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A Framework for Teaching Scientific Inquiry in Upper Secondary School Chemistry

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Abstract: A framework for teaching scientific inquiry in upper secondary chemistry education was constructed in a design research consisting of two research cycles. First, in a pilot study a hypothetical framework was enriched in collaboration with five chemistry teachers. Second, a main study in this community of teachers and researchers was conducted on the process of designing teaching scientific inquiry based on the enriched framework. Also, the enactment by five teachers and 80 students (age 17) of a designed inquiry module on "Diffusion: moving particles" was studied. This resulted in a theoretically and practically founded framework for teaching scientific inquiry, in which an iterative cycle of inquiry for students and a student inquiry community are essential. © 2010 Wiley Periodicals, Inc. J Res Sci Teach 47: 788–806, 2010

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In many countries science education standards urge engagement of secondary school science students in inquiry-based learning (cf. National Research Council, 1996, 2000).

By emphasizing scientific inquiry in science curricula, teachers are challenged to come up with new approaches that feature inquiry as essential for student learning. Following teachers' enactment of teaching scientific inquiry in secondary schools, critics have brought up that the school version of scientific inquiry portrays a narrow and incomplete image of real scientific research (Hodson, 1996; Magnusson, Krajcik, & Borko, 1999; Wellington, 2000; Yerrick, Parke, & Nugent, 1997). Moreover, findings from educational research evidence that science teachers meet constraints in teaching scientific inquiry that fosters scientific inquiry learning in a classroom setting (cf. Crawford, 2007; Gallagher, 1989; Lunetta, 1998; Lunetta, Hofstein, & Clough, 2007).

In 1999 scientific inquiry became part of the student chemistry examination program of upper secondary education in the Netherlands. At that time, several teachers asked our teacher education institutes for advice and support on how to teach scientific inquiry. Both the teachers' practical problems and the findings from the educational research have spurred us on to set up a design research to investigate scientific inquiry teaching in upper secondary school chemistry.

Inquiry teaching and learning has been the object of many studies (Lunetta et al., 2007), but what is new in our research is that we intended to involve the teachers in designing and evaluating scientific inquiry teaching in order to cooperatively generate a theoretically and practically founded framework. A framework that would assist teachers in developing a research-based approach to teaching scientific inquiry in the context of their own classrooms.

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Theoretical Perspective

Principles for Designing Scientific Inquiry Teaching

Scientific inquiry refers to: ‘‘the systematic approaches used by scientists in an effort to answer their question of interest’’ (Lederman, 2004, p. 309). Furthermore, for educational purposes, Lederman suggests to distinguish between scientific inquiry, ‘‘it is useful to conceptualize scientific inquiry as the process by which scientific knowledge is developed,’’ and the nature of science, ‘‘by virtue of the conventions and assumptions of this process, the knowledge produced necessarily has certain unavoidable characteristics’’ (p. 308).

However, in an extensive review of the literature on inquiry teaching and learning at secondary school science level, Lunetta et al. (2007) found that inquiry processes are often taught as a set of steps. Steps that contain inquiry activities like: defining questions and formulating hypotheses; designing and planning experiments; collecting and analyzing data; summarizing results and reaching conclusions; and communicating the findings of the inquiry. Of course, these activities are of importance in scientific inquiry and as such visible in various instructional models of teaching scientific inquiry (e.g., Bybee, 1997; Lawson, 1995). Trumbull, Bonney, and Grudens-Schuck (2005) evidenced, however, that secondary school science students did not necessarily develop an understanding of scientific inquiry as a process of knowledge development when teachers just involved them in those inquiry activities. As was suggested in various studies (cf. Roth, 1995; Van Aalsvoort, 2000; Wenger, 1998) a better student understanding of scientific inquiry can be created when authentic scientists practices and their experiences are taken as an example to design such teaching.

Research findings show that scientific researchers experience research as a complex, cyclic and iterative process (cf. Blaxter, Hughes, & Tight, 1996; Hodson, 1993; Jenkins, 1999; Polanyi, 1958; Woolnough, 1998). Moreover, scientists argue and negotiate in their scholar communities to produce scientific knowledge (Coppolla, 2007).

In relation to teaching, as supported by a social constructivist point of view (cf. Driver, Asoko, Leach, Mortimer, & Scott, 1994; Palinscar, Magnusson, Marano, Ford, & Brown, 1998) creating an inquiry community in the classroom could be an essential part in designing scientific inquiry teaching. Moreover, in such a community new knowledge is acquired, communicated and negotiated among secondary school chemistry students as was evidenced by Van Rens (2005).

Harwood (2004) interviewed practicing scientists and found that they keep on asking questions when they do research. Consequently, he proposed to guide the whole student inquiry process by using a question driven ‘‘inquiry wheel’’ model. This model helps to conceptualize the cyclic and iterative character of an inquiry process, but is not related to any disciplinary knowledge and as such unconnected with knowledge development.

From a study carried out among 1,200 students in secondary science education, Millar, Lubben, Gott, and Duggan (1994) derived the so-called Procedural And Conceptual Knowledge in Science (PACKS) model. They emphasized in the PACKS model that learning about inquiry means that students need guidance in conceptual and procedural understanding as well as the coherence between them.

Research evidenced that scientific inquiry is a cyclic and iterative process. Therefore, we consider *guiding students to conduct a cyclic and iterative inquiry process* as the first design principle (A) for scientific inquiry teaching. This sole principle is not enough to foster student scientific inquiry learning: it should be complemented with the arguing and negotiating aspect that guides authentic scientists practices. Therefore, we consider *creating an inquiry community* as the second design principle (B) for scientific inquiry teaching.

Design Principles and Classroom Practice: A Hypothetical Framework

Lotter, Harwood, and Bonner (2007) found that one of the core conceptions that guide teachers in designing scientific inquiry-based teaching is their students. Therefore, we take research on student inquiry learning as a means to construct a hypothetical framework that unfolds the two design principles (A and B) towards actual classroom practice.

Regarding principle (A) a cyclic and iterative inquiry process we take the stance that this learning process is affected by the student willingness (e.g., Gott & Duggan, 1996) in relation to their knowing as well as their ability (e.g., Lunetta et al., 2007).

On the level of student willingness in scientific inquiry learning Palmer (2009) found that students were motivated when teachers confronted them with an authentic problem that they should solve. Moreover, Fairbrother (2000) concluded that the inquiry culture in the classroom also contributed to the motivation of the students.

Regarding the student knowing and ability in scientific inquiry, we claim that the PACKS model of Millar et al. (1994) is the most valuable model. First, the model conceptualizes that teachers should guide a cyclic and iterative process of student understanding of conceptual and procedural knowledge in inquiry learning. They argued that conceptual understanding relates to students' understanding of: the aim and nature of the inquiry; the relevant disciplinary concepts; and the concepts of empirical evidence. Additionally, they claimed that procedural understanding relates to the student level of interpreting the inquiry problem, their experimental skills, and their ability to draw and evaluate conclusions. Second, we expect that the PACKS model can serve as a means to bring out teachers' explicit and implicit conceptualizations of how to design teaching scientific inquiry. These conceptualizations are essential for teachers to reflect on their design of scientific inquiry teaching as was found by Windschitl, Thompson, and Braaten (2008).

