The CoChemEx Project: Conceptual Chemistry Learning through Experimentation and Adaptive Collaboration

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Abstract. Chemistry students, like students in physics, mathematics, and other technical disciplines, often learn to solve problems algorithmically, applying well-practiced procedures to textbook problems. But often these students do not understand the underlying conceptual aspects of the problems they solve algorithmically. One approach to overcoming this problem is to have students solve chemistry problems in a *virtual laboratory* (VLab), a software environment that simulates a real experimental setting and supports inquiry learning of chemistry concepts. We propose to further assist chemistry students in their conceptual learning through having pairs of students collaborate on problems, assisted by computer-mediated *collaboration scripts* that guide the student through the stages of scientific experimentation and that can *adapt* to a particular student's (or dyad's) skills. In the early stages of the CoChemEx (COllaborative CHEMistry EXperimentation) project, we have performed a preliminary, low-tech study comparing how singles and dyads solve chemistry problems using the VLab with and without scripts. In this paper, we define the problem and research hypotheses we address, discuss our approach and technology, and report on early progress.

1 Introduction

A central issue in chemistry education is teaching students to problem solve *conceptually* rather than simply apply mathematical equations. Research in chemistry education has shown that students tend to learn and solve problems "algorithmically" but often do not grasp the deeper conceptual aspects of chemistry and reasoning necessary to be more creative and flexible problem solvers [1, 2]. While chemistry students often have success on problems that are very similar to ones illustrated in a textbook or demonstrated in a classroom, they tend to struggle with problems that could be solved with similar techniques but are not obviously of the same type (e.g., the source and target problems do not share surface features). This difficulty is due to students lacking the conceptual understanding of chemistry to recognize similar core problems that come in "different clothes."

There is some evidence in chemistry education research indicating that collaborative activities can improve conceptual learning [3, 4]. Other studies, while not focused specifically on conceptual versus algorithmic learning, have demonstrated increased performance, as well as motivational benefits of collaborative learning in chemistry [5, 6]. In general, however, there is a paucity of controlled experimentation on the potential benefits of collaborative learning in chemistry. However, such evidence exists in math [7], biology [8], physics [9, 10], and scientific experimentation [11]. Some of our own experimental work in collaborative learning has led to promising preliminary results in conceptual learning in the domain of algebra [12]. In sum, results from collaborative learning research convinced us that it would be worthwhile investigating the advantages of collaborative activities on the acquisition of conceptual knowledge in chemistry.

Our plan is to support collaborating students through the use of *collaboration scripts,* prompts, questions, and assigned roles that guide students through collaborative work (e.g., [13, 14]). Much research has shown that fruitful collaboration does not generally occur by itself (e.g., [15]). Collaborative partners often do not engage in productive interactions and thus miss the opportunity to benefit from their collaboration. In order to ensure that students can actually profit from their collaboration, it is important that collaborative partners learn how to work together in productive ways. Research in the area of collaborative inquiry learning, particularly relevant to the experimental framework we have in mind (and to the interests of this workshop), has also uncovered a need for scaffolded collaboration [16]. Also relevant is work in scientific scaffolding, an area we currently have less knowledge of but will review and assess during the next stage of our project (e.g., [17]).

In general, we believe that it would be best to scaffold collaboration in an *adaptive* fashion, emphasizing and fading structured support for collaboration according to the particular needs of the collaborators. Some work has uncovered the dangers of over-scripting; that is, providing too much structure and support for collaboration [18]. Identifying and being sensitive to such situations in real time will require adaptation. Some of our work suggests this direction, as well: Results of one study [19] indicated that collaboration scripts were beneficial both to collaboration and domain learning. However, in a more recent study [20] it was found that students observing a model of collaboration (i.e., a worked collaboration example) collaborated better and learned more than students who followed a script. One possible conclusion is that students were overwhelmed by the concurrent demands of collaborating, following the detailed script instructions, and trying to learn through reflection. Taken together, these studies strongly suggest that different students, under different circumstances, may benefit from different types of collaboration support; a collaborative learning system that can *adapt* its support might prove quite powerful. In summary, the two primary hypotheses of our project, with the second built on the first, are:

H1*: Computer-mediated collaboration within an experimental framework, and facilitated by collaboration scripts, can promote the creation and strengthening of conceptual stoichiometry knowledge components.*

