisticated knowledge seeking analogous to scientific inquiry. We argue that the interrogative approach to inquiry can productively be applied for conceptualizing inquiry in the context of computer-supported learning.

1. Introduction

The purpose of the present study is to integrate two theoretically and practically important domains of investigation, one falling in the area of cognitive science and the other in the philosophy of science. From cognitive research on educational practices have emerged computer-supported learning environments which are designed to facilitate higher-level practices of inquiry in education. Jaakko Hintikka (1982, 1985) and Matti Sintonen (1984, 1989, 1996a) have developed the *Interrogative Model of Inquiry* (I-Model) in which scientific inquiry and knowledge acquisition generally are viewed as a question-answer process.

The present investigation aims to examine whether the I-Model could be applied to analyze the cognitive value of research questions in the context of computer-supported collaborative learning. We propose that the interrogative approach comes closer than traditional approaches to representing genuine knowledge-seeking both in the sciences (including mathematics and the humanities) and in educational

contexts. Moreover, it draws attention to the important systematic role of a specific category of questions, viz. explanation-seeking why-, how-, and some classificatory what-questions, to the heuristic and pedagogic value of a joint attempt to make these questions more precise and to find information which serves the purpose of constructing answers. The present study examines the extent to which school children are able to generate new subordinate questions to answer their explanation-seeking principal question and analyzes the relationship of this process of question transformation and the advancement of the students' understanding.

In the following sections, we will present a short review of recent advances in cognitive research on educational practice and basic assumptions of the interrogative theory. This review is followed by a report of an empirical research project on the process of question-transformation in the context of computer-supported learning. At the end of the paper, pedagogical implications of the I-Model are discussed.

2. Facilitating Scientific Thinking in Education

An analogy between the history of science and the development of scientific thinking in childhood as well as between scientific thinking and children's thinking has been a very important foundation of cognitive research on educational practices. The physicist Pierre Duhem (1954, p. 268) asked why, "in the intellectual development of each man should we not imitate the progress through which man's knowledge of science has been formed?" Since then, several philosophers and historians of science (Kitcher 1988; Thagard 1992) as well as cognitive researchers (e.g., Duschl et al. 1992; Piaget & Garcia 1989; Scardamalia and Bereiter 1994) have argued that there is a close relationship between the process of scientific thinking and learning science as well as between the philosophy of science and science education. Relying on Kuhn's (1962) theory of scientific revolutions, for instance, Posner et al. (1982) have argued that conceptual change in education recapitulates historical development of science. Accordingly, they proposed that Piaget's *assimilation* represents Kuhn's normal science and *accommodation* corresponds to scientific revolutions based on the process of resolving anomalies.

However, past efforts to bring scientific inquiry into schools have failed to mirror the actual practice of scientific inquiry. Scardamalia & Bereiter (1994) have, nevertheless, argued that there are *no* compelling reasons why school education should not have the basic dynamic characteristic of scientific inquiry. The analogy between school learning and scientific inquiry is based on a close connection between processes of learning and discovery. Inquiry pursued for producing new knowledge and inquiry carried out by learners working to acquire and understand new knowledge are based on the same kinds of cognitive processes. Learning, analogously with scientific discovery and theory formation, is a process of working toward more thorough and complete understanding. Although students are learning

already existing knowledge, they may be engaged in the same kind of extended processes of question-driven inquiry as scientists and scholars.

In the present study, the sustained processes of advancing and building of knowledge characteristic of scientific inquiry are called knowledge-seeking inquiry. Several, concurrent, cognitive research projects share the common goal of fostering such research-like processes of inquiry in education (e.g., Carey & Smith 1995; Perkins et al. 1995; Scardamalia & Bereiter 1994). Knowledge-seeking inquiry entails that knowledge is not simply assimilated but constructed through solving problems of explanation and understanding. Through intensive collaboration and peer interaction, resources of the whole learning community may be used to facilitate advancement of inquiry. To support participation in knowledge-seeking inquiry technology supported learning environments have been designed, such as the Computer-supported Collaborative Learning Environment, CSILE (see Scardamalia & Bereiter 1993). Common to those environments is the provision of tools to the users for collaboratively producing and discussing knowledge and solving problems together.

3. The Interrogative Model of Inquiry

Why are questions so important in the process of inquiry? What are the advantages of the question-answer view in the study of collaborative learning? From a cognitive point of view, inquiry can be characterized as a question-driven process of understanding. Without a research question there cannot be a genuine process of inquiry although information is frequently produced at school without any guiding questions. The Interrogative Model of Inquiry (I-Model) was initiated by Jaakko Hintikka in the 1970s and developed by him and his coworkers into a full-blown view: scientific inquiry and knowledge acquisition generally are viewed as a question-answer process. Although the interrogative process can be formalized by using the logic of questions (see Hintikka 1988), here we view the model more informally as a conceptual tool for analyzing the question-driven process of inquiry. The model has been applied to a range of topics from explanation and discovery to history of science, such as Darwin's theory of evolution (see Sintonen 1990b, 1991).