Davis (2003) evidenced that science teachers find it difficult to design community based scientific inquiry teaching that engages students in knowledge development, whereas Grindstaff and Richmond (2008) concluded that social-cognitive support in a community is engendered if there is sufficient similarity within the inquiry problem. Taking both findings into account we propose, regarding the second design principle (B), that the inquiry process in the community should be directed towards a common inquiry problem. Within this setting the students can produce various inquiry results and debate the results of their inquiry in a critical discourse with fellow "researchers."

Van Berkel, De Vos, Verdonk, and Pilot (2000) argued that critical discourse is also needed at secondary school level. Critical discourse enhances student understanding that discourse is essential for scientific knowledge development (cf. Latour, 1987; Lederman, 1992), and that it can lead to new questions and bring about further inquiry (cf. the vision of Popper, 1959).

In sum, the hypothetical framework for the first design principle (A) of guiding a cyclic and iterative inquiry process contains three components: (A1) create an authentic inquiry problem and inquiry culture in class; (A2) provide opportunities for students to get to understand the aim and nature of the inquiry, the disciplinary concepts and the concepts of empirical evidence; and (A3) provide opportunities for students to interpret the problem, to apply experimental skills and to draw and evaluate conclusions. The second design principle (B) of creating an inquiry community contains four components: (B1) create work being done on a common inquiry problem; (B2) let students produce inquiry results; (B3) organize critical discourse; and (B4) stimulate knowledge development and further questions.

Knowledge Development in Scientific Inquiry Teaching

Curriculum material that specifically addresses designing and teaching scientific inquiry has been studied in various ways (e.g., Crawford, 2007; Tal, Krajcik, & Blumenfeld, 2006; Songer, Lee, & Kam, 2002), but we argue that few studies incorporate both design principles A and B. Moreover, in our study teachers and researchers collaborate in the knowledge development on designing and enacting scientific inquiry teaching. This cooperation is needed, because Keys and Bryan (2001) found that in real practice teachers enacted preset inquiry teaching materials to foster student inquiry learning in a completely different way as was intended by the educational experts. From this study Keys and Bryan concluded that the teachers enactment was substantially affected by their beliefs about scientific inquiry, student inquiry learning and about their role in the teaching process.

In line with Hoban (2003), we follow his proposition that the teachers' enactment is also affected by the fact that the teachers themselves are not involved in the research objectives of building and sustaining knowledge on teaching scientific inquiry.

McGoey and Ross (1999) compared science teachers' reports to educational research reports and marked the difference between the two as "how to" as opposed to "how come." They argued that the theory-practice gap could be bridged by research starting from the teacher's perspective. Wallace (2003) emphasized three essentials, founded on social constructivist models of learning and teaching (Vygostky, 1978). First, teaching is situationally determined and therefore learning about teaching requires a focus on actual classroom practice. Second, learning about teaching needs discourse so as to develop a mutual language. And third, learning about teaching needs collaboration. To bring these three together, working and learning in a community of teachers and educational researchers seems to be a necessary condition (cf. Bennett & Lubben, 2006; Nentwig, Demuth, Parchmann, Gräsel, & Ralle, 2007). Although research on the design process in design communities (Lynch, Pyke, & Jansen, 2003) is scarce, the basic premise behind the importance of such communities is that innovative teaching materials that are designed in collaboration with teachers will be feasible in practice, because the teachers' knowledge and ability is also taken into consideration (cf. Keys & Bryan, 2001; Lijnse, 1998; Ogborn, 1997) and will enhance a mutual process of conceptualization teaching scientific inquiry (Lotter et al., 2007).

Therefore, our expectation is that the hypothetical framework in which the two proposed design principles and their components are integrated will enable us—teachers and researchers—to design activities on teaching scientific inquiry that are feasible in practice, and will lead to a theoretically and practically founded framework for teaching scientific inquiry in upper secondary school chemistry.

This expectation leads to the research question in our study: What are the essentials of a theoretically and practically founded framework for teaching scientific inquiry in upper secondary school chemistry?

Method

Research on design and enactment of teaching scientific inquiry in upper secondary school chemistry is a complex process. Kelly (2003) and Van den Akker, Gravemeijer, McKenny, and Nieveen (2006) argued that the method of design research with successive cycles is a suitable method for studying such complex processes.

Chemistry teachers from 10 schools were invited to participate in our design research. Five teachers from different schools reacted positively and participated on a voluntary basis in the community, meeting every 6 weeks for a period of 3 years.

Given our intention to involve upper secondary chemistry teachers and their expertise (Eilks, 2003; Keys & Bryan, 2001) in designing and enacting teaching scientific inquiry, we opted for a design research with two cycles: a pilot study and a main study.

In the pilot study we aimed at two things. First, we wanted to reveal knowledge on the starting position of the five chemistry teachers and their students (age 16) regarding scientific inquiry teaching and learning. We considered this knowledge to be crucial for our second aim. Our second aim firstly concerned to obtain data on the mutual process of conceptualization by the five teachers and two researchers of the hypothetical framework for the design principles (A and B). Secondly, we aimed at studying the mutual process of designing scientific inquiry teaching in our community as well as the enactment of the designed scientific inquiry teaching by three teachers and their students (age 16) in class. Moreover, we studied the students' willingness, knowing and ability regarding scientific inquiry learning.

In the main study the findings from the pilot study were extensively debated in our community to trigger a mutual process for a further design on scientific inquiry teaching. Moreover, the enactment of that design by three teachers from the community and two teachers from outside the community and 80 chemistry students (age 16–17) was studied.

In both studies we opted for a strategy that creates an equal partnership between the teachers and the researchers in the community.

The data collection and analysis, results, discussion and conclusion from the pilot study will be described first, followed by the main study.

The First Cycle: Pilot Study

Data Collection and Analysis

Regarding their starting position the five teachers were interviewed with a semi-structured questionnaire. The interviews were transcribed and analyzed on the level of qualification, the teachers' conception of scientific inquiry teaching and their teaching experience regarding teaching scientific inquiry.

To obtain data from the mutual process of conceptualizing and designing scientific inquiry teaching, all meetings of the design community were immediately afterwards recorded by one of the researchers. The written reports were sent to all participants and were verified by them. Then we mutually analyzed these reports on an achieved consensus on the two design principles. Additionally, in our community an analysis was done on the appearance of the hypothetical framework components in the designed inquiry-based teaching.

Three teachers were observed in their classes by one of the researchers during the enactment of the designed inquiry-based teaching on ‘‘Desiccants’’ concerning the best drying agent for running shoes. The teachers verified the field notes. These notes were mutually analyzed on the teachers’ focus in their teaching of scientific inquiry.

To gain more knowledge on the components of design principle (A) one of the researchers interviewed 47 students (age 16) about their (un)willingness during the time that they investigated the inquiry problem in ‘‘Desiccants.’’ The interviewed students came from seven different chemistry classes of the five teachers. One of the researchers categorized the student answers in willingness and unwillingness.

Then, regarding the student knowing the discourse in one group of three students in each of the seven classes ($n = 21$) was audio-taped and transcribed. The transcripts were mutually analyzed on student understanding of the aim and nature of the inquiry problem, the relevant chemical concept and the concepts of evidence; the three aspects of component A2 in the hypothetical framework.

We also collected the inquiry plans and the written reports of 22 student teams in the seven classes ($n = 66$), in order to obtain data regarding the student ability. In our community the plans and reports were analyzed with the categories (i–ix), in accordance with Chinn and Malhotra (2002), as shown in Figure 1.