H2*: Computer-mediated collaboration within an experimental framework, and facilitated by* ***adaptive*** *collaboration scripts, can promote the creation and strengthening of conceptual stoichiometry knowledge components.*

Our goal is to help students actively process the material they encounter, moving them away from the mechanical, algorithmic approach taken by many chemistry students. We believe the collaborative setting will increase the likelihood that students capitalize on the learning events offered by the experimental chemistry environment. Further, we believe that students at different levels of knowledge and skills will benefit more or less from collaborative support, so we intend to enforce and/or fade support based on dynamic estimations of each student's skills and an assessment of the on-going collaboration.

In this paper, we first discuss the technical and pedagogical approaches we plan to take, describing the existing technologies and scripting approach we will use to test our hypotheses. We are a multi-disciplinary team, composed of computer scientists, educational psychologists, and artificial intelligence specialists, and the technical members of our team have, in part, previously developed the technologies that will be used. Our pedagogical approach is also based on the prior research of the educational psychologists on our team. We next discuss the work that we have thus far done, in particular a “low-tech” study (i.e., a study involving some technology, but also work on paper) to test some of our ideas. We will discuss what we have learned from the study and how these lessons will impact our way forward. Finally, we discuss our future plans; in particular how we plan to build from the general concept discussed above to a full-fledged collaborative software system that will be used to support scientific inquiry learning and test the hypotheses H1 and H2.

2 Technology Integration in the CoChemEx project

To test our hypotheses, we are in the process of developing collaborative extensions to the VLab software, a web-based software tool that supports chemistry experiments [21], by integrating it with an existing collaborative software environment, Cool Modes [22], and then running studies that compare individual learning with scaffolded, collaborative learning. Figure 1 illustrates our concept regarding a collaborative inquiry environment and also shows the VLab and Cool Modes software. What is shown in the figure is not yet implemented; rather, it is a storyboard containing individual pieces of software that we will integrate as part of the final system.