In the interrogative model, inquiry and knowledge-seeking are viewed as games in which an inquirer attempts to establish a suitable cognitive objective, such as finding out whether B or not-B, or which individuals have a property P, or even why a state of affairs or regularity C obtains. There are, in fact, two types of questions in the model. First, there are the initial big questions which serve to define the goal of inquiry, expressed as propositional ("Is B the case or not?") or wh-questions ("Where (who etc.) is B?") or explanation-seeking how- and why-questions ("How does B work?", "Why does B occur in circumstances C?"). However, inquiry would be too easy if one could put a big why- or how-question to Nature directly. The initial questions, those that involve large theory claims, characteristically are not in

the form to which Nature can respond. What the inquirer tries to do is find an *indirect* way of constructing an answer by formulating a series of small questions, and by attempting to derive an answer to the initial question from these. The Inquirer, then, attempts to find – or rather, construe – an answer to the initial big question by forcing Nature to yield unambiguous answers to her or his small questions, answers which the Inquirer then can draw upon in the interrogative derivation of the chosen conclusion.

There is also another distinction in the I-model which bears on inquiry and learning, viz., that between types of questions. The most restrictive ones are yes-no questions where there are only two alternative answers. Wh-questions, in turn, take individual terms as answers. Here the inquirer knows that the answer is of a particular type and must, e.g., mention a person (who?), location (where?) or some like individual to count as an answer at all. Why- and how questions (as well as covert explanation-seeking or some category-requiring questions like "What is the reason for B's being a C") are even looser still: sometimes the questioner literally does not know what type of an answer would count as appropriate. It follows that the conditions for an answer to be conclusive or satisfactory are different for wh-questions and why-questions: an answer to the former type of question is conclusive if the inquirer is able to identify the individual person or location referred to. In the latter case the conclusiveness condition is difficult to specify in advance apart from saying: once the answer is known the inquirer should be in the position to understand why B is a C. And the complexity and contents of a conclusive answer may vary from individual to individual.

As a result, the Interrogative Model of Inquiry conceptualizes a dynamic process of inquiry through which new knowledge and understanding emerge by separating two types – and levels – of questions (Hintikka 1985; Sintonen 1984). On one hand, there is an initial principal or big question which is determined by the cognitive goals of inquiry. On the other hand, there are small subordinate questions to which answers are needed in order to approach the principal question. Principal questions are often explanation seeking in nature and arise when an agent tries to fit new phenomena to his or her already existing knowledge. The two levels of questions differentiated by the model are a dynamic feature that fosters acquisition of new information during the process of inquiry (Sintonen 1993). The inquirer tries to answer the big question through using his or her existing knowledge and new information obtained in the form of answers to a series of subordinate questions. Advancement of inquiry can be captured by examining a chain of questions generated. By finding answers to subordinate questions, an agent approaches step by step toward answering the big initial question, and thus changes his or her epistemic situation. That new questions are generated from one's original question in a successful process of inquiry has been pointed out by several cognitive researchers (Ram 1991; Scardamalia & Bereiter 1992; Simon 1977).

From a historical perspective the interrogative view is perhaps the first explicit view of how knowledge is acquired and how it can be transmitted in both science

and in everyday life. For example, Socratic dialogues were based on the assumption that questioning is the method of bringing forth knowledge (Meno, p. 85d), and Aristotle's four types of causes are best viewed as answers to four distinct types of explanation-seeking why-questions (Moravcsik 1974; Sintonen 1989). Similarly, the early modern advocates of the scientific method, from Francis Bacon to Immanuel Kant and William Whewell, viewed inquiry as a process in which Nature is subjected to a series of questions (Sintonen 1990a). From the pedagogic perspective, the interrogative view has the advantage that it specifically connects scientific inquiry with knowledge seeking generally. Questions and answers are the currency of our daily speech acts and deeply entrenched in our cognitive capacity. Scientific research differs from ordinary thinking in that it is geared to exploring the consequences of highly structured and hierarchically layered conceptual networks, but the difference is one of degree rather than of principle. But questions also have an important role in scientific inquiry: inquiry, especially in basic science, characteristically starts with a question which arises from the discrepancy between theoretical expectations and observational or experimental results. And a perspicuous way to represent and outline a research project is to cast it in the form of one or more initial questions and a request to make these questions more precise and answerable through observations and experiments.

The basic intuition in the interrogative view, therefore, is not a novel one. What is new is the use of an explicit distinction between the various types of questions and the logically defined conditions for their conclusiveness or satisfactoriness (to the inquirer, with a particular epistemological background etc). Similarly, this paper suggests that using this logic to pave the way from large explanation-seeking questions to conclusive answers has pedagogic merits which have gone unnoticed so far.