Furthermore, the discussions within the community on the results from the pilot study in relation to the two design principles and the components of the hypothetical framework were immediately after each meeting documented by one of the researchers. The written reports were verified by all participants and after that mutually analyzed in relation to the components in the framework.

Results

Regarding the starting position of the five teachers, analysis of the interview transcripts revealed that all teachers had a Master’s degree in chemistry, a degree in chemistry teaching and more than 5 years of experience in upper secondary chemistry teaching. They all regarded scientific inquiry as a list of inquiry activities (cf. Lunetta et al., 2007) without any reference to either the cyclic and iterative character of an inquiry process or the need to create an inquiry community. Furthermore, they only had experience with supervising prescribed practical student activities, which indicates that at least in their chemistry classes, students had no experience with scientific inquiry learning. However, all teachers expressed willingness to change their teaching method to an approach of more open inquiry problems.

Six meetings, each of 2 hours, were needed to discuss the two design principles and the three components in the hypothetical framework. Analysis of the written reports revealed, as shown by three teacher quotations from reports, that regarding design principle (A) there was a consensus on: ‘‘guide students to conduct a complete inquiry,’’ ‘‘give the students freedom and responsibility in planning and conducting an

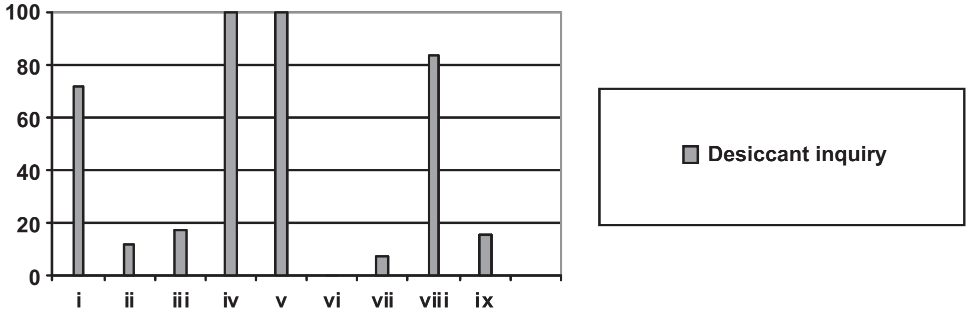


Figure 1. The domain of student (n = 66) ability in the Desiccant inquiry project, in %, with: formulate inquiry question (i); formulate hypothesis (ii); identify/select variables (iii); choose measuring instrument (iv); handle equipment (v); repeat experiments (vi); handle data (vii); infer conclusions (viii); and evaluate conclusions (ix).

inquiry'' and ''we are not well-informed on what our students' starting position is, regarding willingness, knowing and ability to conduct scientific inquiry.''

Eight student inquiry projects were designed. Analysis of these projects showed that, regarding principle (B), we were able to plan that students would work in groups on an open but common inquiry problem and we expected them to produce inquiry results. It turned out that ''organizing critical discourse'' and ''stimulating new knowledge and further questions'' were not realized, because these were, as one of the teachers stated: ''a bridge too far to achieve.'' Moreover, all teachers felt secure to teach these projects, because they chose to start with small scale inquiry projects of two or three chemistry lessons, related to topics that soon would be addressed in the student curriculum.

Analysis of the teachers' enactment showed that the three teachers first focused on the practical feasibility—issues of equipment, safety and disposal—next on questioning the content of the inquiry and that they finally hardly focused on the inquiry's quality.

The student interview data analysis revealed that willingness was predominantly determined by freedom of planning and working on a full inquiry process about an unknown and scientific problem ($n = 40$), whereas unwillingness was mostly related to ''being not in the mood'' ($n = 7$).

The transcripts showed that all seven groups ($n = 21$) planned and conducted experiments for the inquiry problem on ''Desiccants.'' The students used resources such as the Internet and textbooks to get clarity on the concept of a drying agent, but most students did not really show deep level understanding for example they thought a drying agent to be a kind of sponge without any bonding of water molecules. Many students also had difficulty comprehending the scientific character of the inquiry, showing little knowledge of accuracy, reliability and validity in the inquiry. However, they did have enough knowledge of the relevant equipment they needed for the experimental part of the inquiry, which showed that they understood the aim of the inquiry task.

The analysis regarding the student ability categories, shown as (i–ix) in Figure 1, revealed that 72% of the students formulated an inquiry question (i). It also showed that all students were able to choose measuring instruments (iv), to handle the equipment (v) and that 84% of the students related observations to conclusions (viii). The weaker aspects in the student ability component were on: formulation of a hypothesis (12%; ii); identification and selection of variables (18%; iii); repetition of experiments (0%; vi); handling of data, use of tables and graphs (8%; vii); and evaluation of the conclusion (16%; viii).

In four meetings we discussed the previous results in relation to the hypothetical framework. The analysis of the written reports resulted in the following enriched framework of the design principles (A and B) for teaching scientific inquiry in upper secondary school chemistry:

A. *Guiding a cyclic and iterative scientific inquiry process*. The framework should support the domains of willingness, knowledge and ability of the students.
   A1. For the domain of *willingness* the teacher should give students freedom in planning. They should be allowed to carry out a full inquiry process on a to them unknown problem. Moreover, the inquiry should have a scientific character and the student activities should be partly structured so that the teacher can hold a grip on the process and the students keep understanding what they are doing.
   A2. For the domain of *knowing* the students should be guided in understanding the relevant chemical knowledge, the knowledge on practical equipment (cf. Nakhleh, Polles, & Malina, 2002) as well as the concepts of evidence: accuracy, reliability and validity (cf. Gott, Duggan, Roberts, & Hussain, 2009; Gott & Roberts, 2008).
   A3. For the domain of *ability* the students should be allowed to practice: formulating an inquiry question and hypothesis, identifying and selecting variables, choosing measuring instruments, handling equipment, repeating experiments, handling data, and inferring and evaluating conclusions.

B. *Creating an inquiry community.* An inquiry community of students should be made operational by the formation of inquiry teams in each class.
   B1. *Common inquiry problem.* The student teams should be allowed to inquire a sub question of their interest on a common problem. This should enhance creating an authentic inquiry community and should make it easier for the students to assess and discuss the inquiry results of their peers.

B2. *Inquiry results*. Student teams should be required to produce and publish the results of their inquiry project, by which enabling their work to be assessed by their peers and by external experts.

B3. *Critical discourse*. Students should be involved in peer reviewing and discussing the quality of each others' inquiry as well as the results. To achieve this an Internet symposium among teams from different schools should be established.

B4. *New knowledge and further questions*. The students should explicitly describe their new knowledge and further inquiry questions.

Discussion and Conclusion

The design principles (A and B) are feasible to trigger mutual conceptualization on scientific inquiry teaching. They can also trigger a discussion with upper secondary chemistry teachers on designing teaching scientific inquiry. With the hypothetical framework as a lead it is possible to reach consensus on the cyclic and iterative character of scientific inquiry and to design small scale inquiry projects with teachers, who are inexperienced in teaching scientific inquiry. This is where the framework can serve as a scaffold in a cooperative design process of teachers and researchers.