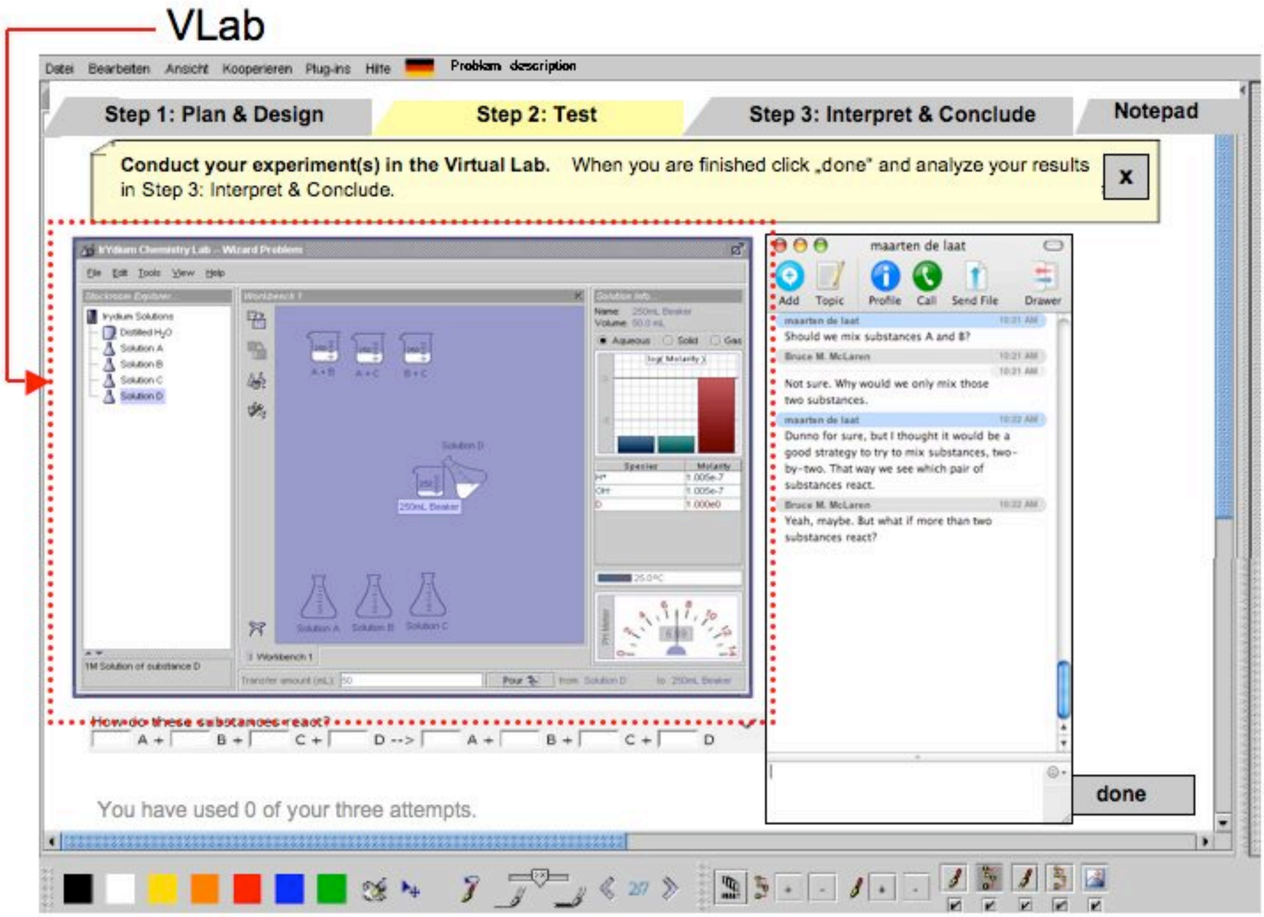

Figure 1: A mock-up of how students will collaboratively solve stoichiometry problems in the CoChemEx system. This is the workspace seen by one of the collaborators.

The VLab, indicated on the left side of the figure, was developed by Dave Yaron, a chemistry professor on the faculty of Carnegie Mellon University, to support students in solving problems in a virtual chemistry laboratory. The VLab software, which is currently implemented to be run stand-alone, i.e., by a single student on a single machine, provides virtual versions of many of the physical items found in a real chemistry laboratory, including chemical substances, beakers, Bunsen burners, etc. It also has meters and indicators that provide real-time feedback on substance characteristics, such as molarity. The idea behind the VLab is to provide the student with a "genuine" laboratory environment in which they can run experiments to solve given chemistry problems. Thus, the VLab can be seen as one way to support inquiry learning.

Cool Modes, the application within which VLab will run (the rest of what is shown in Figure 1), is a collaborative software tool designed to support "conversations" and shared graphical modeling facilities between collaborative learners on different computers. It provides users with a variety of plug-in objects, such as the "chat" area shown on the right side of the figure and a graphical argument space, each of which has its own semantics and underlying representation. All users have access to a shared workspace, essentially what is shown in Figure 1, which is visible to all collaborators and may be updated by any participant in the collaboration. Cool Modes has been used in a wide variety of collaborative learning and working scenarios, involving discussion maps, interactive simulations, and the joint construction of formal models.

Recent Cool Modes extensions support the use of inquiry and collaborative scripts through explicitly defined representations [23]. New objects adhering to a well-defined API may be added to Cool Modes. We will use a design pattern that called the "Scalable Adapter" as a means to allow the VLab and the pre-existing plug-in components of Cool Modes to exchange data with one another. Use of this design pattern is part of a more general project in which the technical partners on the CoChemEx project (i.e., Harrer, Pinkwart, Scheuer, and McLaren) to connect differently targeted learning environments to one another.

3 The Pedagogical Approach

We will use an adaptive scripting approach in an attempt to promote the collaborative processes that we hypothesize to be helpful to conceptual learning in chemistry. A simple illustration of how this might work is shown in Figure 1. As the student collaborates with his or her partner (working on a separate computer), he or she will have access to a number of tools. The VLab provides the basic experimental tool and will be the core collaborative component. The chat window, shown on the right, supports free-form communication between the students, in particular a way to explain, ask/give help, and co-construct conceptual knowledge. An "argument space," not shown in the figure but which will be available on the tabs labeled "Step1: Plan & Design" and "Step 3: Interpret & Conclude" in Figure 1, will allow the collaborators to discuss their hypotheses and results and also to communicate general ideas. We hope this tool will scaffold a conceptual understanding of the experimental process. A "Notepad" tab will allow each of the participants to record their notes and ideas using free-form text. Finally, the "Step 1," "Step 2," and "Step 3" tabs implement a script to guide the students' experimental process. In Figure 1, the collaborating students are working on "Step 2: Test" in which they collaboratively perform an experiment with the VLab.