4. Computer-Support for Inquiry Learning

It is generally believed that children are not capable of participating in these kinds of advanced scientific processes of inquiry, and, therefore, conventional pedagogical practices are not aimed at encouraging them. However, new computer-supported learning environments emerging from cognitive research promise to facilitate participation in these higher-level processes of inquiry in education. Several important aspects of knowledge-seeking inquiry characteristic of scientific research are implemented in the structure of the CSILE environment (Scardamalia & Bereiter, 1993). CSILE is a networked learning environment for fostering higher-level processes of inquiry in elementary education. CSILE is an environment for building, articulating, exploring, and structuring knowledge. The system contains tools for text and chart processing, and a central part of the system is a communal database for producing, searching, classifying, and linking knowledge. In order to facilitate in-depth processing of knowledge, the students themselves are responsible for producing all knowledge in the database. The system facilitates

sharing of cognitive achievements by providing each student an access to all text-notes, comments and charts produced by the fellow students. CSILE is designed to foster collaborative learning through its advanced facilities for searching out and commenting on knowledge. Students use CSILE by writing notes, creating charts, and reading and commenting on each other's productions in the context of such domains of knowledge as mathematics, physics, biology, and history.

Miyake & Norman (1979) argued that in order to ask valuable questions, students ought to have a minimum amount of domain-specific knowledge. Yet there are convincing reports that even when students do not know a topic very well they are able to ask cognitively valuable questions. In one series of investigations, questions were analyzed from elementary school children working with the CSILE environment (Scardamalia & Bereiter 1992). Although there was substantial variability between the students, they were frequently also able to identify conceptually advanced questions. Scardamalia & Bereiter (1992) reported that a significant proportion of questions generated by students were regarded by experts as representing significant additions to knowledge or an advance in conceptual understanding if successfully answered. Further, there is evidence that participation in an extended process of inquiry fosters children's ability to ask complex questions (Brown & Campione 1994). By engaging students in generation of their own questions and theories, they may be guided to see themselves as contributors to knowledge, or as prospective scientists (Scardamalia & Bereiter 1993; Cognition and Technology Group at Vanderbilt 1997).

Scardamalia & Bereiter (1992) provided evidence that students are able to generate cognitively valuable questions when they are not required to be able to provide answers to their questions. If students are, on the contrary, so required, it is likely that in order to avoid failure and save cognitive effort they would adopt a strategy of asking questions to which they already know an answer or have information very easily available. Hatano & Inagaki (1992) observed, correspondingly, that performance orientation and a need for correct answers is counter-productive from the viewpoint of comprehension activity. Scardamalia & Bereiter's (1992) study indicated, further, that if students were asked to generate questions before introducing a new topic, they were likely to ask knowledge-based questions, i.e., questions derived from their need to understand and focused on things they were genuinely interested in and wondered about.

The purpose of the present study is to analyze whether elementary school children, collaborating within a computer-supported classroom, may profitably participate in question transformation that characterize practices of scientific research. Technical infrastructure for the study was provided by the Computer-supported Intentional Learning Environments, CSILE (Scardamalia & Bereiter 1993). CSILE provides means for the entire learning community to work together for solving shared questions. A question-driven process of inquiry is fostered by CSILE's Thinking Type system for entering thoughts and ideas. The students are asked to categorize their computer entries according the basic categories of inquiry, such as

intuitive theories (My Theory) or scientific information (New Information). Specific thinking types for two levels of questions structure the students' cognitive activity in a way that corresponds to moves in the interrogative process: *Problem* represents the initial principal question and *INTU* (I-Need-To-Understand question) represents small questions articulated for answering the big question. These levels of question facilitate a dynamic process of question transformation that constitutes the core of the interrogative process. The implementation of Carl Bereiter and Marlene Scardamalia's (1994) knowledge-building theory in CSILE's design and pedagogy appears to elicit a process of question transformation characteristic of the interrogative process. In order to examine this hypothesis, the study focuses on analyzing the nature of research questions generated by CSILE students: how the students transformed their principal research questions to new, more specific ones, and how students' commitment to an extended and in-depth interrogative process of inquiry affected their conceptual advancement.

5. Method

5.1. PARTICIPANTS

The study was based on an analysis of CSILE students' written productions, posted to CSILE's database. CSILE has been used as a part of normal education by these elementary school students. The study material represented data occurring naturally while the students carried out their study projects, working with CSILE. The study material represented productions of 28 grade 5/6 (10- and 11-year-old) students over a period of one year at an inner-city public school in Toronto, Canada.