Moreover, the findings show that four aspects are important in enhancing the learning process within the community. Firstly, it is important to take ample time to let the participants in the design community exchange ideas and achieve insight on the meaning of the various components in the hypothetical framework. Secondly, it is a necessity for researchers to know what the teachers are used to when designing scientific inquiry teaching, which is in accordance with Lijnse (1998), Lunetta (1998), Keys and Bryan (2001), and Eilks (2003). Thirdly, it is important to know more about the student willingness, knowledge and ability regarding scientific inquiry, which supports the findings of Lotter et al. (2007) that one of the core conceptions that guide teachers in scientific inquiry-based teaching is their students. And last, the results regarding both teachers and students, but especially the latter, are essential for the discussion in the community on the enrichment of the hypothetical framework.

Furthermore, the results of the enactment of the small scale projects in the classes show that the part of the framework regarding the teaching of the concepts of evidence (accuracy, reliability and validity) is difficult to achieve (Van Rens & Dekkers, 2001).

The Second Cycle: Main Study

The second research cycle involved three phases: (i) a phase of designing a scientific inquiry teaching module in which the conceptualization of the enriched framework was studied; (ii) an enactment phase in which three teachers of our community and two teachers from outside the community were studied when they taught the designed scientific inquiry module to 80 students (age 16–17); and (iii) a reflection phase in which the results of the design phase and the enactment phase were cooperatively mirrored to the enriched framework.

Each phase will be separately described in data collection and analysis, results, and discussion and conclusion, followed by a general section on discussion, conclusion and implications at the end of this article.

Design Phase

Data Collection and Analysis. The use of the enriched framework in the design community was documented by writing a report immediately after each meeting by one of the researchers and by audio-taping all the sessions. The written reports were verified by all participants. These reports and the transcripts of the audio-tapes were mutually analyzed for components of the two design principles (A and B) in the enriched framework.

Results. As a community we applied the enriched framework to design an inquiry module on "Diffusion: moving particles." This took six meetings of each 2 hours. The module involved a period of 3 months with six chemistry periods of 50 minutes in class and additional activities outside the chemistry classes: in total about 20 hours of students' work.

The topic of inquiry regarded the relation between the masses of hydrated ions ($M^+ + 6H_2O/M^- + 6H_2O$) and the distances the hydrated ions traveled in de-ionized water. This topic was chosen by the teachers, because in accordance with the chemistry curriculum the topic of salts, solubility and precipitation would soon appear in chemistry classes. Moreover, the teachers searched various resources and literature for an authentic research article that would comply with the components of the design principles (A and B) and would serve as an example for the students. The article of Nemetz and Ball (1995) on ‘‘A liquid-phase diffusion experiment’’ met the criteria as agreed upon in the design community. First, this article showed the format and structure of a research article, the way to formulate a research problem and research question, how these two are related to chemical theory, and the way discussion and conclusions are reported. Second, the article showed some weaknesses in the authors’ research method that should be recognized by the students, encouraging them to ‘‘go for a better quality in their inquiry.’’

Furthermore, the designed module was consistent with the components of principle A (*guiding the conduction of a cyclic and iterative inquiry process*) as it contained a teaching-learning strategy, planned teacher activities and supportive materials to guide the student activities.

The teaching-learning strategy included seven phases (all include motivation as well), so that the conduction of a cyclic and iterative inquiry process (principle A) would be brought about:

(1) orientation on chemical research in general and on the inquiry problem;
(2) orientation on chemical knowledge and its acquisition;
(3) orientation on experimental skills and their acquisition;
(4) orientation on the concepts of evidence: accuracy, reliability and validity and their acquisition;
(5) application of chemical knowledge and knowledge of the concepts of evidence;
(6) application of experimental skills and knowledge of the concepts of evidence;
(7) reflection on chemical knowledge, knowledge of the concepts of evidence, and experimental skills.

The planned teacher key activities were selected and made explicit:

I. The introduction of the inquiry project. The teacher explained the rationale behind the set up of the inquiry project and encouraged the students to join the inquiry community and to make inquiry teams of two or three students.
II. A class discussion on a ‘‘demonstration experiment’’ on the diffusion of hydrogen chloride (g) and ammonia (g), enacted by the teacher, was conducted in such a way that students were asked individually to predict what could happen and why, to observe what actually happens and to explain the observations (cf. White & Gunstone, 1992).
III. The teams conducted a ‘‘guide experiment’’ with a crystal of potassium iodide released at one side, and a crystal of lead (II) nitrate on the other side of a Petri dish half filled with de-ionized water, resulting in a yellow precipitate. The teacher guided small group discussions on how the distance traveled by the ions could be accurately measured and what would be meant by reliability in this experiment.
IV. Student teams listed all variables that could influence the distance traveled by the ions as seen in the guide experiment. Then the teacher guided a class discussion on variables by questions like: ‘‘What can be measured?’’ and ‘‘What is the difference between dependent, independent and control variables?’’
V. Students, as a team, critically studied the research article ‘‘A liquid-phase diffusion experiment’’ by Nemetz and Ball (1995). The teacher focused the discussion in the various groups on questions about accuracy, reliability and validity as well as on data handling.
VI. The teacher brought about a class discussion on the causes of inaccuracy in Nemetz and Ball’s research.
VII. The teacher coached each team in the iterative process of problem finding, problem formulation and drawing up a detailed plan for their scientific inquiry. Each team was allowed to formulate its own inquiry question and work plan. The role of the teacher was to a large extent that of a senior researcher, coaching many teams. The teacher focused on general issues, asked questions for clarification, gave advice where to find more detailed (chemical) information and stimulated discussions between the students.
VIII. After a check on safety of the teams’ inquiry plans and approval of these plans by the teacher, the teams conducted their experiments in the school laboratory, gathered and analyzed data, drew

> some preliminary conclusions (also by checking accuracy, reliability and validity) and were iterated to redo experiments. The main role of the teacher was now to supervise, coach and stimulate discussions about the quality of the inquiry activities.

For principle B ''*creating an inquiry community*'' the teachers guided students to work in teams on a common problem about diffusion of hydrated ions in de-ionized water. Each team wrote (at least) two versions of an article to report about the results of their inquiry. The first versions of the articles were published on a website. Each team was linked to a team of another school that conducted the module ''Diffusion: moving particles'' in the same period: they were each other's peer reviewers. The teams discussed, by means of e-communication in an Internet symposium, the quality of their inquiries in the same way as they practiced assessing the research article of Nemetz and Ball (1995). They also discussed the quality of further questions that were brought up by the inquiry results. The various discussions in the symposium were visible for all participants in the inquiry community. With the received comments from their peers, each team rewrote the first version of the article, resulting in the final version, and submitted the article again for publication.

All these activities were enhanced by the students' knowing beforehand that a jury, that was independent of the teachers and researchers, would assess the teams' final inquiry articles, nominate five inquiries and present a research award for the best inquiry article. This article was to be published in a Dutch science magazine.

A website with several functions was launched. First, to portray the inquiry community, consisting of all participating schools and their inquiry teams. Second, to deliver the student materials: the workbook with worksheets, a cyber tracker with topic relevant sites and an applet on dissolving a crystal. Third, to facilitate a platform for the peer discussion in an Internet symposium. Fourth, to publish the students' first and final articles. And last, to announce the nominees for the inquiry award and the winning team.