Since the students are not likely to chat or use the other helpful collaborative mechanisms without prompting or support, the script is intended to prompt the students to take certain steps and ask one another questions. Our idea is to have the students initially follow the steps shown in the tabs, modeled informally on the steps of the experimental process [24, 25], and then allow more open exploration after the first pass. During the experimental steps the students will be prompted with questions intended to elicit explanations, reflection, and help giving/receiving. Scripting is not a simple process of coercing students to take prescribed steps; it can also provide a means for students to reflect on and learn the experimental and problem solving process. For instance, if the collaborators veer far from the script and/or appear to show a lack of conceptual understanding in their use of the tools within Cool Modes, it may be an opportunity for the script to present a prompt with a question, such as, “Did you know that you combined unequal amounts of A and C? Can you explain why you did this?” Providing such a dynamic reaction, based on the specific actions of and knowledge about the collaborators, is one of the stiffest challenges on this project and one we intend to address with machine learning techniques, as discussed in the concluding section of this paper. This example is intended only to provide a glimpse of the adaptive scripting idea we have in mind.

Our approach to scripting is to guide the collaborating students through phases of scientific experimentation and problem solving. The specific approach we have adopted – and have tested in the study described in the following section – is based on the kinds of cognitive processes identified as typically used by experts as they solve scientific problems experimentally [24, 25]. For instance, de Jong has identified Orientation (identification of main variables and relations), Hypothesis generation, Planning (schedule for inquiry process), Experimentation (changing variable values, predictions, interpreting outcomes), Monitoring (maintaining overview of inquiry process and developing knowledge), and Evaluation (reflecting on acquired knowledge) as steps that scientists take. Our idea, again illustrated in Figure 1, is to guide students through steps such as these but in a less strict and somewhat simplified manner. For instance, “Step 1: Plan & Design” corresponds to de Jong’s Orientation, Hypothesis generation, and Planning steps.

Our system will give students general guidance on these steps and prompt them with relevant questions as they solve a VLab problem collaboratively. This approach is similar to that of White and colleagues [26] who also provided guidance to students collaboratively solving scientific problems through the prompting of metacognitive steps in scientific reasoning (e.g., Question, Hypothesize, Investigate). Van Joolingen and colleagues have also developed a collaborative environment, Co-Lab, designed to scaffold students as they step through scientific problem solving [27]. However, our aim differs from both of these prior efforts in that we will specifically test how such an approach can bolster the collaborators’ *conceptual knowledge* of domain content. Furthermore, we intend to explore how we can make the approach more effective through the use of AI techniques that *adapt* the script and feedback to students.

4 The “Low-Tech” Study

The first step of our project was to run a preliminary study of the pedagogical approach (i.e., collaborative scripting) described above, as well as to evaluate the use of the VLab and problems that can be solved with it. We refer to this as a “low-tech” study because while the subjects in the study *did* use the VLab, they *did not* use the full collaborative system conceptualized above and illustrated in Figure 1, since the system is currently under development. Furthermore, the study was intentionally done with a small N, as it was designed to give us initial impressions, rather than a summative evaluation. The bottom line is that such a study *cannot* tell us whether a system like that in Figure 1 could lead to conceptual learning gains or test hypotheses H1 and H2, but the results *can* provide ideas and clues about how to design and implement a system, which was the primary goal of the study.

4.1 Method

4.1.1 Design and Participants

We tested and compared four conditions in a 2 x 2 design, as shown in Table 1. A total of 24 subjects participated, with 4 in each of the cells of the table (i.e., 4 individuals in each of the singles conditions, 4 dyads in each of the dyad conditions).

