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**Collaborative Inquiry Learning: Models, Tools, and Challenges**

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Running head: COLLABORATIVE INQUIRY LEARNING

## Collaborative Inquiry Learning: Models, Tools, and Challenges

### Abstract

Collaborative inquiry learning is one of the most challenging and exciting ventures for today's schools. It aims at bringing a new and promising culture of teaching and learning into the classroom where students in groups engage in self-regulated learning activities supported by the teacher. It is expected that this way of learning fosters students' motivation and interest in science, that they learn to perform steps of inquiry similar to scientists and that they gain knowledge on scientific processes. Starting from general pedagogical reflections and science standards the article reviews some prominent models of inquiry learning. This comparison results in a set of inquiry processes being the basis for cooperation in the scientific network NetCoIL. Inquiry learning is conceived in several ways with emphasis on different processes. For an illustration of the spectrum, some main conceptions of inquiry and their focuses are described. In the next step, the article describes exemplary computer tools and environments from within and outside the NetCoIL network that were designed to support processes of collaborative inquiry learning. These tools are analysed by describing their functionalities as well as effects on student learning known from the literature. The article closes with challenges for further developments elaborated by the NetCoIL network.

Keywords: Inquiry learning, collaboration, computer-based learning environments

## Introduction

Collaborative inquiry learning is a mixed term whose meaning is derived from the demand of practicing inquiry in science education (National Research Council, 1996) and the increasing proliferation of computer-supported collaborative learning (CSCL) in the past few years (Koschmann, 1996; Koschmann, Hall, & Miyake, 2001; Strijbos, Kirschner, & Martens, 2004). As a result of collaborative inquiry learning, students acquire knowledge of how to do science as a common endeavour, they learn about the nature of science and the scientific content. By the development of powerful computer-based learning environments (de Corte, Verschaffel, Entwistle, & van Merriënboer, 2003) collaborative inquiry learning gained additional options. Learning technology can support students as they work in collaborative inquiry projects by taking over some of the teachers' responsibilities and enabling direct exchange among students, also across wider distances and at different times.

The purpose of this article is twofold. First, we present the theoretical foundations and connotations of the term 'collaborative inquiry learning' to clarify its meaning and importance for science education. Second, we highlight the benefits of computerised tools in enabling and enhancing collaborative inquiry learning processes. We provide, therefore, examples of computer-based learning environments designed by several established work groups, in particular by members of our scientific network NetCoIL. The network consists of scientists from Canada, the U.S., the Netherlands, Norway, Spain and Germany and has been established to compare and integrate different technological approaches.

### The importance of collaborative inquiry learning

The call for inquiry learning is based on the conviction that science learning is more than the memorization of scientific facts and information, but rather is about understanding and applying scientific concepts and methods. This special emphasis on methods can be traced back up to the work of Dewey (1910, 1938). He argued that scientific knowledge develops as

Collaborative inquiry learning

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1  
2  
3 a product of inquiry. Therefore, students' attitude to find inquiry-based solutions for authentic  
4  
5 problems should be promoted. Dewey's historical notions are in accordance with current  
6  
7 approaches of situated learning (Greeno, Collins, & Resnick, 1996; Henning, 2004). Situated  
8  
9 learning aims to prevent what Whitehead (1929) termed 'inert knowledge'. Knowledge is  
10  
11 considered as 'inert' when there is a lack of knowledge transfer in problem solving situations  
12  
13 that demand the use of already acquired knowledge (Renkl, Mandl, & Gruber, 1996). **By**  
14  
15 **inquiring complex problems** knowledge may become less inert and more applicable (Edelson,  
16  
17  
18  
19  
20  
21 2001).

22  
23 Moreover, national guidelines for science education stress the special value of inquiry  
24  
25 learning. The National Science Education Standards of the U.S. put strong emphasis on  
26  
27 activities that investigate and analyse science questions (National Research Council, 1996).  
28  
29 **Like real scientists students should** study the natural world, make their own observations and  
30  
31 propose explanations based on the evidence of their own work. In Germany, as a political  
32  
33 reaction to the mediocre performance of German students in the Programme for International  
34  
35 Student Assessment (Centre for Educational Research and Innovation, 2001), national **science**  
36  
37 education standards were **introduced** in four main competence areas: domain-specific  
38  
39 knowledge, methodological knowledge, communication, and **judgement** (Sekretariat der  
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The area 'methodological knowledge' encompasses many inquiry learning related  
activities and emphasises the importance of this educational dimension.

51 Inquiry learning often incorporates an element of **collaboration meaning the engagement**  
52  
53 of participants in a common endeavour (Dillenbourg, 1999). There are a number **of arguments**  
54  
55 why collaboration among learners is effective for inquiry-based learning. According to socio-  
56  
57 constructivistic learning theories (Duit & Treagust, 1998) knowledge emerges by  
58  
59 collaborative search of problem solutions in communities with distributed information among  
60  
its **members**. Piaget (1926) pointed at the importance of social interaction for the emergence

Collaborative inquiry learning

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1  
2  
3 of cognitive conflicts. These socio-cognitive conflicts form the basis of considerable cognitive  
4  
5 developments and performances and might appear in inquiry learning processes as well  
6  
7 (Lethinen, 2003). Finally, Vygotsky's (1978) idea of the 'zone of proximal development' has  
8  
9 been helpful for understanding the effects of collaborative experiences; **collaborating peers**  
10  
11 **offer zones of proximal development to each other. Crook (1991) further developed the idea**  
12  
13 **to capture the whole of the context formed by classmates, the teacher, and technical media in**  
14  
15 **which learning takes place. In the meantime theoretical reflections and empirical studies have**  
16  
17 **demonstrated the potential of student collaboration, the role computer tools can play to**  
18  
19 **support it as well as conditions for success (e.g. Pilkington, 2004; Pilkington & Walker,**  
20  
21 **2003).**

22  
23  
24  
25  
26  
27 Taken together, theoretical arguments, current educational policy demands, and empirical  
28  
29 **evidence** form the basis to promote collaborative inquiry learning in science education. In the  
30  
31 following, we take a closer look at the meaning of inquiry learning and how its processes can  
32  
33 be supported by computerised learning tools.

### 34 35 36 37 38 39 Characterising collaborative inquiry learning

40  
41 Albeit the importance of inquiry learning is widely recognised, it is difficult if not impossible  
42  
43 to give a commonly accepted definition (Cuevas, Lee, Hart, & Deaktor, 2005). Wheeler  
44  
45 (2000) complains that the word 'inquiry' is handled rather elastically to fit people's differing  
46  
47 worldviews. Notions of inquiry differ along several dimensions, two of which are outlined  
48  
49 now. First, different understandings of inquiry may arise from specific objects to be  
50  
51 investigated. Arts and humanities, e.g. seek specific kinds of entities, mostly different from  
52  
53 physical objects that are quantitatively measured and possibly described by mathematical  
54  
55 formalism. For the domain of *science* learning Quintana, Reiser, et al. (2004, p. 341) define  
56  
57 'inquiry as the process of posing questions and investigating them with empirical data, either  
58  
59 through direct manipulation of variables via experiments or by constructing comparisons  
60

1 Collaborative inquiry learning

2  
3 using existing data sets.’ We agree and would like to add the remark that ‘data’ does not  
4  
5 necessarily refer only to quantitative data but also to qualitative data. For example, in a Co-  
6  
7 Lab inquiry **project** on ‘water management’ students manipulate quantitative parameters of a  
8  
9 leaking water tank to understand and model its outflow behaviour (Bosler, Bell, & van Gastel,  
10  
11 2004). In contrast, the subject of ethology draws on observation, classification and  
12  
13 interpretation of animal behaviour. This type of qualitative inquiry is supported by the  
14  
15 software Animal Landlord (Smith & Reiser, 1998).  
16  
17