5.2. STUDY MATERIAL: CSILE'S DATABASE

The analysis concerned three different projects, Force, Cosmology, and Electricity, in physics; and one project, Human Biology, in biology. The purpose of the Force project was to explain different forms of force, especially gravity. In the Cosmology project the students were asked to explain how the universe began, what the universe was made of, how the universe changed, and how it will be in future. Although the students worked in the Force and Cosmology projects in small groups to collaboratively solve their research problems, the design of the Electricity project was different in that each student worked individually to solve eight research questions common to the whole class. The Human Biology project focused on examining biological processes in the human body, such as how cells or the circulatory system function.

In working with CSILE, the students produced daily, or at least several times a week, computer entries called "notes" in the context of their study projects. These written productions (or "postings" to the database) from CSILE's database were analyzed through qualitative content analysis (see, for example, Chi 1997). The

analysis focused on the basic categories of CSILE students' knowledge-seeking inquiry, i.e., research problems, intuitive explanations, scientific information sought by students, and comments.

In order to make a reliable qualitative classification of the material possible, CSILE students' notes were first partitioned into *ideas* (regarding segmentation of data for content analysis, see Chi 1997). An idea as the unit of analysis corresponded to the basic elements of CSILE students' inquiry, e.g., their research questions, intuitive explanations, pieces of scientific information or explanation sought by them, or comments between the students. The reliability of partitioning was assessed by asking two independent coders to segment 200 notes into ideas. The Pearson correlation between number of ideas identified by the two coders was 0.94.

5.3. QUALITATIVE ANALYSIS OF CSILE STUDENTS' RESEARCH QUESTIONS

The main categories of CSILE students' knowledge were their *research questions* and content ideas. Research questions were separated from the students' textnotes by following explicit labeling such as "Problem" or "I Need to Understand". In cases where the students did not explicitly label their research questions, these were separated from contents of their textnotes. *Content ideas*, i.e., intuitive knowledge and scientific information generated by the students, represented the main body of their textnotes.

The epistemological nature of the students' research questions was analyzed by classifying each research question according to whether it was fact- or explanation-seeking in nature. *Why* and *how* questions are typical explanation-seeking questions and cannot be satisfactorily answered without elaborating an explanation. In many cases also *what* questions require articulation of explanation; e.g., "what are the reasons for gravity?" or "what is inside of a battery?" *Wh*-questions (i.e., *who, where, when*, and *how many* questions) were considered to represent fact-seeking questions that can be answered by providing factual information. Further, the *origin of research question* was analyzed. A student-generated research question was created by a student him- or herself, whereas a given question was provided by the teacher.

The cognitive value of CSILE students' research questions was assessed by analyzing the extent to which they transformed their principal research questions into more specific ones. Each research question was classified according to whether it was a principal question or a subordinate question (Level of Research Question). All questions provided by the teacher and common to all students in the context of a study project were regarded as principal questions. Further, conceptually independent research questions generated by a student in the context of a study project were classified as principal questions. New research questions generated in the context of one or another principal question represented subordinate questions. All questions representing thinking type INTU (I Need to Understand) were regarded

as subordinate questions. If a student was examining the same issue in several notes, the beginning problem (P) was interpreted as the principal question, and the subsequent problems (P and INTU) as subordinate questions. The reliability of classifying a student's research questions as principal and subordinate questions was assessed by asking two independent coders to classify 99 questions generated by the students in the Cosmology project. For information on questions common to the study project as a whole, and each note's principal research question, the agreement coefficient was 0.86. Mean number of subordinate questions was calculated by taking the mean of a student's number of subordinate questions in physics (three projects) and number of subordinate questions in biology.

5.4. ASSESSMENT OF DEEPENING OF EXPLANATION

The deepening of explanation scale was designed to capture in-depth advancement of inquiry, i.e., the extent to which a student was able to propose new explanatory scientific concepts and theories in his or her inquiry.

The purpose of the *deepening of explanation scale* was to assess whether a student progressed in the search of new explanatory scientific knowledge in the course of his or her inquiry. Degree of deepening explanation refers to in-depth advancement in a student's search for explanatory scientific information. Deepening explanation entails that knowledge produced by a student becomes increasingly sophisticated and articulated in the course of inquiry through adoption of explanatory scientific concepts and theories. Strong deepening of explanation entails that a student succeeds in answering his or her research questions by finding significant pieces of explanatory scientific information. The deepening of explanation scale aimed to capture in-depth conceptual advancement in physics. The scoring for the scale was based on the following guidelines:

1. *No advancement*. A rating of 1 was assigned to a student's process of inquiry if he or she did not succeed in finding new explanatory scientific information and, therefore, did not advance in his or her inquiry.

2. *Small advancement*. A rating of 2 was assigned if a student found some pieces of new explanatory scientific information. This information, however, left a major part of the students' research questions unanswered and did not have a very high explanatory value. There was only a small likelihood that the new information would have considerably facilitated the student's conceptual understanding.