Discussion and Conclusion. The results in the design phase show that the components of the enriched framework are feasible to create a further conceptualization of scientific inquiry teaching by reflection (cf. Windschitl et al., 2008) in a community of teachers and researchers. Comparison of the designed student inquiry module on ''Diffusion: moving particles'' to the small scale inquiry project on ''Desiccants'' shows this elaboration. Moreover, the designed module on diffusion complies better with design principles (A and B) than the desiccants inquiry project. Therefore, it can be concluded that the teachers' conceptions of scientific inquiry teaching are broadened compared to their showed conceptualization in the pilot study.

Enactment Phase

Data Collection and Analysis. Following Cobb, Stephan, McClain, and Gravemeijer (2001) we used the class with the teacher as a unit for data gathering and analysis. In this case study design (Yin, 1994) five chemistry teachers—of which three (T1–T3, see Table 1) were members of our community—and 80 students (age 16–17) from five classes at different upper secondary schools were involved in the enactment of the inquiry module ''Diffusion: moving particles.'' The two teachers (T4 and T5) who were not involved in our community were experienced upper secondary chemistry teachers, but were not used to scientific inquiry teaching at all. These two teachers received all the designed materials by mail. They studied the materials and used them in their chemistry classes.

To determine whether the students were conducting a cyclic and iterative inquiry process (principle A) we used several instruments in order to allow for triangulation (Cohen & Manion, 1994).

First, each of the five teachers (T1–T5) was observed and audio-taped when they enacted the key activities (I–VIII). Table 1 was used as an observation scheme. The teacher activities were recorded: enacted as designed ($\surd$), poorly enacted (±) or not enacted (–). Immediately after the lesson in which key activities were enacted the teachers verified the observation results. Then the results of all five teachers were combined. Additionally, the audio-tapes of each teacher were transcribed and verified by the teachers. The transcripts were used to mutually analyze the quality of the enactment of the key activities.

Second, we measured the *student willingness*. The students ($n = 80$) individually gave, immediately after the lesson in which the teacher enacted the key activity, their judgment—rating ''motivating,''

Table 1
Teacher key activities as conducted by T1–T5: √ enacted, ± poorly enacted and — not enacted

Teacher Activities	T1	T2	T3	T4	T5
Orientation on inquiry task and Nemetz and Ball's research					
I. Introduce inquiry project	√	√	√	√	±
II. Discuss prediction, conclusion and explanation	√	√	√	√	√
Assessment of Nemetz and Ball's research					
III. Discuss accuracy and reliability	√	√	√	√	√
IV. Discuss variables	√	√	√	√	√
Assessment of Nemetz and Ball's research					
V. Discuss presentation and interpretation results	√	√	√	√	√
VI. Discuss causes of inaccuracy	√	√	√	√	—
Students inquiry					
VII. Discuss inquiry plans	√	√	√	√	√
Conduction of the inquiry plans					
VIII. Guide student experimental work	√	√	√	√	√

"interesting," and "of learning value to them"—on the activities I–VIII by giving a mark (1, poor; 10, excellent). For each teacher key activity the students' ratings were analyzed on mean and standard deviation.

Moreover, we determined the *student knowing*. Immediately after each lesson the individual worksheets ($n = 80$) as well as the inquiry plans and final articles of 34 teams were collected. The student worksheets and the final articles were mutually analyzed on student understanding of the concept of diffusion.

The inquiry team's work plans were used to cooperatively analyze the student understanding of the inquiry method and the suitability of the selected equipment.

To measure the student knowledge on accuracy and reliability a specific test ($\alpha = 0.77$) was developed (for three of the 10 questions, see Appendix A), based on materials from Gott, Foulds, Johnson, Roberts, and Jones (1997), Gott, Foulds, Jones, Johnson, and Roberts (1998), and Gott, Foulds, Roberts, Jones, and Johnson (1999). The test was administered to 68 students as a pre-test at the start of the module and 3 months later as a post-test at the end of the module. The test results were, at least for the open parts in the questions, independently scored by two researchers ($\kappa = 0.85$). For the concept of validity we mutually analyzed the definitions that individual students ($n = 80$) wrote in the glossary of their workbooks.

To determine the *student ability* the team's ($n = 34$) first and final article was assessed for the quality of the categories i–ix as presented in Figure 1, except for handling equipment (v). In this comparison an analysis scheme based on Gott and Duggan (1996) and Oost (1999) was used (Van Rens, Pilot, & Van Dijk, 2004). The inter-rater reliability was $\kappa = 0.89$. To determine whether there was any difference between the five classes of the different schools one-way-ANOVA tests were done, followed by a paired *t*-testing for five categories: (a) quality of the inquiry question (i), (b) description of the conduction of the experiments (iii, iv, and vi), (c) presentation of the data (vii), (d) interpretation of the data (viii), and (e) evaluation of the conclusion (ix).

To determine whether an "*inquiry community was created*" (principle B) an open-ended interview was carried out with each of the five teachers after the module was finished. In this interview questions were asked about the achievement of an inquiry community (a), the suitability of the inquiry problem (b), the critical discourse in the Internet symposium (c) and whether the student had acquired new knowledge and had come up with new questions (d). The interviews were transcribed, verified by the teachers and then mutually analyzed and interpreted in our community.

Data on the opinion of the students ($n = 80$) were gathered through an e-mailed questionnaire on the same issues (a–d). For the first three questions a five-point Likert scale was used (1 = poor, 5 = very good). Concerning the fourth issue, two open questions were posed: "Mention two things you learned from the inquiry module," and "Did the inquiry project prompt you to further questions that you would like to inquire? If so, which one(s)?."

The answers on the Likert scale were averaged. The answers to the open-ended question about learning were mutually categorized into the domains of student willingness, knowledge and ability.

Results. Key activity I was poorly enacted by teacher T5 (Table 1), but he did spend some time on the introduction of the project in the next lesson. Moreover, teacher T5 let the discussion on causes of inaccuracy (activity VI) in Nemetz and Ball's research happen completely freely within the groups, but verified that all groups discussed inaccuracies (Transcript 1).

Transcript 1. *Two students, Chris and Tom, from teacher T5's class in interaction in key activity VI*

Transcript: Class of T5, line 317–333. Teacher appears in italic (*T*).

T: so how far have you come? Chris: we think that inaccuracy relates to the instrument they [Nemetz and Ball] used. *T: what do you mean by that?* Tom: eh, we came up with, they used millimeter paper to measure the distances traveled by the ions . . . so, as such the instrument is good. *T: explain?* Chris: yeah, from the guide experiment we know that the precipitation line [$PbI_2(s)$] is not a very fine line so we feel that the [millimeter] paper will do. Tom: but we also discussed whether they accurately measured the distances traveled. *T: so?* Tom: so we feel . . . you can't tell what's behind the comma. *T: true, and what can you do about that?* Tom: just read it in whole millimeters and eh . . . Chris: eh, we think, but we are not quite sure, that they should have independently read the measurements and then compare them, because it is difficult to estimate the millimeters in such a thick line. *T: those are good thoughts, so think of them when you select the measuring instrument and do the readings in your own inquiry.*

Further analysis of the transcripts regarding the eight key activities showed that all five teachers enacted these activities with enough quality. As an example, the enactment of key activity II of teacher T3 on the prediction and explanation in the demonstration experiment of the diffusion of the gases HCl and NH_3 is presented in Transcript 2.