18  
19 Second, descriptions of inquiry learning choose different degrees of concretion in regard to  
20  
21 student activities; three degrees are specified in the following. Some inquiry models, often  
22  
23 with a socio-cognitive background, leave a lot of freedom to learner groups to define their  
24  
25 own processes when inquiring. The “knowledge building” approach by Scardamalia and  
26  
27 Bereiter (1991) describes inquiry as an unpredictable, holistic process of creative  
28  
29 development of ideas within a community of learners. Due to the interdisciplinary generality  
30  
31 of this approach learning processes are not defined as a set of operations typical for doing  
32  
33 research, but more generally as generating, classifying, representing, linking, and annotating  
34  
35 elements of knowledge. Consequently, this approach is not only suitable for education, but,  
36  
37 e.g. also for the contexts of health care, business and community affairs, etc. (Scardamalia  
38  
39 2004). Inquiry models of another category are more specific about distinct inquiry processes  
40  
41 (activities) that students are supposed to go through. Some models even define one or a small  
42  
43 number of pathways students should take through the activities. The inquiry cycle by White  
44  
45 and Frederiksen (1998), for example, consists of the iterated activity sequence “question –  
46  
47 predict – experiment – model – apply”; this inquiry cycle is embedded in students’ reflective  
48  
49 assessment activities.  
50  
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57  
58 Further difficulties in defining inquiry learning arise from the fact that inquiry learning  
59  
60 can be seen in close relation to problem-based (Evenson & Hmelo, 2000), project-based  
(Blumenfeld et al., 1991), or discovery learning (Gijlers & de Jong, 2005). For instance,

Collaborative inquiry learning

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3 problem-based learning is described as student-centred activities around a rich problem that  
4  
5 affords free inquiry by students (Barrows, 1985; Evenson & Hmelo, 2000). The greatest  
6  
7 correspondences of inquiry learning are probably to project-based learning which 'is a  
8  
9 comprehensive perspective focused on teaching by engaging students in investigation. Within  
10  
11 this framework, students pursue solutions to nontrivial problems by asking and refining  
12  
13 questions, debating ideas, making predictions, designing plans and/or experiments, collecting  
14  
15 and analyzing data, drawing conclusions, communicating their ideas and findings to others,  
16  
17 asking new questions, and creating artefacts.' (Blumenfeld et al., 1991, p. 371). Referring to  
18  
19 Edelson, Gordin, and Pea (1999, p. 394) discovery learning characterises a narrower term: 'In  
20  
21 our conception of learning from inquiry, students can discover scientific principles through  
22  
23 their own inquiry activities, but discovery is not the only mechanism for learning from  
24  
25 inquiry.'

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31  
32 Quintana et al. (2004) divide the processes of inquiry into three broad categories: sense  
33  
34 making, which involves basic operations like hypothesis formation or data analysis, process  
35  
36 management, which stands for strategies to control the inquiry process, and articulation and  
37  
38 reflection which include constructive, evaluative and articulating processes. For our purposes,  
39  
40 i.e. tying computerised tools to specific collaborative inquiry learning processes, these  
41  
42 categories seem too general. Therefore, we compared recent approaches of science education  
43  
44 experts characterising the process of inquiry learning to find out what the approaches have in  
45  
46 common. The results of this search are presented in Tables 1 and 2.

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52  
53 Please insert Tables 1 & 2 here

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57  
58 **The ten groups of investigators** (Cuevas et al., 2005; Friedler, Nachmias, & Linn, 1990;  
59  
60 Gijlers & de Jong, 2005; Harms, Mayer, Hammann, Bayrhuber, & Kattmann, 2004; Löhner,  
van Joolingen, Savelsbergh, & van Hout-Wolters, 2005; National Research Council, 1996;



Collaborative inquiry learning

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3 Schecker, Fischer, & Wiesner, 2004; Schwarz & White, 2005; Singer, Marx, Krajcik, &  
4  
5 Chambers, 2000; Windschitl, 2004) in Tables 1 and 2 were selected to cover a wide range of  
6  
7 inquiry processes and terminology. We tried to build a synthesis out of their specifications.  
8  
9 By compiling a variety of approaches to inquiry, we determined a set of nine categories that  
10  
11 captured the space of ideas about inquiry held by the investigators. The nine categories were  
12  
13 labelled as ‘main inquiry processes’ and are shown in the leftmost columns of our Tables. In  
14  
15 Tables 1 and 2, we associated authors’ inquiry processes to our nine categories. The processes  
16  
17 are not listed in a fixed chronological order: Students may go through the processes in the  
18  
19 order needed and return to them if necessary. Analyses of practice have shown that science  
20  
21 inquiry can take a variety of forms (McGinn & Roth, 1999; Windschitl, 2004).

22  
23  
24  
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26  
27 Orienting and asking questions are almost always the first processes of an inquiry.  
28  
29 Students make observations or gaze at scientific phenomena that catch their interest or arouse  
30  
31 their curiosity. Ideally, they develop questions by themselves. A particular difficulty in a  
32  
33 domain to be explored is to formulate “good” questions that are relevant and may be  
34  
35 investigated by scientific means. Arriving at good questions may typically take several  
36  
37 attempts as insight in the domain grows (cyclic progression of inquiry).  
38  
39

40  
41 Hypothesis generation is the formulation of relations between variables (de Jong & Njoo,  
42  
43 1992). Stating a hypothesis is a difficult task for many students. In early stages of the inquiry  
44  
45 process, students often do not know which items and quantities to focus on from a scientific  
46  
47 point of view. Another problem is that learners and even university students simply do not  
48  
49 know what a hypothesis should look like. They do not recognise that it consists of variables  
50  
51 and a relation between them and – in many scientific fields – should take the form of an ‘if-  
52  
53 then’ statement (de Jong & van Joolingen, 1998; Njoo & de Jong, 1993).  
54  
55

56  
57 Planning in the narrower sense involves the design of an experiment to test the hypothesis  
58  
59 and the selection of appropriate measuring instruments for deciding upon the validity of the  
60  
hypothesis (Harms et al., 2004). In the broader sense, planning also incorporates the use of

Collaborative inquiry learning

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3 suitable metacognitive strategies. In open inquiry, students are given the opportunity to  
4  
5  
6 organise their learning at times independently from the teacher which demands the use of a  
7  
8 number of organisation, control, and monitoring strategies termed process management  
9  
10 strategies by Quintana et al. (2004) or regulative processes by de Jong (2005).  
11

12 Investigation as the link to natural phenomena is the empirical aspect of inquiry learning.  
13  
14 It includes the use of tools to collect information and data, the implementation of experiments,  
15  
16 and the organization of the data pool (Harms et al., 2004). The types of information and data  
17  
18 needed are widely different across domains and also depend on whether an investigation is  
19  
20 qualitative or quantitative.  
21  
22  
23

24 Analysis and interpretation of data form the basis of empirical claims and arguments for  
25  
26 the proposition of a model (Windschitl, 2004). Frequently, students' interpretation of data  
27  
28 results in the confirmation of the current hypothesis even in the face of counter evidence. This  
29  
30 phenomenon is known as 'confirmation bias'. Another cognitive hurdle for learners seems to  
31  
32 be the interpretation of graphs, e.g. as a result of a computer simulation (de Jong & van  
33  
34 Joolingen, 1998; Mokros & Tinker, 1987).  
35  
36  
37

38 Model exploration and creation is a fundamental aspect of science learning (Schwarz &  
39  
40 White, 2005; Windschitl, 2004; Niedderer, Schecker, & Bethge, 1991). Models are used in  
41  
42 science for several purposes (Justi & Gilbert, 2002). Students should learn to explore, create,  
43  
44 test, revise and use externalised scientific models that may express their own internalised  
45  
46 mental models (Gilbert & Boulter, 1998; Gobert, 2000; Gobert & Tinker, 2004). For our  
47  
48 purposes, we define modelling as building a cohering whole of objects and relations in order  
49  
50 to represent a target area of reality, to reproduce observations from this area, to predict  
51  
52 developments, or even to affect developments in this area. This broad definition includes  
53  
54 models in all possible domains created in a variety of formats: crafted objects as models,  
55  
56 propositional models, free sketches, formalised graphical models, mathematical models, or  
57  
58 software models.  
59  
60

1  
2  
3 **In conclusion and evaluation activities, students extract the results from their inquiry.**

4  
5  
6 Conclusions might be drawn from data and in comparison with models, theories or other  
7  
8 experiments (Harms et al., 2004). Evaluation is a reflective process helping students to judge  
9  
10 their own research. When students apply their research results to a new problem they learn to  
11  
12 evaluate whether the results fit the theory or have to be reconsidered. By evaluating the  
13  
14 attributes of each activity and its function in scientific inquiry, students grow to understand  
15  
16 the nature of inquiry learning (White & Frederiksen, 1998).  
17