Table 1: 2 x 2 Design of Low-Tech Study

	Dyads/Singles	
Script yes/no	**Scripted Dyads** (N=4)	**Scripted Singles** (N=4)
	Unscripted Dyads (N=4)	**Unscripted Singles** (N=4)

The participants were students at two U.S. universities, most of whom but not all, were enrolled in first or second semester chemistry classes. 12 females and 12 males participated. Participants enrolled for the study using a Survey Monkey website, in which they filled out a brief pre-questionnaire, containing three pretest questions used to assess the students' chemistry knowledge. Sixteen of the subjects were assigned to dyads, using the pre-questionnaire scores to pair students homogeneously (i.e., out of a total possible score of 8, subjects were paired if their scores were within 2 points of one another). The pretest scores were also used to balance the conditions (i.e., some high scoring singles/dyads were placed in the scripted condition, some in the unscripted condition). Four of the 24 subjects reported that they had used the VLab before. Each subject was paid $30 (U.S.) for participation.

4.1.2 Procedure and Materials

The subjects and dyads were asked to go through the following four phases.

Phase 1 – Pretest & Preliminaries. Participants were welcomed, the consent form was read to them, and they were asked to sign the form and fill in a short questionnaire, containing background questions (e.g., "How often do you use a computer?" "Rate your knowledge in stoichiometry."), as well as a single pretest chemistry problem, which, along with the pre-questionnaire and posttest chemistry problems, were chosen based on their coverage of important conceptual knowledge components in chemistry (e.g., molarity, solution volume, law of definite proportions), as defined by our chemistry expert (the CMU chemistry professor mentioned previously). The pretest and posttest problems were isomorphic to one another, as regards the conceptual components covered.

Phase 2 – Familiarization. Participants sat in front of a computer where they watched short chemistry videos, covering subject matter relevant to the problems they would subsequently be asked to solve in Phase 3 (i.e., limiting reagents, titration). Subjects were given a step-by-step explanation of the use of the VLab (which was available over the web on the computer) and were instructed to follow the steps on the computer to familiarize them with VLab use. Participants were also given a "reference sheet" with chemistry content that could be used as an aid during the solving of problems in Phase 3.

Phase 3 – Problem Solving. Participants were asked to solve two stoichiometry problems using the VLab – the "Oracle" problem, involving limited reagents, and the "DNA" problem, involving titration. They were given approximately a half-hour to solve each problem, with the order of problem presentation balanced across conditions. According to their condition, the subjects were given different materials. The unscripted conditions (both singles and dyads) were given general instructions on paper, which said, for instance, that they could use scratch paper and a calculator as aids. The unscripted singles were asked to speak out loud as they solved the problems, while the unscripted dyads were asked to collaborate and discuss the problems, but with no additional guidance or instruction provided. The scripted conditions (both singles and dyads) were given similar general instructions on paper, except that they were also given a *paper script* containing the experimentation steps identified by de Jong [24] with each step having associated instructions (e.g., "Come up with an experiment for each hypothesis") and/or questions to discuss (e.g., "What chemical principles might you need?"). The subjects in both scripted conditions were instructed to follow the steps sequentially, as much as possible, and to tic mark the associated instructions and questions as they completed and/or discussed them. As in the corresponding unscripted conditions, the singles were asked to speak out loud about what they were doing and thinking, while the scripted dyads were asked to talk with one another. In all conditions, the experimenter encouraged the participants to speak out loud, while in the scripted conditions, the experimenter additionally encouraged the subjects to follow the steps of the script and tic mark completed steps, if they were not doing so. Camtasia, a screen and audio recording software tool from TechSmith Corporation, was used to record all of the steps taken in the VLab, as well as all speaking by participants. In addition, VLab actions were logged to a database.

Phase 4 – Posttest & Exit Interview. All participants were asked to complete a brief post-questionnaire (e.g., "Rate the difficulty of the problems") and to solve two posttest questions of moderate difficulty. The participants were also interviewed by the experimenter (and recorded by Camtasia) regarding their impression of the study and materials (e.g., "Did the videos help you solve the problems?" "Do you have any suggestions for improving the experimentation steps?" (scripted conditions only)).

4.2 Results

Most of the participants (and dyads) completed all four phases of the study in 2 to 3 hours, with an average problem-solving time of 20 minutes for the DNA problem, and 37 minutes for the Oracle problem. The average problem-solving time and the number of problems solved by condition are shown in Table 2.