3. *Moderate advancement*. A rating of 3 was assigned if a student found several significant pieces of explanatory scientific information and clearly made progress in his or her inquiry. These pieces of new information provided answers to some of his or her main research questions, and were likely to facilitate his or her conceptual understanding. However, the explanatory value of new pieces of information found by the student was only moderate; i.e., the concepts in-

troduced were not central from the viewpoint of problems studied or already introduced by other students in the class.

4. *Strong advancement*. A rating of 4 was assigned if a student found substantial pieces of new explanatory scientific information, particularly introducing new theoretical concepts or explanatory theories that provided answers to his or her most important research questions. These pieces of information were not only highly likely to facilitate the student's conceptual understanding but also had a potential for significantly contributing to advancement of the whole group.

The reliability of the scale was assessed by asking two independent coders to evaluate deepening of the students' explanations in the Cosmology and Human Biology projects. The correlation between the scores for the two coders was 0.85 for the deepening of explanation scale. A score for mean deepening of explanation was obtained by taking the mean of a student's scores of deepening of explanation in the three physics study projects and his or her deepening-of-explanation score in biology.

5.5. EXPERT EVALUATIONS OF THE COGNITIVE VALUE OF STUDENTS' QUESTIONS

Finally, the cognitive value of CSILE students' research questions was assessed using expert evaluations. The three internationally regarded philosophers of science from well-known Canadian and Finnish universities that participated in the above reported study were asked to evaluate the cognitive value of CSILE students' research questions in two cases of the students' groupwork in physics and two cases in biology. One of the experts, however, evaluated only one case of physics and two cases of biology.

6. Results

The study indicated that the students were themselves able to generate a series of research questions that were meaningful and valuable from the viewpoint of the cognitive goals of their inquiry. The qualitative content analysis revealed that approximately 90% of the research questions ($f = 983$) generated by the students were explanation-seeking in nature, such as the following: "Why do you get some diseases once, and some diseases many times?", "Why do humans see everything right side-up although the picture projected on retina is upside down?" or "If the Earth is round then why don't people or things fall off the bottom since it is the opposite of the right side up?"

On average, each student produced 35 research questions across the four study projects. In each project, they articulated several subordinate questions to help answer their principal research questions. Table I presents a series of a CSILE group's research questions concerning how the brain works. The series consists of two levels of questions, i.e., the group's main research question (PQ)

Table I. An example of generation of subordinate questions in the context of neural biology

PQ:	What kind of cells are there in the brain, and how do they differ from the other cells in the body? (RO)
INTU:	How do the glial cells hold the brain together? (RO)
INTU:	I need to understand what the glial cells look like before I can understand how glial cells hold the brain together. (JH)
SQ:	What do neuron cells look like and how do they work? (JH)
INTU:	I need to understand how many neuron cells are in the brain before I can understand how neuron cells work. (JH)
INTU:	How do neuron cells know whether to pass on information or to stop the message? (RO)
SQ:	How does the brain store information? (SM)
INTU:	How does the long-term memory store the information? (JH)
SQ:	What are the different parts of the brain and what are they used for? (RO)
INTU:	(…) RO said that the cerebellum controls the different parts of the body with its different parts. I don't understand how it uses these different parts and what those different parts are. (JH)

The research questions presented in the table were generated over a period of approximately four weeks while students participated in the Human Biology project. The questions reproduced are from a large body of intuitive theories, pieces of scientific information, and comments and did not necessarily follow one another immediately. At the end of each question appears initials of the student who constructed it.

and new subordinate research questions (represented by new problems (SQ) or I-Need-to-Understand, INTU, questions) emerging in the process of inquiry.

From Table I, it can be seen that the group advanced from a rather general principal question (PQ) concerning what kinds of cells there are in the brain to more specific ones. The principal research question of the group was "What kinds of cells are in the brain and how do they differ from other cells?" The students started from rather vague theories according to which the brain cells are "more developed" or "bigger" than other cells of the body. Examination of new scientific information suggested that there are two types of brain cells; neurons and glial cells. New information seemed to make articulation of more specific research questions possible: "How do glial cells hold the brain together?" and further, "What do neuron cells look like and how do they work?" The analysis indicated that the students continuously built on each other's work and further articulated problems and concepts generated by the other students, during the time period examined.

Another study group examined, in the context of the Human Biology project, how the human brain processes visual information (see Table II). The group started from a rather vague question, "Where is the eye's control panel located?". Comments given by other students in the class pushed the group to articulate a more specific and promising principal question, "How does the eye function?" The problem to be explained was why humans see everything right side-up although the

Table II. An example of generation of subordinate questions in the visual perception case

P0:	Where is the eye's control panel located. (O)
PQ:	How does the eye function? (M)
INTU:	How the eye sends pictures to the brain. (AM)
(SQ)	INTU: How the parts of the eye help get to the message to the brain. (M)
(SQ)	P: How is the eye similar to a camera? (S)
(SQ)	P: I have researched the eye and the camera and found they are very similar in many ways. I have written this note because I found that both the eye and the camera see a picture upside down. I would like to know why that happens and how. (AM)
(SQ)	P: How does the message that the eye is sending get to the brain? (S)

The research questions presented in the table were generated over a period of approximately four weeks while students participated in the Human Biology project.