18  
19  
20 Communication represents the collaborative element of inquiry learning. Communication  
21  
22 is a process that may span all other processes of scientific inquiry starting with the  
23  
24 development of a research question and ending with the presentation or reporting of results. A  
25  
26 common kind of support to structure communication processes is the use of collaboration  
27  
28 scripts (Kollar, Fischer, & Slotta, 2005). Students learn how to make claims on the basis of  
29  
30 data and to provide reasons why the data support their claims. While communicating, the  
31  
32 learners are also forced to reflect their own work.  
33  
34

35  
36 Prediction 'is a statement about the value(s) of one or more dependent variables under the  
37  
38 influence of one or more independent variables.' (de Jong & van Joolingen, 1998, p. 189). In  
39  
40 a prediction learners express their beliefs about the dynamics of a system, while in a  
41  
42 hypothesis the relations of the variables are emphasised. This last category may also  
43  
44 symbolise the unfinished inquiry process after reaching a conclusion where new questions and  
45  
46 hypotheses arise from the research results. Therefore, some authors prefer the representation  
47  
48 of scientific inquiry in form of a cycle (Schwarz & White, 2005; Windschitl, 2004).  
49  
50  
51

52  
53 **Tables 1 and 2 show that well-known inquiry conceptions** use a series of processes and  
54  
55 leave out other processes. **The order of our nine main inquiry processes is not fixed, but very**  
56  
57 **likely** to be found are orientation and questioning in the beginning, processes of investigation  
58  
59 like experimenting in the middle, and finalizing activities like conclusion and evaluation at  
60  
the end.

### Tools supporting collaborative inquiry learning

There are several arguments based on theory and empirical studies about how computerised tools can support student inquiry. Two very general reasons for the use of computer tools for inquiry have been described in the research literature (e.g. Edelson et al., 1999; van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005; Lehtinen, 2003). First, computer tools help students to focus on higher learning processes being characteristic for inquiry. Computers support learners in planning investigations or constructing knowledge by assuming large parts of routine processes like calculating, acquiring, sorting, or visualising data, retrieving and saving information. Second, the computer system can be controlled by the learners themselves. They can access information and hints via the interface on their own initiative and do not necessarily have to rely on the teacher. Self-regulated learning with all its positive effects on motivation can be realised.

In the first part of this article a collection of inquiry processes was presented, comprising several established accounts of inquiry learning and covering a general notion of scientific inquiry. Starting from this conception of inquiry we now intend to show examples of computerised assistance for processes within this spectrum and to describe their effects on students' learning processes as reported in research literature. Tools from the NetCoIL partners formed the starting point of this collection, complemented by tools from several other learning environments. The tools are collected so that different accounts of inquiry in different domains and all processes in Tables 1 and 2 are covered. Of course, the collection cannot give a complete overview of all tools designed to support the listed processes. Its intention is to show examples of sound development and define a wide scope for integration attempts as carried out, for example, in the NetCoIL project (cf. the concluding section on future challenges). Table 3 gives a brief overview of the tools mentioned in the following and of some research findings on their effects on students' learning processes.

1 Collaborative inquiry learning

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6 Tools supporting orientation and asking questions

7  
8 Computer tools can support processes of orienting and asking questions by catching learners'  
9 interest and curiosity, produce a trade-off between free and guided learning, and provide  
10 learners with continuous thought-provoking impulses. Computer environments can facilitate  
11 questioning by focusing students' attention to important aspects of the phenomenon under  
12 investigation as shown by Hmelo and Day (1999) when evaluating biomedical simulations –  
13 the 'DxR simulation of Mrs. Buchanan' – enriched by 'contextualised questions'.

14  
15 To arouse students' interest and curiosity several tools covering the whole scope of  
16 multimedia applications can be used, presuming that the issue of appealing design is taken  
17 into account. Some examples from the Viten learning environment ([www.viten.no](http://www.viten.no)) suitable at  
18 lower secondary level are given. On the basis of classroom trials, Viten projects were and are  
19 repeatedly optimised to arouse student interest (Jorde, Strømme, Sorborg, Erlien, & Mork,  
20 2003). The Viten project 'Bears' uses short introductory text windows illustrated with  
21 beautiful photos from nature. Viten's 'Earth Processes' program takes students on a short time  
22 travel by way of animations. Another approach has established the extensive use of video  
23 material designed like detective novels: the series of the Adventures of Jasper Woodbury for  
24 students in grades 5 and up (Cognition and Technology Group at Vanderbilt, 1993, 1997). A  
25 videodisk presents an exciting story anchoring a complex and challenging student task.  
26 Learners develop problem-solving skills while planning, for example, a complex trip or  
27 making business plans.

28  
29 A balance between freedom and guidance in an inquiry learning environment should give  
30 students options to develop their own questions. While orienting, students should be able to  
31 get an impression of how the first steps of the investigation could look to make plans. In the  
32 Co-Lab project 'Greenhouse effect', for example, students are introduced to the first level by  
33 an assignment text that advises them to look around, to experiment with a simplified

Collaborative inquiry learning

12

1  
2  
3 simulation of the sun-and-earth configuration, and to build a simple model of these processes  
4  
5 (van Joolingen et al., 2005; www.co-lab.nl; cf. Figures 1 and 3). This gives guidance for first  
6  
7 orientation about what to do, but there is still a lot of freedom for learners to develop their  
8  
9 own research questions during their investigations.  
10  
11

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15 Please insert Figure 1 about here  
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19  
20 Since complex problem fields can not be investigated in just one attempt, structures of the  
21  
22 learning environment should allow for continued inquiry. Progressive questioning can be  
23  
24 supported, for example, by using the Computer-Supported Intentional Learning Environment  
25  
26 (CSILE) or its successor Knowledge Forum (Scardamalia & Bereiter, 1991; Rahikainen,  
27  
28 Lallimo & Hakkarainen, 2001; Scardamalia, 2004), or software with similar options like  
29  
30 Synergeia and FLE3 (Rubens, Emans, Leinonen, Gomez-Skarmeta & Simons, 2005). They  
31  
32 offer a knowledge building tool that enables learners to add their own notes to a communal  
33  
34 database. Notes have to be labelled ‘question’, ‘my theory’, ‘plan’, etc. (‘thinking types’);  
35  
36 scaffolds explaining the characteristics of each thinking type are offered. This way, students  
37  
38 are supported in collaborative knowledge building and development of explanations and new  
39  
40 questions throughout an ongoing inquiry (Scardamalia, 2002); the tool fosters constructing a  
41  
42 joint problem space as opposed to merely individual understanding (Cohen, 1995).  
43  
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#### 50 51 Tools supporting hypothesis generation

52  
53 A computer tool specialised in supporting hypothesis generation is the  
54  
55 ExplanationConstructor (Sandoval, 2003, Sandoval & Reiser, 2004). The software provides  
56  
57 several windows: The Organizer is used to develop questions and lists titles of corresponding  
58  
59 explanations. These are elaborated in detail by the learners in another window. The learners  
60  
link their explanations to pieces of evidence, i.e. diagrams with data, shown in a third

Collaborative inquiry learning

1  
2  
3 window. Further Explanation Guides make the important components of a scientific  
4  
5 explanation in a specific field, e.g. in the field of natural selection explicit (Sandoval &  
6  
7 Reiser, 2004). **The tool facilitates students' construction of sound causal explanations in the**  
8  
9 **field of evolution, but additional epistemic discourse seems to be necessary to enhance their**  
10  
11 **ideas of the nature of science (Sandoval, 2003).**

12  
13  
14 In order to prepare sound and systematic testing of ideas, students – like scientists – need to  
15  
16 assume specific relations between variables. The Hypothesis scratchpad (van Joolingen & de  
17  
18 Jong, 1991), that was also integrated in several learning environments like SimQuest (van  
19  
20 Joolingen & de Jong, 2003) and SMISLE (van Joolingen & de Jong, 1996), addresses some of  
21  
22 the obstacles in hypothesis generation by providing the structure a hypothesis should have. In  
23  
24 a recent version of the tool two collaborating students can compose 'if-then' hypotheses using  
25  
26 selective lists of variables and qualitative descriptions of their development. **In studies, the**  
27  
28 **Hypothesis scratchpad helped learners with their initial exploration of the hypothesis space**  
29  
30 **which resulted in more, better and more explicitly tested hypotheses. Further, the tool made**  
31  
32 **learners more aware of the hypothesis generation process (van Joolingen & de Jong, 1993).**  
33  
34 **But usability problems led to the development of a Proposition table that offers a list of fully**  
35  
36 **specified hypotheses to be rated with truth-values and tested by the learners (cf. van Joolingen**  
37  
38 **et al., 2005, p. 675).**