Table 2: Problem-Solving Times and Numbers of Problems Solved by Condition

Condition	N	Avg. Time DNA	Avg. Time Oracle	Solved DNA	Solved Oracle
Scripted Dyads	4	19 min	43 min	3	2
Scripted Singles	4	20 min	39 min	3	1
Unscripted Dyads	4	18 min	27 min	4	3[1]
Unscripted Singles	4	21 min	36 min	2	2

The Oracle problem appeared to be harder for most participants as reflected by the problem-solving times, but also by the number of singles/dyads who correctly solved the problems: 12 of 16 solved the DNA problem, while only 8 of 16 singles/dyads correctly solved the Oracle problem.

Table 3: Pre-Posttest Results of the Low-Tech Study (Highest possible score on pre- and posttest = 5)

Condition	N	Pretest (stdev)	Posttest (stddev)	Gain (stddev)
Scripted Dyads	8	4.44 (0.82)	4.31 (0.88)	**-0.13** (0.52)
Scripted Singles	4	3.88 (1.11)	4.38 (1.25)	**0.50** (1.48)
Unscripted Dyads	8	3.56 (0.62)	4.06 (1.37)	**0.50** (1.49)
Unscripted Singles	4	4.38 (0.63)	4.38 (0.63)	**0.00** (1.08)

The pretest, posttest, and gain (posttest – pretest) results are given in Table 3. Due to the small sample size we cannot report meaningful statistical results. However, descriptively, the data reveal no substantial differences in the gain scores between the four conditions. The scripted dyad condition performed the poorest in the pre-post test analysis; it was the only group that scored lower on average on the posttest than the pretest.

However, we have done a preliminary analysis of the VLab logs, calculating how many times each VLab action (e.g., add flask, mix solution, move object) was taken, on average, in

[1] In one session we had technical problems; the fourth dyad would probably also have solved this problem.

each condition. One interesting finding was that the scripted conditions performed far fewer "mix solutions" actions (singles = 64.1; dyads = 75.5) than the unscripted conditions (singles = 151.1; dyads = 238.3). We will return to this result in the discussion below.

Due to the large amount of video, audio, and log data generated during the study, we have not fully analyzed these materials yet. We anticipate a full analysis of the data will be completed by the summer of 2007, and we will fully report the results in a subsequent paper (and during the talk at the workshop).

4.3 Discussion

The scripted dyad condition performed the poorest in the pre-post test analysis; it was the only group that scored lower on average on the posttest than the pretest (-0.13; see Table 3). Moreover, in the interviews after the problem solving the scripted dyads unanimously expressed the view that the script was not helpful. Comments included:

- "it's just the type of thing you kinda do automatically … that scientific method stuff you learned about in middle school"
- "it was a little bit much … just with all the detail … I think just naturally solving the problem we go through most of this stuff …"

On the other hand, there is some evidence that both collaboration and scripting made a positive difference. With respect to collaboration, notice, from Table 2, that the collaborative conditions solved more problems than the singles conditions: the dyads solved 12 problems (7 DNA, 5 Oracle) while the singles solved only 8 problems (5 DNA, 3 Oracle). This effect cannot be explained as a time effect as Table 2 shows: the dyads used less time for their problem solving (18.5 min DNA, 35 min Oracle) than the singles (20.5 min DNA, 37.5 min Oracle).

Furthermore, the scripted conditions, both singles and dyads, performed far fewer "mix solution" actions in solving both the Oracle and DNA problems, meaning they took less steps to achieve similar results – a measure of efficiency. This result could indicate that even though students did not find the script helpful, it did help to improve their experimentation: by following the script students might have designed their experiments according to their hypotheses, rather than pursuing a trial and error strategy. We will take a closer look at the collaborative processes to find out if this impression is correct, and if so, why it is not reflected in the pre-post gains. (It should be noted that the standard deviations were rather high on the number of mix solutions actions taken. Again, this data will require additional analysis.)

Finally, perhaps the combination of collaborating with a partner, following the script, and using the VLab on the computer may have proved too much for the scripted dyads. The scripted singles had only two of these problem-solving aids to work with (i.e., the script and the VLab) and achieved the highest gain (0.5, tied with the unscripted dyads; see Table 3) with greater satisfaction with the scripts: 2 out of 4 self-reported that the scripts were helpful, e.g. "It challenged me to consider my own thought process and because of that I think I was able to solve the second problem faster."