"picture" projected on retina is up-side down. Explanations provided by the group represented two different theories, and the members of the group moved back and forward between these alternatives. A part of the group argued that the brain sees "pictures" and very closely followed the analogy between an eye and a camera in relation to transformation of the picture. Other members of the group argued that the brain sees "waves". The table shows how the questions generated by the group became increasingly sophisticated in the course of inquiry.

An examination of the present and other study groups' inquiry indicated that in the course of their inquiry, the groups repeatedly generated new subordinate questions in answering their principal questions. The students did not move randomly from one to another research question; former questions and tentative answers to those questions appeared to give an impetus to articulation of further questions and controlled the direction of subsequent inquiry. An analysis of CSILE students' processes of inquiry at the individual and small-group level suggested that the process deepened when a student generated a new subordinate question. Generation of a new, unrelated problem only extended the process, but did not deepen it.

Special scales designed to measure deepening of the students' explanations were used to assess advancement of their explanations. The analysis revealed that there was a close association between the mean scores of deepening of explanation and the mean number of subordinate questions generated with $r(28) = 0.63$, $p < 0.001$ (partial correlation controlled for ability level). A scatterplot of mean scores of deepening of explanation and mean number of subordinate questions is presented in Figure 1.

From the scatterplot presented in Figure 4-13, one can infer that regardless of the close overall association, it was possible to achieve the same degree of deepening of explanation with a varying mean number of subordinate questions. This apparently was because the relevance of questions generated varied between students and projects. Further, conceptual advancement was partially dependent on other factors such as success in searching for relevant, explanatory, scientific
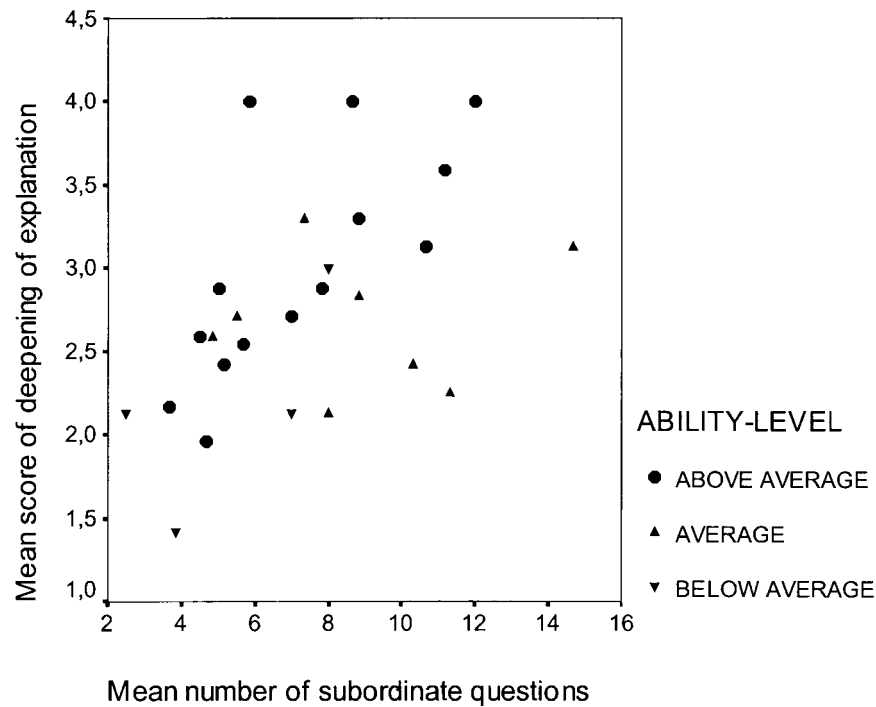
Figure 1. Mean number of subordinate questions for individual students displayed in a scatterplot against mean scores of deepening of explanation.

information. It is noted that some students did not explicate, i.e., record, all steps of their inquiry in CSILE's database by articulating or externalizing corresponding subordinate questions. Even though high achieving students were more likely to productively engage in the interrogative process, many students representing average and below-average school achievement progressed significantly in their inquiry. Although the relation between the degree of deepening of explanation and the mean number of subordinate questions is a correlational one, and cannot establish a causal relation, the results indicated that, overall, the generation of new specific research questions may facilitate, or somehow contribute to, engagement in deepening levels of explanation especially in contexts in which students representing different levels of school achievement are studying collaboratively and support each other.