#### 47 48 Tools supporting planning

49  
50 An option to support planning is to **divide** complex tasks into an ordered list or an unordered  
51  
52 set of activities. Some learning environments, like KIE (**Knowledge Integration Environment**;  
53  
54 Linn, 2000), WISE (**Web-based Inquiry Science Environment**; Slotta, 2004) and Viten (Jorde  
55  
56 et al., 2003), offer an ordered list of events and activities for access via a navigation panel.  
57  
58 Students are free to access activities in an order they choose, but the listed order from top to  
59  
60 bottom is likely to be chosen (cf. Figure 4). Other systems, like Symphony and Co-Lab, invite

1  
2  
3 learners to plan deliberately and divide the inquiry process into a manageable set of activities.  
4  
5 Based on iterated development and testing, Symphony offers planning support at different  
6  
7 levels (Quintana, Eng, Carra, Wu & Soloway, 1999): The ‘conductor window’ proposes meta-  
8  
9 process activities like revising the plan, doing the next activity, etc. The ‘inquiry map’ shows  
10  
11 five possible activities: develop problem, collect data, visualise data, model data, and review  
12  
13 progress. Activity rationales are explained by rollover guides. Students can plan an  
14  
15 investigation by sequencing these activities in a table. And ‘flow diagrams’ visualise tool use  
16  
17 procedures. The Co-Lab environment provides learners with a process coordinator tool that  
18  
19 shows five high-level activities (starting out, modelling and hypothesising, collecting  
20  
21 information, drawing conclusions, finishing) as well as subordinate activities along with  
22  
23 descriptions and hints (van Joolingen et al., 2005; see Figure 1). Students may work on the  
24  
25 steps in the order they choose and can add individual steps and edit them. When a designer or  
26  
27 a teacher is setting up a Co-Lab project, the process coordinator’s support can and should be  
28  
29 faded out over the sequence of project submodules. Manlove, Lazonder, and de Jong (2007)  
30  
31 found that regulative support through the process coordinator helped students in tasks like  
32  
33 writing lab reports, but not in graphical modelling; it seems even to draw off time from  
34  
35 modelling. As a consequence, the authors argue for regulative support that is closely adapted  
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37 to task activities and interweaved with content support.  
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### 52 53 54 55 Tools supporting investigations

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57 Studies reveal several difficulties students have with running investigations, e.g. they do not  
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59 know which variables to focus on, how to conduct conclusive and efficient experiments, and  
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tend to confirm their original hypothesis (de Jong & van Joolingen, 1998, p. 184-185).



1 Collaborative inquiry learning

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3 Computer assistance has the potential to reduce the complexity of phenomena, to focus on a  
4 smaller set of items and variables, and to offer a ‘model progression’ over several levels (van  
5 Joolingen et al., 2005). Further measures support successful learning with simulations, among  
6 them the use of multiple representations, ‘tailorability’ of tools (Blake & Scanlon, 2007),  
7 prompting for reflective activities (Pilkington & Parker-Jones, 1996; White & Frederiksen,  
8 1998), and interpretative cues (Reid, Zhang, & Chen, 2003). Some examples of different  
9 types of investigation and corresponding tool support are given: In Viten projects, **different**  
10 **representations** of information are offered within the software environment. The project ‘On  
11 thin ice’ provides an animation showing the basic structures of earth’s radiation balance and  
12 how it is affected by factors like deforestation, combustion of fossil fuels, traffic, and volcanic  
13 eruptions. The animation has text windows on demand. Another animation, complemented by  
14 voice information, briefly explains what climate models are and what they can predict. In a  
15 following section of the project, students can retrieve time series of averaged data from expert  
16 projections. Additionally, the project gives students a short list of appropriate web links where  
17 they can deepen the knowledge gained so far. On the whole, Viten stimulates students to  
18 collect various types of information by using rich multimedia functionality. A similar  
19 approach is taken by WISE.

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43 The Co-Lab environment has a focus on experimentation and the collection of quantitative  
44 data through measurement. The challenge is to reproduce the experimental data through  
45 system dynamics modelling. Each Co-Lab submodule offers a phenomenon of a specific type,  
46 either a simulation, a remote experiment, or expert datasets. In Co-Lab’s ‘Water  
47 Management’ project, for example, students can experiment with a water tank that has a  
48 variable in- and outflow of water. At the first level, the water tank is presented as a simulation  
49 in which students can vary the tank diameter, the initial tank level, the flow from a tap  
50 (inflow) and the hole diameter at the bottom (outflow, **see Figure 2**). At **following** levels  
51 students can run remote experiments with a real water tank located at the AMSTEL Institute  
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Collaborative inquiry learning

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3 in Amsterdam and with more complex models of polders and rivers (model progression).  
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5 Regulative support for student investigations is delivered via the ‘process coordinator’ (see  
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7 above), further experimental support through a lab manual and help files (van Joolingen et al.,  
8  
9 2005).  
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### 12 13 14 15 Tools supporting analysis and interpretation

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17 Analysis and interpretation processes are carried out in order to check one’s own hypotheses  
18  
19 against new information and data. For this purpose, it is first necessary to represent data in a  
20  
21 format appropriate for analysis. Software environments that put emphasis on data analysis like  
22  
23 Cool Modes (Pinkwart, 2005, 2003) and Co-Lab offer graph tools and table tools for the  
24  
25 dynamic representation of experimental or modelled datasets (Figures 1 and 2). In addition,  
26  
27 Co-Lab offers a data fitting tool able to fit several mathematical functions to experimental  
28  
29 data graphs. Using this tool, students may get an idea of how they could quantitatively model  
30  
31 data they gathered in experimentation (van Joolingen, et al., 2005).  
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36 The Cool Modes environment additionally supports the interpretation of data in diagrams  
37  
38 or tables. Learners are given the option to attach their own notes as handwritten or textual  
39  
40 annotations to data windows (Lingnau, Kuhn, Harrer, Hofmann, Fendrich & Hoppe, 2003).  
41  
42 Using multiple workspaces and layers flexibly, Cool Modes can display different tools, e.g. a  
43  
44 graph window and a note window, next to or on top of each other. Direct reference to data  
45  
46 representations becomes possible and facilitates data interpretation – also in collaborative  
47  
48 processes (see Figure 2; Manlove, Lazonder, & de Jong, 2007). A similar function is available  
49  
50 in the software Progress Portfolio (Loh, Radinsky, Russell, Gomez, Reiser & Edelson, 1998).  
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52 The tool can be used to document findings like images or data tables and record student  
53  
54 understanding and thinking related to the artefacts.  
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60 An interesting data analysis feature is implemented in the software Galápagos Finches  
from the BGuILE curriculum (Reiser, Tabak, Sandoval, Smith, Steinmuller & Leone, 2001).

Collaborative inquiry learning

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3 A central feature of Galápagos Finches is a data query tool. It helps students retrieve data  
4  
5 from a large data base to explain a historic event of natural selection. Through the structure of  
6  
7 the data query interface students are guided to choose between a longitudinal data analysis,  
8  
9 i.e. a comparison of seasons, and a cross-sectional analysis, i.e. a comparison of finch  
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11 subgroups. Further, they have the choice among a number of birds' physical characteristics  
12  
13 and can select whether they want to examine the distribution of a characteristic, individual  
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15 differences, or relations between two characteristics. After students have constructed a  
16  
17 specific query the data is shown in diagrams of the selected type. The data query tool reduces  
18  
19 the space of imaginable queries so that learners can more easily find their way within an  
20  
21 acceptable time and construct an explanation for the historic event of selection. **In this way**  
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23 they learn typical patterns of explanation in the field of natural selection.  
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### 38 Tools supporting modelling

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40 In accordance with the broad definition of modelling given above, several tools **can be**  
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42 **considered** that support modelling **at different levels of abstraction**. A crucial issue here is to  
43  
44 enable modelling at a level accessible to a **particular group of learners (Miller, Ogborn, et al.,**  
45  
46 **1993; Webb, 1994)** as well as the learners' advancement towards **higher abstraction and**  
47  
48 **complexity, e.g. from qualitative to quantitative modelling**. The WISE project 'What's in a  
49  
50 house?' aims at **modelling in terms of crafting a small house that would be energy efficient in**  
51  
52 **a desert environment**. The WISE computer environment supports the design process by  
53  
54 providing evidence of how plants manage to survive in the desert and by focusing on specific  
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56 physical characteristics of these plants. Using a text tool, students express their insights in  
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58 design principles and how they could be realised in a desert house.  
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Graphical modelling helps students represent and manipulate abstract and complex concepts and structures (Miller et al., 1993; Niedderer et al., 1991); it can be supported in different ways. Several environments like Synergeia, Cool Modes, and Co-Lab provide a whiteboard function useful for students in developing first ideas for problem solution (Rubens et al., 2005; Lingnau et al., 2003; van Joolingen et al., 2005): Learners may draw sketches and attach annotations in order to represent the problem at a very concrete level. Environments like WISE and Cool Modes include mapping tools, similar to the MindManager or the CMap Tools, which are specialised at constructing and analysing logical structures of terms (concepts). Mapping software helps construct integrated knowledge and retrieve information (Novak, 1990; Novak & Cañas, 2008). Similarly, the Expert Builder supports students at primary level in visualising and manipulating knowledge and inference structures (Webb, 1994).