5 Conclusion

We are not discouraged about collaborative scripting, despite the mixed results of the first, exploratory study. It was not especially surprising that the scripted dyads reported problems in dealing with the paper-based script, along with everything else they had to do – especially if they believed they had already internalized the experiment script. As mentioned earlier, some of our previous work had already led to the observation that overload is possible when dyads of students work with scripts [20]. We intend to investigate ways to avoid the apparent cognitive load experienced by the scripted dyads by (1) having students collaborate on certain experimentation phases, while working individually on others [19], e.g. having students first work individually with the experimentation script on problems, followed by scripted collaboration on other problems, and (2) investigating ways we can provide adaptive online feedback that is sensitive to the cognitive load on and progress of the students. We have already reacted to the complexity of the script uncovered in this first study by consolidating and reducing the scientific steps the students must take in the design of our system. More specifically, the three steps illustrated by the tabs in Figure 1 are a pragmatic simplification of the experimental steps suggested by de Jong and Klahr/Dunbar in earlier work.

Not visible in Figure 1 is our intention to use argumentation and discussion graphs as a means for supporting collaboration between students. For instance, suppose that while the collaborating students are working on "Step1: Plan & Design" from Figure 1, they are encouraged to use an argumentation tool. With such a tool, the students could make claims, provide supporting facts, and make counter-claims about their ideas and beliefs. Such an approach might allow students to better understand one another's ideas, as well as reflect on their own ideas. In addition, taking such an approach will allow us to leverage the AI work we are doing on another project, ARGUNAUT, in which we are using machine-learning techniques to identify salient features of e-discussions for the purpose of providing guidance to a teacher/moderator [28]. Our initial results on the ARGUNAUT project have been very promising. Such an approach could be used as a key component of an adaptive collaboration system, with machine learning classifiers used to identify when students are (or are not) using appropriate collaborative and domain problem solving techniques.

As previously explained, we have not yet had the opportunity to analyze fully the large amount of data generated during the study. We believe this data will prove very valuable in assessing how students interact with the VLab, how they collaborate with and without a script, and, consequently, how we should implement scripts and adaptive scaffolding in a collaborative system – one that we hope will lead to better conceptual learning in chemistry.

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6 References

[1] Bodner, G. M., & Herron, J. D. (2002). Problem-solving in chemistry. In (J.K. Gilbert *et al*, Eds.) *Chemical education: Towards research-based practice*. Kluwer Academic Publishers. 235-266.

[2] Gabel, D. L., Sherwood, R. D. & Enochs, L. (1984). Problem-solving skills of high school chemistry students. *Journal of Research in Science Teaching*, 21 (2), 221-233.

[3] Towns, M. & Grant, E. (1998). 'I believe I will go out of this class actually knowing something:' Cooperative learning activities in physical chemistry. *Journal of Research in Science Teaching*, 34, 819-835.

[4] Fasching, J. L. & Erickson, B. L. (1985). Group discussions in the chemistry classroom and the problem-solving skills of students. *Journal of Chemical Education*, 62, 842-848.

[5] Ross, M. & Fulton, R. (1994). Active learning strategies in the analytical chemistry classroom. *Journal of Chemical Education*, 71, 141-143.

[6] Sumfleth, E., Rumann, S., & Nicolai, N. (2004). Kooperatives Arbeiten im Chemieunterricht. [Cooperative Work in the Chemistry Classroom]. *Essener Unikate, 24*, 74-85.

[7] Hooper, S. (1992). Effects of peer interaction during computer-based mathematics instruction. *Journal of Educational Research, 85* (3), p.180-189.

[8] Okada, T., & Simon, H. A. (1997). Collaborative discovery in a scientific domain. *Cognitive Science, 21*(2), 109-146.

[9] Hausmann, R. G., Chi, M. T. H. & Roy, M. (2004). Learning from collaborative problem solving: An analysis of three hypothesized mechanisms. In K. D. Forbus, D. Gentner & T. Regier (Eds.), 26nd annual *Conference of the Cognitive Science Society* (pp. 547-552). Mahwah, NJ: Lawrence Erlbaum.

[10] Plötzner, R., Fehse E., Kneser, C., & Spada, H. (1999). Learning to relate qualitative and quantitative problem representations in a model-based setting for collaborative problem solving. *The Journal of the Learning Sciences*, 8, 177–214.