Further, it was also noticeable that, in their comments on each other's research questions, the students were able to help their fellow students select manageable and specific research questions instead of general questions about the topic. Many comments by others were apparently intended to show that a student did not genuinely focus on his or her principal research question but wandered unproductively around peripheral areas of the topic. Through social interaction pointing out inadequate presuppositions, these students were guided to focus on more productive

research questions, for example: "I think that you should describe and tell more in your theory about how the UNIVERSE will change in the future, and less about how the people will change in the future and how they will know more about the universe in the future because that is not really the question you are researching" (student NE).

The cognitive value of CSILE students' research questions was confirmed by an expert evaluation of three internationally regarded philosophers of science from well-known Canadian and Finnish universities. According to the experts' overall evaluation, CSILE students' research questions were at a high level of sophistication, and, if successfully answered, were likely to produce new conceptual understanding. Moreover, two out of the three experts noticed the student-generated research questions formed a pattern, which allowed the students to answer their main research questions by generating a series of more specific questions. Although the third expert agreed with the other experts that many of the CSILE students' research questions were valuable, he criticized some of the questions as being based on wrong presuppositions.

7. Discussion

The purpose of the study was to analyze whether elementary school children are able to profitably participate in an interrogative process of inquiry. The study was based on a working assumption that through qualitative analysis of CSILE students' productions one can obtain cognitively valuable information about sustained processes of inquiry that are difficult to study by any other means. Given that the focus of the study was on CSILE students' written productions, it should be understood that our conclusions about cognitive processes and changes in the background of phenomena studied should be taken as tentative and inferential; such conclusions require confirmation from further, authentic classroom studies. CSILE's database represented a huge amount of unique and content-rich material concerning elementary school students' sustained processes of knowledge-seeking inquiry in an authentic school environment. In fact, there is "a trade-off between experimental control and richness and reality" in cognitive research on educational practice (Brown 1996, p. 400).

The study indicated that CSILE students participated in extended processes of question-driven inquiry and systematically generated their own intuitive theories. Everyone who has been working with very young students in the context of computer-supported learning has noticed that it is a remarkable and extraordinary educational achievement to get very young students engaged in a systematic process of question transformation. Setting up a question and finding a tentative answer did not mean the end of inquiry, as is often the case in school learning; it was only a beginning of a gradually deepening inquiry. The epistemic value of CSILE students' knowledge-seeking inquiry seems partially to be based on a

process in which social communication pushed a student to pursue question-driven inquiry further than he or she might originally have been able to go.

Participation in these higher level practices of inquiry appeared to be facilitated by CSILE's thinking-type system for entering thoughts and questions. Thinking types guided the students in categorizing their computer entries as problems, subordinate problems, intuitive theories and new scientific information and correspondingly structured their cognitive activity. Hence, the higher-order knowledge concerning the process of inquiry was represented not only in persons but also scaffolded in the environment of cognitive activity. This appeared to foster engagement in higher-level practices of inquiry as well as development of the students' epistemological awareness concerning the process of inquiry (compare Perkins 1993).

The study indicates that the interrogative approach to inquiry can productively be applied for conceptualizing processes of inquiry in the context of computer-supported collaborative learning. Thus a number of features of the I-Model make it particularly suitable as the logical and epistemological basis of inquiry learning and computer-supported collaborative learning. Unlike many traditional approaches in the philosophy of science, the I-Model seems to be particularly useful for educational contexts because it is based on a dynamic and pragmatic conception of inquiry.

The interrogative model is not just a procedure for representing accomplished results but also for searching new information. Sintonen (1993) argued that in actual problem-solving situations, an agent has to start generating questions and theories before all necessary information is available. In the interrogative process, initially very general, unspecified and "fuzzy" questions are transformed to a series of more specific questions. As a consequence, the process of inquiry often has to start with a 'theory to work with' that is transformed into a more sophisticated one as the process goes on. According to the model, this kind of theory may function as a tool of inquiry in spite of gaps, weaknesses, unclarities or other limitations. A critical condition for progress is that an agent focus on improving his or her theory by generating more specific questions and searching for new information. The dynamic nature of inquiry is, further, based on the fact that new questions emerge in the process of inquiry that could not be anticipated when the principal question was first raised (Sintonen 1990a).

Thus, the model also meets another desideratum which previous "logical" models have hardly even recognized, namely that it construes the search for explanations as a process which, in representing inquiry as a step-by-step procedure, captures the dynamics of theory building – and hence learning. The demand for dynamics has been voiced in philosophy of science by the historicist critics of the positivist view in particular (Kuhn 1962; Hanson 1958; Toulmin 1972; Shapere 1977 – see Suppe (1977) for an overview), but the interrogative proposal suggests that there is a strategy behind the procedure. Theories are not conceived with full details at the outset, but must rather be developed from vague initial hunches.