In addition to qualitative graphical support, some tools have semi-quantitative and quantitative modelling features. The environments Model-It™ (Metcalf, Krajcik & Soloway, 2000), ModelsCreator and its successor ModellingSpace (Avouris, Margaritis, Komis, Saez & Meléndez, 2003) try to connect closely to everyday objects and terminology to make modelling accessible to young students. For several fields of investigation the software provides palettes of images from everyday objects. ModellingSpace also allows for the creation of new entities represented by photos or even video frames recorded by the user (Papadimitriou, Fiotakis, Stoica, Komis, & Avouris, 2006). Learners may select or create objects and attach observable variables to them, e.g. the 'water level' to a 'barrel'. They decide which variables affect others and define relations in a semi-quantitative manner choosing from a set of relation graphs or propositional relations. Complex networks of objects and relations can be defined and their behaviour be tested. This type of software provides particularly good support for the first steps of modelling by bridging the gap between real-life objects and scientific concepts (Metcalf et al., 2000; Papadimitriou, Fiotakis, et al., 2006).

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3 In contrast, system dynamics modelling rests upon the distinction between stock and flow  
4 quantities. It requires some domain knowledge and modelling skills from the outset. Stock-  
5 and-flow modelling tools, similar to the well-known STELLA software, are offered within the  
6 environments Cool Modes and Co-Lab (Figure 3). Just as ModellingSpace, Co-Lab offers to  
7 define semi-quantitative model relations first and to enter mathematical relations later (van  
8 Joolingen et al., 2005). An ongoing challenge consists in developing environments that allow  
9 for as seamless transitions between different types (levels) of modelling as possible. Several  
10 studies showed that student modelling needs intensive scaffolding, for example through the  
11 teacher (Li, Law, & Lui, 2006) or content-specific help files (Manlove et al., 2007).  
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### 27 Tools supporting conclusion and evaluation

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29 In the case of software support for reflective processes like conclusion and evaluation,  
30 different levels can be distinguished, viz. more elementary levels of data and artefact  
31 interpretation or handling (see also the section on analysis and interpretation) and higher  
32 levels of reflecting and valuing results in a broader context (Tabak, Sandoval, Smith,  
33 Steinmuller, & Reiser, 1999).  
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41 At an elementary level, evaluation can be supported by storing and recovering artefacts  
42 generated by the learners in their work processes. This function is provided by the Co-Lab  
43 repository, where students' graphical models and experimental datasets can be saved and  
44 retrieved (van Joolingen et al., 2005). In the FLE3 environment, students use the WebTop tool  
45 to store different items (documents, web links, knowledge building notes, artefacts) and  
46 publish them to (parts of) the learning community (Rubens, et al., 2005). Several  
47 environments, for example the ThinkerTools, employ reflective tasks to make students  
48 evaluate and reflect more deeply and generally (White & Frederiksen, 1998). The systems  
49 WISE and Viten provide electronic student notebooks: Learners are asked at several points to  
50 think about questions that challenge them to reflect more deeply, to see things from another  
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perspective, or to apply knowledge built in the preceding section. The student answers about the project are saved in the notebook and can be reviewed as a whole at any time by the student or by the teacher for assessment purposes. Viten also allows teachers to give electronic feedback to students via an assessment tool judged helpful by teachers and students (Jorde, et al., 2003). Studies showed that these note tools can support reflective processes, however, the depth of the teacher's interaction with the inquiring students has a clear effect on the degree of knowledge integration (Slotta, 2004). A first illustration for high-level reflective tasks is taken from the WISE project 'Too fast, too furious?' on airbags in car traffic for grades 9-12 (McElhaney & Linn, 2008). In the first part of the project, students simulate the airbag's and the driver's motion in order to learn about the dangers and conditions of using airbags. At the end of this part, they are asked to review their work on the basis of their notebook. Then, further aspects for reflection are raised: First, students are required to formulate their conclusions on the role of body height, collision speed, and a car's crash zone. In the next activity, the students' assignment is to write a report to the 'Insurance Institute for Highway Safety' including recommendations for the design of cars and airbags. In a further step, learners are asked to consider different simulations of car crashes and models from other scientific domains and to reflect on general issues of modelling (Figure 4; cf. Slotta, 2004).

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In order to support reflection at a high level, Viten tends to assign a complex, reflective task at the end of a project. In the Viten project 'On thin ice' the final task is to write an article on one of eight topics to be published online for the learning community. The project 'Gene technology' invites students to a role-play debate in a TV discussion program on the topic 'Should we allow gene-modified food in our country?'. Students may choose one of five different positions including the hosts of the discussion program. Some basic arguments as

Collaborative inquiry learning

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well as guidelines and web links for preparation of the discussion are provided. Challenging debates on controversial topics are promising in fostering deep reflection and ensure peer interaction in knowledge construction when sufficiently guided by the teacher (Mork, 2005).

### Tools supporting communication

Admittedly, computer-mediated communication has constraints when compared to face-to-face communication, one of the most natural processes for human beings. Although computer technology is constantly progressing, a much narrower stream of a person's messages is transferred and time delays hamper the communicative flow. A chat tool, as, for example, implemented in Co-Lab and in the Cool Modes system (Lingnau et al., 2003), transfers learners utterances as written messages without auditory or other sensory cues of nonverbal communication. Further, written communication is clearly slower than spoken exchange. Communication via a forum, being a central tool in Knowledge Forum (Scardamalia, 2004), has the same characteristics. **Some forums work with even** greater time delay (see below). Modern technologies like 'voice over IP' or video conferences enrich the message stream with auditory or visual information, thus having the potential to preserve some of the nonverbal parts. Currently they still suffer from narrow bandwidths that slow down the simultaneous transfer of audiovisual data.

Nevertheless, there are **significant** benefits of computer assistance for communication opening interesting perspectives for learning. **First, computer communication is able to avoid biases that might arise e.g. from socioeconomic or ethnic differences or class ranks. Second, it can foster the engagement of some of the more retiring students (Gobert & Tinker, 2004).** **Another** advantage is that communication via the computer can be logged easily and may be looked up later. Students may resume their prior work processes or enter a discussion at a later point of time. Teachers who are responsible for several learning groups also may use the data asynchronously for coaching or for assessment purposes (Jorde, et al., 2003). The

Collaborative inquiry learning

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3 asynchronous option eliminates the need to respond to everything immediately and enables  
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5 parallel processing for students and teachers. Asynchronous work becomes particularly  
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7 interesting when learning groups at different locations collaborate, possibly even across time  
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9 zones (Slotta, Jorde, & Homes, submitted). Restrictions imposed by communication tools  
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11 may in some cases even be beneficial. It is possible to guide learners by defining requirements  
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13 for the communicative process. The environment CSILE, its commercial successor  
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15 Knowledge Forum (Scardamalia & Bereiter, 1991; Scardamalia, 2004) as well as Synergeia  
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17 and FLE3 (Rubens et al., 2005) require students to label the type of the message they enter  
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19 into the forum. This has the potential to **yield deeper reflection on the rationale of the ongoing**  
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21 **inquiry, but seems to need sufficient practice to be successful (Veermans & Cesareni, 2005).**  
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23 Further, it was observed that slowed communication, e.g. through a chat tool in Co-Lab, can  
24  
25 force learners to focus more clearly on the task they are working on and reduce off-task  
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27 communication (Sins 2006). Scripted **argumentation, e.g. prompted through a script window,**  
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29 **is reported to have similar benefits, depending, however, on students' internal scripts and**  
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31 **skills (Kollar, Fischer, & Slotta, 2005, 2007).**