Transcript 2. *T3 in discourse with the class on prediction and explanation in the demonstration experiment.*

Transcript Teacher (T3): line 105–113 [. . .] 124–126, teacher in italic (*T*)

Dirk: Oh, I thought just in the middle. *T: Because?* Dirk: I think, when they [the particles] have the same velocity it does not matter, then they will meet there [in the middle] *T: Yes . . . Jordi what do you think?* Jordi: I also think in the middle, because they have the same velocity. *T: Anybody who thinks it is not in the middle? (five out of 24 students) Erwin?* Erwin: I think that the ammonia or NH_3 particles are heavier so they move slower and those of HCl are lighter. So they will not meet in the middle [. . .] *T: How do you know that the NH_3 particles are heavier?* Erwin: Because there are four atoms and the other one has two atoms. *T: Who agrees with Erwin?* Karel: I don't, because the atoms are so light that it does not matter. The velocities will be equal. [A lot of agreement in class] *T: Nobody thinks it is at the right side of the tube [the correct answer]?* [Nobody] *Now, I won't say what's right or wrong. I am just interested in your prediction and explanation. So let's have a look at the experiment and observe what happens.*

The averaged *student willingness'* ratings on the teacher's key activities I–VIII gave for all eight activities scores between 6.7 and 8.0 with standard deviations between 0.2 and 0.3. The highest average scores with 8.0 were given to activity II and VIII, respectively the discussion with the prediction, conclusion and explanation in the demonstration experiment and the teacher's guidance of the inquiry teams during the time that they actually conducted the planned experiments of their inquiry.

Regarding the *student knowing*, analysis of the worksheets and final articles revealed that student understanding of the concept of diffusion and the movement of hydrated ions changed from 59% of the students (after the demonstration, key activity II: predict, observe, explain activity) to 79% (after the guide experiment, key activity III) to every single student (in the articles).

Moreover, the student inquiry team plans' analysis ($\kappa = 0.91$) revealed that all of them showed an adequate and scientific method. All teams also selected suitable equipment for the planned experiments.

For the student understanding of accuracy and reliability it turned out that their average scores had significantly improved with 3.46 points—the maximum amount of points that could be achieved in the test was 10—when the post-test and pre-test results were compared ($p < 0.01$, $n = 68$). For example in the post-test 81% of the students ($n = 68$) drew a graph to explain their conclusion on the growth of the puppies; question 8 (i) in Appendix A. Regarding reliability, in question 8 (ii), 75% of the students mentioned in the post-test the lack of repetition of measurements and the importance of the deviation between the measurements. Analysis of the students' definitions of validity revealed that 75% wrote a definition like "whether the inquiry method fits the inquiry question."

One-way-ANOVA tests showed that there were no significant differences between the five classes of the different schools. However, the paired *t*-testing showed that the student teams ($n = 34$) improved significantly in the description of the execution of the experiments [$t(33) = -3.29$ ($p < 0.001$)], interpretation of data [$t(33) = -3.31$ ($p < 0.001$)] and evaluation of the conclusion [$t(33) = -3.35$ ($p < 0.001$)].

Regarding the *student ability* a further analysis of the inquiry plans and the final articles revealed that 15% of the students ($n = 80$) formulated unambiguous, relevant and concrete inquiry questions. 25% of the students converted data into a correct graph and applied in this context the concept of reliability.

In the open-ended interviews, concerning principle B, all five teachers stated that the design of the inquiry module ''Diffusion; moving particles'' facilitated them to establish indeed an inquiry community with a suitable inquiry problem. It also gave the students enough freedom and structure to keep them motivated. Additionally, it induced new inquiry questions as well as student interest and learning on diffusion, especially on the microscopic level and on the concepts of evidence, of which particularly accuracy and validity.

All teachers mentioned that coaching the teams on an inquiry problem they themselves were not conversant with created a lot of motivation for them (Transcript 3). Furthermore, they said that the Internet symposium was a valuable activity, but that its benefits could be improved by organizing a more structured teacher guidance.

Transcript 3. *Teacher T1 expresses own motivation*.

Transcript: Interview T1, line 28–31. Teacher (*T*).

T: I was encouraged by the questions the students put in their inquiry plans. This was very motivating to me, so I became very involved in their inquiries. I started to look up things that I was unfamiliar with and I asked a lot of questions that I had never asked before in practical activities. In fact, during the whole module we constantly discussed on variables and what makes a good inquiry. [. . .]

The e-mailed questionnaire was filled out by 75% of the students. The averaged scores showed 4.1 for the inquiry community and 4.4 for the suitability of the inquiry problem, whereas the Internet symposium had an average score of 3.1. Regarding the open questions, 60 of the student responses (82%) could be categorized into the domain of knowledge, for example: ''I learned that ions in water are surrounded by water molecules''; and ''I now understand the difference between a variable and a factor.'' Seven student responses (12%) were related to the domain of ability, for example: to write criticism on a report; and to assess an inquiry. Two responses were related to the domain of willingness: ''After the introduction of the teacher I thought it would be very boring, but by the time we started with our inquiry question the whole thing changed.'' Moreover, all students who responded indicated that they had further questions, for example: ''We found in our experiment that our school building is not level. What experiments can we do to falsify or verify this''?

Discussion and Conclusion. The observations of the teaching of scientific inquiry in the classrooms (Table 1) show that the teachers, including those teachers who were not involved in our community, enact the activities as intended in the design to a very large extent. This envisages a certain strength on how the design principles (A and B) are worked out in a teaching-learning strategy with explicit teacher activities.

All teacher's key activities are positively scored by the students regarding their *willingness* as can be seen in the scores of the averaged students' ratings on ''motivating,'' ''interesting,'' and ''of learning value to them.'' This shows that the inquiry-based learning was not hampered by students' willingness and that the demonstration experiment and the teacher guidance is highly appreciated by the students.

From the results regarding the *student knowing* three conclusions are inferred. First, regarding student understanding of the concept of diffusion it is concluded that during the inquiry process more and more students improved their understanding of diffusion of ions in water. Second, it is inferred that all students used a scientific approach in their inquiry, which according to Millar et al. (1994) is difficult to achieve. In the PACKS project the findings showed that students made little use of a scientific approach in inquiry tasks that did really need such an approach. Third, from the results in the pre-test and post-test on accuracy and reliability it is concluded that student understanding of accuracy and reliability significantly improves.

However, this improvement does not lead for most of the students to a correct application of the concept of reliability in the written articles about their own inquiry.

The results on the paired *t*-testing of categories in the first and final team articles regarding the *student ability* show that students still face problems in formulating inquiry questions and, although the final articles show a significant improvement, in interpreting experimental data.

From results in the open-ended interviews and the student questionnaire it is concluded that all teachers and most students show their satisfaction and appreciation for the inquiry module as a whole and for the details of the teaching-learning strategy and supportive materials. However, the Internet symposium probably needs more teacher guidance, since this is found to be a crucial factor in the student willingness of inquiry-based learning.

Reflection Phase

Data Collection and Analysis. The discussion in our community on the conclusions of phase (i) and (ii) and the comparison of these conclusions with the enriched framework was audio-taped. The transcripts were verified by all participants. Then the transcripts were mutually analyzed on a consensus regarding the components in the framework of the design principles (A and B).

Results. Analysis of the transcripts revealed that the teachers appreciated the enactment of the designed module ‘‘Diffusion: moving particles’’ to a high extent.