[11] Saab, N., van Joolingen, Wouter R., & van Hout-Wolters, B. H. A. M. (2005). Communication processes in collaborative discovery. British Journal of Educational Psychology, 75, 603-621.

[12] Diziol, D., Rummel, N., Spada, H., & McLaren, B. M. (in press) Promoting learning in mathematics: Script support for collaborative problem solving with the Cognitive Tutor Algebra. To appear in Proceedings of CSCL 2007.

[13] Kollar, I., Fischer, F., & Hesse, F. W. (2003). Cooperation scripts for computer-supported collaborative learning. In B. Wasson, R. Baggetun, U. Hoppe & S. Ludwigsen (Eds.), *Proceedings of CSCL 2003* (pp. 59-61). Bergen, Norway: InterMedia, University of Bergen.

[14] O'Donnell, A. M. (1999). Structuring dyadic interaction through scripted cooperation. In A. M. O'Donnell & A. King (Eds.), *Cognitive perspectives on peer learning* (pp. 179-196). Mahwah, NJ: Lawrence Erlbaum Associates.

[15] Dillenbourg, P., Baker, M., Blaye, A., & O'Malley, C. (1995). The evolution of research on collaborative learning. In P. Reimann & H. Spada (Eds.), *Learning in humans and machines: Towards an interdisciplinary learning science* (pp. 189-211). Oxford: Elsevier/Pergamon.

[16] Bell, T., Slotta, J., & Schanze, S. (in press). Perspectives on collaborative inquiry learning: An international network for research, curriculum and technology. Special Issue of the *International Journal of Science Education*.

[17] Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., et al. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13(3),* 337-386.

[18] Dillenbourg, P. (2002). Over-scripting CSCL: The risks of blending collaborative learning with instructional design. In P. A. Kirschner (Ed.), *Three worlds of CSCL. Can we support CSCL* (pp. 61-91). Heerlen: Open Universiteit Nederland.

[19] Rummel, N. & Spada, H. (2005). Learning to collaborate: An instructional approach to promoting collaborative problem solving in computer mediated settings. *Journal of the Learning Sciences*, *14*(2).

[20] Rummel, N., Spada, H., & Hauser, S. (2006). Learning to collaborate in a computer-mediated setting: Observing a model beats learning from being scripted. In S. A. Barab, K. E. Hay, & D. T. Hickey (Eds.) Proceedings of the Seventh International Conference of the Learning Sciences (pp. 634-640). Mahwah, NJ: Lawrence Erlbaum Associates.

[21] Yaron, D., Evans, K. & Karabinos, M. (2003). Scenes and labs supporting online chemistry. Paper presented at the *83rd Annual AERA National Conference*, April 2003.

[22] Pinkwart, N. (2003) A plug-in architecture for graph based collaborative modeling systems. In U. Hoppe, F. Verdejo & J. Kay (eds.): *Proceedings of AIED 2003*, 535-536.

[23] Harrer, A., Malzahn, N., Hoeksema K., & Hoppe U. (2005). Learning design engines as remote control to learning support environments. *Journal of Interactive Media in Education* (Advances in Learning Design. Special Issue, eds. Colin Tattersall, Rob Koper), 2005/05.

[24] De Jong, T. (2006). Scaffolds for computer simulation based scientific discovery learning. In J. Elen, R. E. Clark (Eds.) *Dealing with complexity in learning environments* (pp. 107-128). London: Elsevier Science Publishers.

[25] Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. Cognitive Science, 12, 1–48.

[26] White, B. Y., Shimoda, T. A., & Frederiksen, J. R. (1999). Enabling students to construct theories of collaborative inquiry and reflective learning: Computer support for metacognitive development. *International Journal of Artificial Intelligence in Education*. 10, 151-182.

[27] van Joolingen, W. R., de Jong, T., Lazonder, A. W., Savelsbergh, E., & Manlove, S. (2005). Co-lab: Research and development of an on-line learning environment for collaborative scientific discovery learning. *Computers in Human Behavior*, 21, 671-688.

[28] McLaren, B. M., Scheuer, O., De Laat, M., Hever, R., De Groot, R., & Rose, C. P. (in press). Using machine learning techniques to analyze and support mediation of student e-discussions. To appear in *Proceedings of* AIED 2007, Los Angeles, California, July, 2007.