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34 In order to cover communication in a broad sense, the notion of 'communication through  
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36 the artefact' was introduced (Dix, Finlay, Abowd & Beale, 2004). It is often used in relation  
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38 to graphical models **or maps** built by students. We argue that any tool that supports students in  
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40 constructing, representing and exchanging knowledge enables communication through the  
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42 artefact. Nevertheless, the graphic format deserves particular attention, since it enables  
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44 simultaneous processing of large amounts of information (Mayer & Gallini, 1990). **Suthers,**  
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46 **Vatrapu, Medina, Joseph, and Dwyer (2008) found positive effects on hypothesis generation**  
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48 **and elaboration in asynchronous collaboration when students constructed a 'Knowledge map'**  
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50 **graphically associating hypothesis and data statements in addition to threaded discussion.**  
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52 Further, students can use tools for presenting their inquiry results, a specific form of  
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54 communication. The concept mapping software CMap, for example, includes a presentation  
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Collaborative inquiry learning

mode which allows producing slides like in a PowerPoint presentation, e.g. to show the genesis of a concept (Cañas, Coffey, et al. 2003).

### Tools supporting prediction

While there is no doubt that predicting the outcomes of processes will foster deeper understanding, the question is how to avoid students' predictive activities being superficial or simply omitted during inquiry. Some inquiry environments counteract this problem by prompting student prediction on specific issues. In the WISE project 'Too fast, too furious?' on airbags, the central question is how airbag and driver have to be placed so that the inflating airbag causes no harm. This is clarified by generating diagrams of driver and airbag motion in a car crash. After **gaining** insight into this procedure students are asked to predict the graph of the airbag motion by using a drawing tool. They may then check their prediction using a car crash simulation model that calculates the target graph. **The project's predict-observe-compare-explain pattern produces learning gains depending on a combination of factors: students' goal-oriented planning, experimentation strategies, and domain knowledge (McElhaney & Linn, 2008).**

While students are still free to choose the sequence in a WISE project, the MAC units (Gobert, Buckley, et al., 2004), now embedded in the control environment Pedagogica, really force them to make predictions at certain points, **either in the format of multiple-choice or open-ended questions or graphs.** In the BioLogica™ unit on genetics students learn about genotypes and phenotypes using the fictitious example of dragons (Buckley, Gobert, et al., 2004). In order to test and apply knowledge they have built about 'dragon genetics' the learners are asked to change the allele combinations so that the dragon has two legs, or the task is to change the alleles of a dragon so that its phenotype looks like a comparison dragon; **students' comparison is facilitated by dynamically changing figures of the phenotypes. In a comparative study on the use of reasoning types like e.g. cause-to-effect reasoning, students**

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3 who used BioLogica™ showed higher learning gains than others introduced to genetics in a  
4 traditional way (Buckley, Gobert, et al., 2004). In the Pedagogica unit ‘Gas laws’ one of the  
5 students’ tasks is to model a bike tyre by using the modelling tool NetLogo that allows  
6 building multi-particle models (<http://ccl.northwestern.edu/netlogo>; Wilensky, 1999;  
7 Wilensky & Resnick, 1999). The simple bike tyre model consists of a container and a variable  
8 number of molecules in it that are set in motion by starting the simulation. In order to foster  
9 predictive activity, students are asked to install a specific model configuration and to predict  
10 what will happen when they run the model. Some unexpected events, like particles evading  
11 from the container, may occur (see Figure 5) and cause learners to rethink their model  
12 conceptions.  
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#### 43 Challenges for the future

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45 The previous explanations have shown that collaborative inquiry can be characterised by nine  
46 main inquiry processes. A wealth of computerised learning tools is available for each of these  
47 nine processes. These tools address the important pedagogical issue of helping students  
48 handle difficult scientific learning tasks as independently as possible. They also support the  
49 teacher who can take care of students with learning difficulties more intensively and give  
50 more experienced students a lot of freedom for their own research and testing. However, we  
51 also see a number of challenges in the area of collaborative inquiry learning.  
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3 One challenge refers to providing learners with exactly the support they need, i.e. to  
4 balance **open-ended exploration** and guidance for individual learners. A scaffolding measure  
5 must be suitable to be effective (Quintana et al., 2004). The level addressed should not be so  
6 low that learners **obtain no** new information. On the other hand, the level must not be so high  
7 that the learner cannot integrate the information into his/her knowledge. One option for  
8 providing suitable support draws on the use of diagnostic tools. However, well working,  
9 continuous diagnostics and related adaptive support need intelligent technical design and  
10 consume computational time. A simpler method is to strongly emphasise collaboration in  
11 inquiry learning: Students may often be able to support each other. A learner who profited  
12 from a tool may, for example, inform other students how it worked. In this case, the diagnosis  
13 is performed by the learners themselves, the computer environment only has to support the  
14 flexible exchange of information, e.g. via a **forum for knowledge building** (Scardamalia,  
15 2004) or via a chat function (van Joolingen et al., 2005).

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18 A second challenge consists in the advancement of computer-based learning  
19 environments: Structuring learning environments in a way that learners can use the full  
20 potential of embedded tools is one issue here. Enabling more flexible learning is another.  
21 Flexible learning environments could support the collection of different types of information  
22 – quantitative as well as qualitative data. Further, they could enable different kinds of  
23 modelling – propositional, graphical, by using formulas –, from which the teacher (or even the  
24 students) might choose the most suitable for the lessons. Flexibility in the learning  
25 environment makes even more sense when the learning projects also allow several solution  
26 pathways. This way, learners may encounter the controversial nature of science. Controversial  
27 problems challenge to exchange solutions and therefore are particularly suitable for  
28 collaborative inquiry learning (cf. Slotta et al., submitted). The improvement of learning tools,  
29 of course, has to be subject to formative and summative evaluation. After all, it is acceptance  
30 and effectiveness that decide on using a tool in the classroom.

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3 We see a third challenge in the integration of different learning environments. Within the  
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5 frame of the NetCoIL project, researchers and designers of several learning environments  
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7 cooperate with the aim of using synergies in developing learning tools. Tools that support  
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9 mainly one inquiry process may be integrated into more comprehensive environments.  
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11 Integrating, for example, the Hypothesis scratchpad into Co-Lab or a knowledge exchange  
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13 forum into WISE could fill existing gaps in the learning process support and might prove  
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15 beneficial (cf. van Joolingen & de Jong, 2003). When integrating different tools, it must be  
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17 decided what is technically feasible and, above all, what is desired from a pedagogical  
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19 perspective. Part of the answer can be given from **comparative** studies on real inquiry  
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21 scenarios in the classroom; **attempts in this direction were also part of the NetCoIL**  
22  
23 **cooperation (Urhahne, Schanze, et al., submitted)**. It is not the technical extension of a tool  
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25 that entails better learning, but a good balance of challenge and support for the learners.  
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27 Scientific exchange like in the NetCoIL framework sets the stage for meeting the challenges.  
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Collaborative inquiry learning

Table 1: Comparison of inquiry learning models (to be continued)

Main inquiry processes	Cuevas, Lee, Hart & Deaktor, 2005	Friedler, Nachmias & Linn, 1990	Gijlers & de Jong, 2005	Löhner, van Joolingen, Savelsbergh & van Hout-Wolters, 2005	Schwarz & White, 2005
orientation / question	questioning	define a scientific problem	analysis / orientation	orientation	question
hypothesis generation		state a hypothesis	hypothesis generation	hypothesis	hypothesize
planning	planning	design an experiment	planning		
investigation	implementing	observe and collect data	testing / monitoring	experiment	investigate
analysis / interpretation		analyze and interpret data	data interpretation		analyze
model					model
conclusion / evaluation	concluding	apply the results	evaluation	conclusion	evaluate
communication	reporting				
prediction		make predictions			