Regarding design principle A (*guiding the conduction of a cyclic and iterative inquiry process*) there was a consensus on the three components of willingness, knowing and ability as described in the enriched framework for teaching scientific inquiry. All members of the community agreed upon the importance of the teacher’s guidance of the student activities: study and assess an exemplary research article, plan their own inquiry and execute the experiments. Moreover, regarding design principle B (*creating an inquiry community*) there was a consensus on the necessity of the four components (B1–B4) as were described in the enriched framework. There was also agreement on the necessity of: having team work, investigating an inquiry problem that is unknown to the student and the teacher, publishing of the results, awarding the best student inquiry, team peer reviewing in a guided symposium and formulating further questions in the teams’ articles.

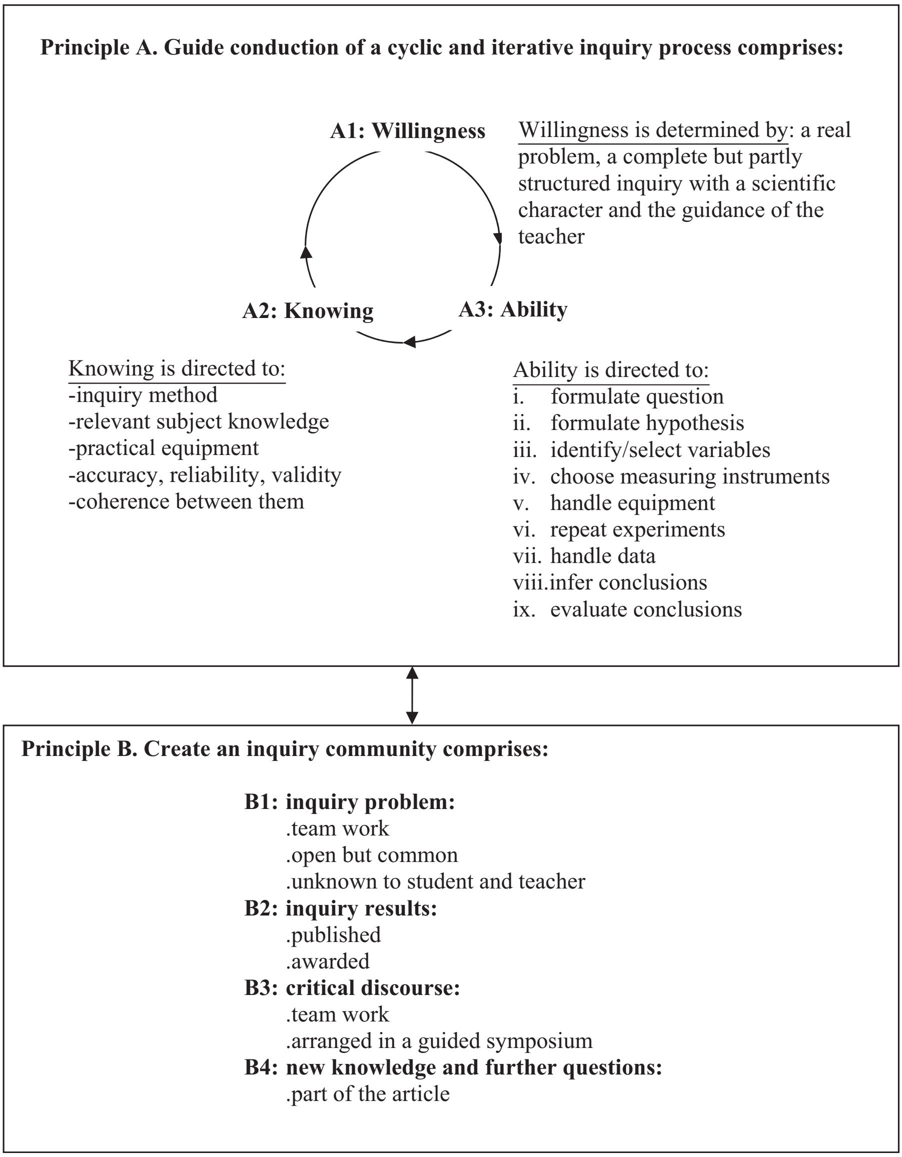
Discussion and Conclusion. The results in the reflection phase show that a further conceptualization of teaching scientific inquiry took place within our community. We argue that the enriched framework needs two additions regarding design principle A (*guiding conduction of a cyclic and iterative inquiry process*). First, the guidance of the teacher should be added to the component student willingness. Second, the student knowing should be directed more explicitly to the inquiry method.

For design principle B (*creating an inquiry community*) the results indicate that a further elaboration for all four components, B1–B4, in the enriched framework occurred.

General Discussion, Conclusion, and Implications

Our research question concerns the essentials of a theoretically and practically founded framework for teaching scientific inquiry in upper secondary school chemistry. A study that is conducted in cooperation with five upper secondary school chemistry teachers who appeared to be just familiar with teaching prescribed student practical work. As is shown in our pilot and main study the used strategy successfully enabled the teachers and researchers to be equal partners in a community that studied the involved essentials. The pilot study also shows that the hypothetical framework, based on two design principles, can serve as a means to mutually conceptualize teaching scientific inquiry and can bring about a consensus on the cyclic and iterative character of scientific inquiry. The main study shows that more debate and reflection in the community leads to a consensus on both the cyclic and iterative character of scientific research as well as the occurrence of research in communities. This indicates the strength of our method of collaborative design-based research, because data on the teaching of scientific inquiry in consecutive cycles gave the participants findings that were reflected on and utilized in the next cycle.

Regarding design principle A (*guiding the conduction of a cyclic and iterative inquiry process*) we identified three components to give teachers the opportunity to guide students in the conduction of a



Principle A. Guide conduction of a cyclic and iterative inquiry process comprises:

Willingness is determined by: a real problem, a complete but partly structured inquiry with a scientific character and the guidance of the teacher

Knowing is directed to:
-inquiry method
-relevant subject knowledge
-practical equipment
-accuracy, reliability, validity
-coherence between them

Ability is directed to:
i. formulate question
ii. formulate hypothesis
iii. identify/select variables
iv. choose measuring instruments
v. handle equipment
vi. repeat experiments
vii. handle data
viii. infer conclusions
ix. evaluate conclusions

Principle B. Create an inquiry community comprises:

B1: inquiry problem:
.team work
.open but common
.unknown to student and teacher
B2: inquiry results:
.published
.awarded
B3: critical discourse:
.team work
.arranged in a guided symposium
B4: new knowledge and further questions:
.part of the article

Figure 2. Theoretically and practically founded framework of the design principles (A and B) with the components A1–A3 and B1–B4 as essentials for teaching scientific inquiry in upper secondary school chemistry.

cyclic and iterative inquiry process. These three components are student *willingness*, *knowing* and *ability* (Figure 2; A1, A2, and A3).

In our pilot study we found that student *willingness* is determined by confronting the student with a real problem (cf. Palmer, 2009) and a complete but partly structured inquiry process. In the main study it is shown that student willingness is also determined by the scientific character of the inquiry and the guidance of the teacher (Figure 2; A1). This guidance is further enhanced if the inquiry problem is also a real problem for the teacher, because this circumstance has a decisive influence on the interaction between teacher and student. The teachers become motivated when their students inquire a problem of which the solution is unknown to them as well. The whole component of student willingness is an extra component compared to the PACKS model.

Our research regarding the student *knowing* component indicates that teaching scientific inquiry needs to give students the opportunity to gain knowledge on: the inquiry method; relevant subject knowledge; practical equipment; the concepts accuracy, reliability and validity; and the coherence between these concepts (Figure 2; A2). Here, explicit teacher guidance concerning the student gain of knowledge on the inquiry method and practical equipment are two extra essentials compared to the PACKS model (Millar et al., 1994).