It turns out, also, that this nurturing involves two sides. On one hand new questions are derived from the vague initial questions, on the other hand so-called auxiliary questions are needed to establish what information is required to answer the initial research question. As the Polish logician Andrzej Wisniewski (1995) in particular has shown, an important part of the erotetic proposal is to analyze how sound questions arise and how information obtained during a process of inquiry helps make these questions more precise. This has important consequences for inquiry learning, a parallel to a result in the theory of explanation.

It has been suggested that the interrogative perspective in scientific inquiry is a misleading metaphor, for it does not illuminate explanation. Thus Belnap & Steel (1976) explicitly ruled out vague why-questions from the province of the logic of questions. This criticism is based on a logical distinction between relatively ill-defined explanation-seeking why-questions and well-defined so called wh-questions (i.e., who-, where-, when-, and which questions) and yes-no-questions. There is a sense in which observations and experiments can be construed as questions: they are set-ups in which the inquirer attempts to derive a conclusive "Yes!" or "No!" to the query concerning a hypothesis. However, the questions that interest us here, i.e., explanation-seeking questions, do not pose a restricted set of alternatives to choose from. Here the problem is to find out the relevant potential answers, and the question often is exactly how the question is to be understood. In earlier works, Sintonen (1989, 1996a) has suggested that these difficulties can be avoided by resorting to suitably rich background theories. Indeed, theories are not quite as amorphous as appears at first sight, and they characteristically serve to chop the unmanageable why-questions into yes-no -questions (and some wh-questions).

The interest of the idea is twofold. First, it suggests that inquirer learners must be conceived as active constructors of knowledge and not passive receivers. This in fact is in keeping with current understanding in cognitive science, as well as with current views about the nature of scientific inquiry according to which scientists engage in a dialogue with nature (through experiments) and fellow inquirers (the social dimension of theory building) (Sintonen 1996b). But secondly, the logical difference highlights a possible pedagogical advance. This can be observed by asking why we need why-questions at all, should not an inquirer learner aim at formulating well-defined wh-questions as well as yes-no-questions from the start? The solution seems to be that why-questions are needed to provide a basis for picking out relevant information from the more or less amorphous background of beliefs, and to focus attention to specific directions and informational needs. In fact we propose to study the role of consciously entertained why-questions as necessary means to advance understanding and enhance metacognition: entertaining a why-question amounts to seeing that the expectations are somehow faulty. Background knowledge makes an event (or type of event) seemingly impossible or improbable, or leaves phenomena unconnected.

The connection to learning and education is obvious. Being able to puzzle over an explanation-seeking question is uniquely human and points to a need to un-

derstand. Such understanding amounts, in part, to an ability to see connections between seemingly unconnected phenomena. What theories (or less ambitious generalizations) do is that they, together with perceptual intake and other sources of information, give rise to questions. But they also suggest possible directions in which potential answers can be sought. Focusing on a why-question is therefore needed to find out the "size and shape" of the potential answers. The fact that practically all of CSILE students' research questions were explanation-seeking in nature indicates that they were genuinely engaged in deepening their understanding.

Science educators have been emphasizing the importance of asking good questions for a long time so that someone might ask whether the interrogative approach offers anything new. It appears to us that what is new about the interrogative approach is to emphasize question-transformation as the very foundation of scientific inquiry; from the interrogative viewpoint research questions are at least as important units in the philosophy of science as theories. Even if educators know that skills of asking good questions are valuable, we do not have well-developed culture of question asking at school and it is very difficult to get students to follow the questions that emerge through their process of inquiry. In this regard, pedagogical models and computer tools elaborated by relying on the interrogative approach appear to be very valuable. The interrogative model encourages science educators to focus more on engaging students in sustained processes of question-driven inquiry than just examining contents of their current beliefs so as to facilitate their conceptual advancement. Finally, the dynamic interrogative theory of inquiry would provide new blood for cognitive scientists who have been analyzing structures of students' content specific knowledge and, thus far, trying unsuccessfully to explain the problem of conceptual change.

A third important feature of the I-Model is that it is amenable to a social interpretation. Traditionally, knowledge acquisition has been conceived as a passive affair or, at best, as construction of a solitary Robinson Crusoe inquirer learner. But as recent advances in science studies and education indicate this image is highly unrealistic and distorts the picture of inquiry and learning beyond recognition. But in the I-model, as developed by Sintonen (e.g., 1996b) the inquirer learner engages in a dialogue in two dimensions. On one hand there is the dialogue with Nature, causal interaction through observations and especially experiments. And obviously understanding how this causal interaction is to be carried out in an orderly fashion is one of the prime tasks of well-conceived science education. But secondly, there is the dialogue with fellow inquirer learners, carried out in a common language, and guided by ordinary norms of social interaction. The advantages of this view are numerous, and a number of studies have shown how students' sociocognitive skills are enhanced through constructive peer collaboration (e.g., Hakkarainen 1998a,b).

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