Table 2: Comparison of inquiry learning models

Main inquiry processes	Harms, Mayer, Hammann, Bayrhuber & Kattmann, 2004	National Research Council, 1996	Schecker, Fischer & Wiesner, 2004	Singer, Marx, Krajcik & Chambers, 2000	Windschitl, 2004
orientation / question	formulate questions	making observations / posing questions		asking questions	observe phenomena / develop question
hypothesis generation			negotiate hypothesis		create hypothesis
planning	planning experiment	planning investigations	plan and design experiment		design investigation
investigation	conduct experiment	using tools to gather data	conduct experiment	data collection, organization	conduct investigation
analysis / interpretation	analysis / interpretation	analyze and interpret data	analysis / interpretation / discussion	analysis	analyze data / connect evidence and claim
model					model
conclusion / evaluation	conclusions	proposing answers, explanations	application to a new problem		
communication	communicating	communicating the results	presentation	sharing and communicating data	
prediction		proposing predictions	new hypotheses		new questions arise

**Table 3: Main inquiry processes, selected tools, and research findings (short notes, more details can be found in the text)**

Main inquiry processes	Exemplary tools supporting the inquiry process	Short notes on some research findings on beneficial effects of tools
orientation / question	Viten Adventures of Jasper Woodbury 'contextualised questions' CSILE / Knowledge Forum Synergeia; FLE3	- arouse interest, motivation (Jorde et al., 2003; CTG at Vanderbilt, 1993, 1997) - focus attention (Hmelo & Day, 1999) - construct joint problem space (Cohen, 1995; Scardamalia, 2002, 2004) - enable progressive questioning (Rahikainen et al., 2001)
hypothesis generation	ExplanationConstructor Hypothesis scratchpad Proposition table	- facilitate causal explanation (Sandoval, 2003; Sandoval & Reiser, 2004) - facilitate exploration of hypothesis space (van Joolingen & de Jong, 1993)
planning	ordered-list navigation (KIE, WISE, Viten) Symphony's conductor window, process map, and flow diagrams Co-Lab's process coordinator	- suggests a learning pathway (Slotta, 2004; Jorde et al., 2003) - support needed at different levels of planning (Quintana et al., 1999) - planning support should be interwoven with content issues (Manlove et al., 2007)
investigation	Viten; WISE SimQuest SMISLE Co-Lab ExplanationConstructor	support measures: - multiple representations (Blake & Scanlon, 2007) - prompts for reflection (Pilkington & Parker-Jones, 1996; White & Frederiksen, 1998) - interpretative cues (Reid et al., 2003) - reduced initial complexity, model progression (van Joolingen et al., 2005)
analysis / interpretation	Cool Modes' graph & table tools Cool Modes' annotation tool Co-Lab's data fitting Progress Portfolio Galapagos Finches' data query	- notes in appropriate format attached to objects facilitate analysis (Manlove et al., 2007) - reduced routine work (van Joolingen et al., 2005) - provided data query patterns (Reiser et al., 2001)
model	WISE whiteboards (e.g. Synergeia; Cool Modes) mapping tools (Mind Manager; CMAP; ExpertBuilder) Model-It™; ModellingSpace system dynamics modelling (STELLA, Co-Lab, etc.)	- level of model abstraction has to fit learners' abilities (Miller et al., 1993; Webb, 1994) - everyday objects facilitate first modelling steps (Avouris et al., 2003; Papadimitriou et al., 2006; Metcalf et al., 2000) - graphical modelling makes abstract concepts accessible (Miller et al., 1993; Niedderer et al., 1991) - mapping helps construct and retrieve integrated knowledge (Novak, 1990) - content-specific support is needed (Li et al., 2006; Manlove et al., 2007)

conclusion / evaluation	repositories (Co-Lab, WISE, Viten, FLE3's WebTop) electronic notebooks / journals (WISE, Viten) reflective tasks (WISE, Viten, BGuILE, ThinkerTools)	- enable flexible sharing of learning objects (Rubens et al., 2005) - provide overview of work results for students and teacher (Jorde et al., 2003; Slotta, 2004) - deepen and extend understanding (Mork, 2005; Slotta, 2004; Tabak et al., 1999) - prompts for reflection are needed (White & Frederiksen, 1998)
communication	chat tool (Cool Modes, Co-Lab, ...) forum tools (Knowledge Forum, Synergeia, FLE3, Viten) conferencing systems communication scripts communication through the artefact (Knowledge map, CMap)	- unbiased communication (Gobert & Tinker, 2004) - logging and assessment (Jorde et al., 2003) - structured and reflective knowledge building (Scardamalia, 2002, 2004; Veermans & Cesareni, 2005; Kollar et al., 2007) - progressive inquiry (Rahikainen et al., 2001) - benefits of graphical/structural representation of concepts (Suthers et al., 2008; Cañas et al. 2003)
prediction	WISE: graph prediction in diagrams and testing Pedagogica / BioLogica™ / NetLogo: prediction of model behaviour and testing	- learning gains through predict-observe-compare-explain pattern (McElhaney & Linn, 2008) - advancement of the use of reasoning types (Buckley et al., 2004)

Collaborative inquiry learning

Figure 1

The screenshot displays the COLAB software interface. At the top, it shows the user 'user1 [en]' in a 'Greenhouse, floor 1, room lab' with 55303 KBs of free memory. The interface is divided into several panels:

- Process Coordinator:** A 'Goal Tree' with tasks such as 'Before you start...', 'Make models and hypotheses', 'Draw a model.', 'Specify the variables and their relations.', 'Formulate a hypothesis.', 'Check the syntax of the model.', 'Change the model to fit the data.', 'Collect data.', 'Draw conclusions.', and 'To finish...'.
- Black sphere simulation:** A window showing a simulation of a black sphere being irradiated. It includes a 'Play' button, a time scale from 0 to 10000 seconds, and control panels for 'Incident radiation' (0.5 W), 'Initial Temperat...' (283 [K]), 'Heat capacity' (50 [J/K]), 'Temperature' (33.4°C), and 'Outgoing radiati...' (2.0 W).
- Graph:** A window showing a plot of 'Temp\_celsius' versus 'time'. The y-axis ranges from 10 to 30, and the x-axis ranges from 0 to 10,000. The plot shows a curve that rises sharply and then levels off.
- Lab manual:** A window displaying text: 'In this laboratory you can experiment with a simulated lab set-up of a black sphere that is irradiated by a lamp. Apart from the lamp the lab room is dark and cold. Starting the experiment by pressing the button [Play] means switching on the lamp.'
- ROOMS:** A section with a 3D model of a lab room and buttons for 'Meeting', 'Hall', 'Logout', and 'Change Floor'.
- USERS IN GROUP ONLINE:** A list of users: Alberto, Manuel, user3, Eduardo, user2, and user1 (active).
- CHATBOX:** A section for communication with a 'Send message' input field and buttons for 'to room', 'to floor', 'Restore', and 'Delete'.
- REPOSITORY:** A section for saving and retrieving data.