For the component of student *ability* the findings in the pilot and main study show that the ability categories (i–ix) as are suggested by Chinn and Malhotra (2002) are essential activities to which the students need to be directed in a scientific inquiry process (Figure 2, A3).

Moreover, the results show that teaching scientific inquiry comprises the components A1, A2, and A3 and that they influence each other in a cyclic way (Figure 2, principle A).

The findings from the main research also show that the teachers guide students to inquire a real problem within a simulated, but in its key elements authentic scientific inquiry community, which is in accordance with design principle (B): *creating an inquiry community.* Inquiry teams from various schools, in order to exceed the school level, create this community. Inquiring a common problem enhances peer review with enough quality, and offers enough freedom for the students to decide on an inquiry question of their own interest within the module's references. This also creates a situation in which the teachers are able to adequately guide the inquiry teams as is shown by the averaged scores of the component of student willingness.

It is concluded that principle B contains four components: the inquiry problem; the inquiry results; critical discourse; and new knowledge and further questions (Figure 2, principle B).

The essentials of a theoretically and practically founded framework, based on two design principles (A and B) for teaching scientific inquiry in upper secondary school chemistry can be found in Figure 2.

Furthermore, the cyclic and iterative inquiry process is made possible with a teaching-learning strategy consisting of seven phases that contain orientation on, information about, acquisition of, application of and reflection on all aspects of a cyclic and iterative inquiry process. Although these phases could presumably be designed and enacted differently, we argue that none of these phases can be ignored. According to us the strength behind the seven phases of the strategy lies in the fact that it allows the teacher and the student repetitive and iterative handling with the *knowing* and the *ability* components of the framework.

For example, in the component of *knowing*, the handling of the concepts of evidence is visible in the orientation on these concepts in the guide experiment, followed by the acquisition of them by an assessment of these concepts in an authentic research article. Students are guided to apply the concepts of evidence in relation to the diffusion of hydrated ions in writing an inquiry plan, conducting the planned experiments and writing about them in a first article as well as reflecting upon them in combination with relevant subject and practical knowledge in a peer review and last in writing a final article. The repetitive and iterative character of the activities has a positive influence on the student understanding of the concepts accuracy, reliability, and validity as is shown in the results in the set test of the main study. Also, the students are good at assessing the concepts of evidence in the exemplary research article, but they show problems in applying reliability in their final articles. This problem is also confirmed by another check in the student workbook's glossaries. A majority of the students still defines reliability as "whether you believe the results." At the moment of writing their final articles the students still do not understand reliability in relation to the data they themselves collected. They seem not to have the right language to express themselves.

The repetitive character of the activities also has a positive influence on the student understanding and deepening of the concept of diffusion and the movement of hydrated ions in de-ionized water (Van Rens, Van der Schee, & Pilot, in press).

Regarding student *ability* the findings in the main study show that the inquiry problem allowed students to conduct a sequence of practice with quality, except for the formulation of inquiry questions and the graphical presentation of the measured data. The difficulties students have in formulating an inquiry question is not because of a lack of clarity on the inquiry topic, as suggested by Blaxter et al. (1996), but because of the teachers' unawareness that students did not dare to adjust or change the inquiry question during the inquiry process. This explanation is supported by the observation that there are no differences between the formulated questions in the team inquiry plans, the first article and the final article. Moreover, formulating inquiry questions is found to be difficult for teachers (Van der Schee & Rijborz, 2003). More focused (just-in-time) practice on the formulation of inquiry questions might be effective (Hofstein, Navon, Kipnis, & Mamlok-Naaman, 2005).

The fact that the students have difficulties with the graphical presentation of measured data is also found in other studies by, for example, Krajcik et al. (1998). Dori and Sasson (2008) argue that computerized laboratories enhance graphing skills, whereas Potgieter, Harding, and Engelbrecht (2008) state that student difficulties with graphical presentation of measured data seem to lie at the mathematics side. The latter is in contrast with the findings in our main study, because the students were capable to identify ‘‘mistakes’’ in the graphical representation of the exemplary research article, which shows that there were no problems with their mathematical understanding. It seems that in our study the students have problems applying this understanding at a later moment with a new set of collected data.

The theoretically and practically founded framework for teaching scientific inquiry has much potential. This can be concluded from the fact that the same design community developed seven more inquiry modules on the basis of the framework. These were: Traditional and modern soap: washing power; Cola and Teeth; Cool: design a cold pack; Salty; Biofuels; Chocolate; Gastronomy and Fermentation (in construction). The gastronomy inquiry module was enacted in 2009 by 875 students and 46 chemistry teachers see: http://www.onderwijscentrum.vu.nl/internetsymposium.

In fact, all these modules were enacted with high quality by many more teachers and students in various countries. Besides the wider feasibility of the modules, it is visible that some of the topics of inquiry are more environmentally and economically embedded; for example, Salty and Biofuels. The module ‘‘Salty’’ contains an inquiry problem on ionic liquids and is centered around the question: Is there an alternative, a ‘‘green’’ solvent, that can replace organic solvents in industrial processes and could ionic compounds provide such a solvent? (Van Rens & Pilot, in press).

This shift in content suggests two things. First, it suggests that the mutual conceptualization on teaching scientific inquiry between teachers and researchers in a design research can gear to one of the aspects of the nature of science; for example, the social and cultural embeddedness of science (Abd-El-Khalick, Waters, & Le, 2008).

Second, it suggests in line with Chinn (2007) that greater autonomy of teachers in the process of knowledge building on teaching scientific inquiry creates more room to integrate scientific inquiry teaching and learning in students' lives and moves towards culture, place and problem-based learning.

Further research in this respect is important for professional development of teachers and the innovation of educational programs regarding the teaching of scientific inquiry.

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Appendix A: Test on Accuracy and Reliability

Question 2 (on accuracy), 8 (on data handling and reliability) and 9 (on variables and reliability).

Encircle in each question your answer and explain why you select that answer

2. Tobias says to Claar:

"Any measurement in a laboratory has an inaccuracy." Agree/Disagree. Explain.

Mirjam and Zoebie got a puppy for their birthday. Mirjam's puppy was called "Bobbie" and Zoebie's was called "Loekie." For 5 weeks Mirjam and Zoebie measured their puppy every week in the same way, at the same time and with the same balance. Their measurements looked like this:

Age of puppy (in weeks)	Mass of Bobbie (in kg)	Mass of Loekie (in kg)
12	6.0	3.0
13	6.5	3.4
14	7.0	3.8
15	7.5	4.2
16	8.0	4.6

(i) Mirjam says: "Loekie grows faster." Agree/Disagree. Explain.

(ii) Their results are reliable. Agree/Disagree. Explain.

9. Vera and Ester want to inquire three types of effervescent tablets. Their inquiry question is: Which tablet falls apart the fastest in a glass of water? For their inquiry they made the following scheme:

We measure in grams	We change the type of tablet	We control
The mass	An aspirin tablet A vitamin C tablet A multivitamin tablet	The temperature of the water The amount of water

(i) Is it a good idea for this inquiry to change the type of tablet? Agree/Disagree. Explain.

(ii) They claim: three measurements with each tablet will be sufficient. Agree/Disagree. Explain.