Figure 2

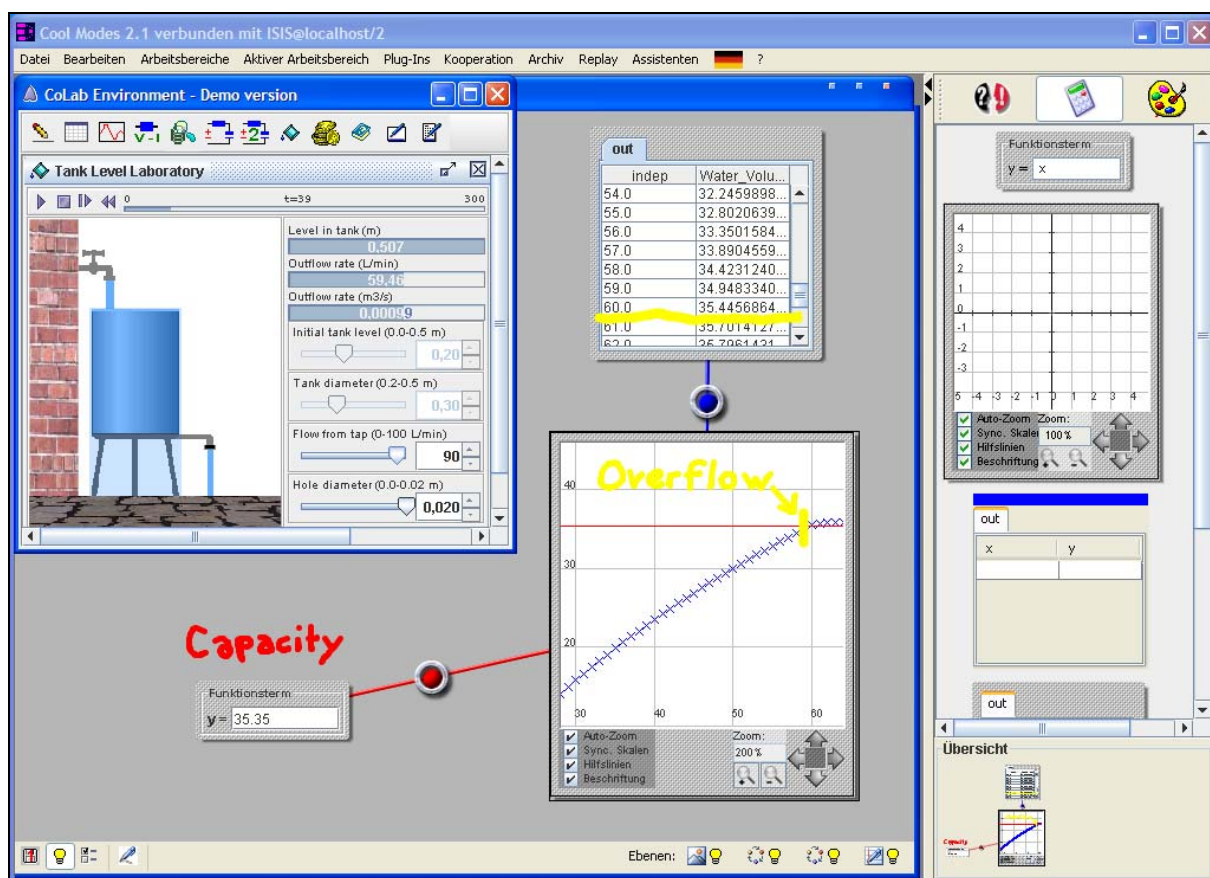


Figure 3

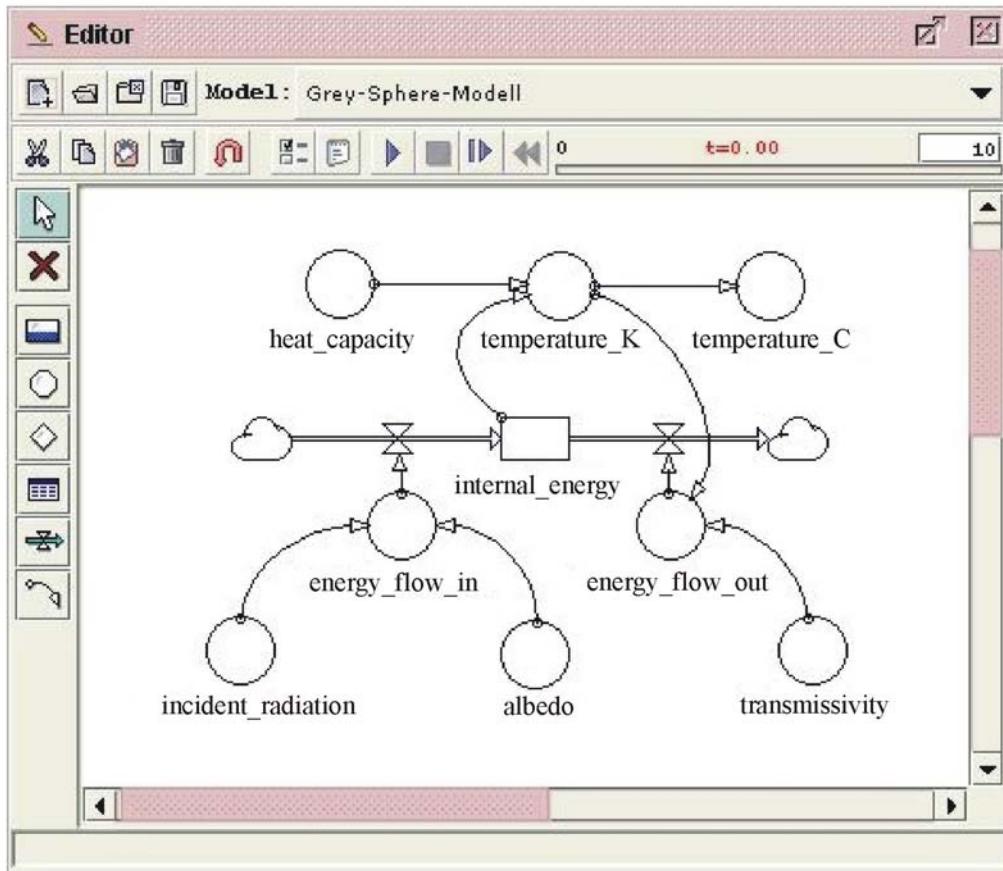


Figure 4

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WISE: Airbags: Too Fast, Too Furious? - Mozilla Firefox

Project Library WISE: Airbags: Too Fast, Too Furi...

**Review Your Findings**

Scientists use computers to make models of all sorts of things, from your knee, to dams, to hurricanes.

Notes

SAVE NOTE

Consider all four models you have seen (three by engineers, one you used in this activity). In what ways are these models like reality?

In what ways are these models NOT like reality?

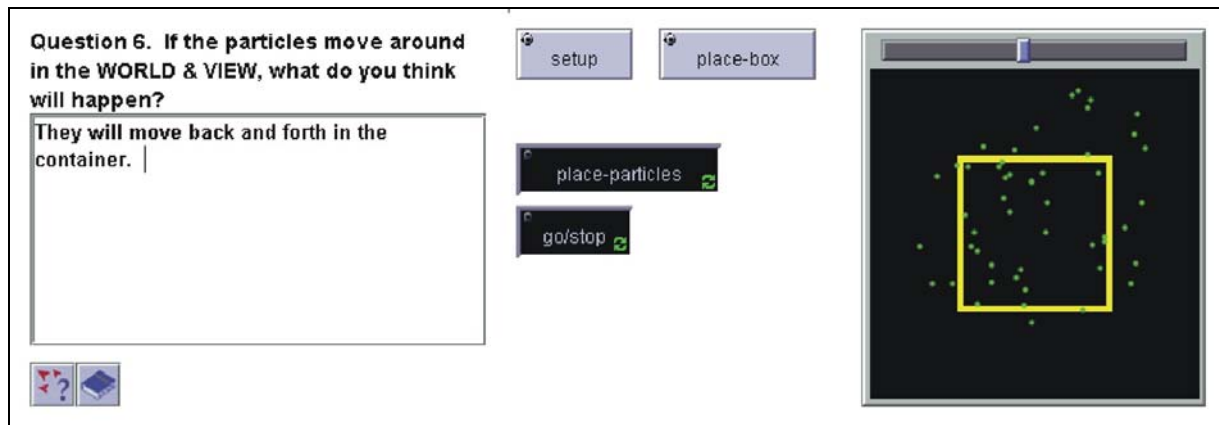
Is it necessary to have multiple models of car crashes, or is one enough? Explain.

help us figure out when drivers are at risk for injury from an airbag.

0.109



Figure 5



For Peer Review Only

## Captions for the Figures for article 1

Figure 1: The Co-Lab environment showing the control panel (tool menu top left, navigator left centre, team locator bottom left), chat tool (bottom centre), object repository (bottom right) and several tools in the work area (process coordinator top left, a simulation top right, a graph tool bottom left, help manual bottom right).

Figure 2: In the NetCoIL project first syntheses of tools were developed: The Co-Lab simulation ‘water tank’ (details in the text) was integrated in the Cool Modes environment that provides its table and its graph tool for this investigation. Further, students’ analysis is supported by Cool Modes’ annotation functionality.

Figure 3: Graphical model editor used to build a simple model of the greenhouse effect (this example was developed in the Co-Lab project).

Figure 4: Evaluative activities in the WISE project on airbags. Activity 6 (see the navigation panel in the left) presents different models of car crashes and from other scientific domains (e.g. models of a knee and of a hurricane) and prompts students to reflect on general aspects of models using the notebook (additional window centre left).

Figure 5: Predictive task in Pedagogica’s unit on ‘Gas laws’. Students are asked to build a simple model of a bike tyre, consisting of a container and some moving particles, and to predict how the particles will move (left). Then they can test their prediction by running their model (right, NetLogo plug-in) and might be surprised by particles evading from the container.