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Enabling Students to Construct Theories of Collaborative Inquiry and Reflective Learning: Computer Support for Metacognitive Development

Barbara Y. White, Todd A. Shimoda *Graduate School of Education, 4533 Tolman Hall, Mail Code 1670, University of California at Berkeley, Berkeley, CA, USA 94720-1670*

John R. Frederiksen *Educational Testing Service*

http://thinkertools.berkeley.edu/tt, Email: thinker@socrates.berkeley.edu

Abstract. To develop lifelong learning skills, we argue that students need to learn how to learn via inquiry and understand the sociocognitive and metacognitive processes that are involved. We illustrate how software could play a central role in enabling students to develop such expertise. Our hypothesis is that sociocognitive systems, such as those needed for collaborative inquiry and reflective learning, can best be understood as a community of interacting agents, who each have expertise in accomplishing particular high-level goals. We introduce a system, named SCI-WISE, that houses a community of software agents, such as a Planner, a Collaborator, and an Assessor. The agents give strategic advice and guide students as they undertake collaborative research projects and as they reflect on and revise their inquiry processes. Students can easily modify SCI-WISE so that it expresses their own theories of how to do inquiry and how best to coach and scaffold the process. We describe curricular activities in which middle school students use SCI-WISE to engage in “inquiry about inquiry,” thereby making inquiry and metacognition topics of investigation. Finally, we discuss how such activities should lead to improvements in their inquiry learning skills as well as to their metacognitive development in general.

INTRODUCTION

Some of the most intriguing and important work in the field of cognition and instruction focuses on students’ understanding of and theorizing about their own cognitive processes. Brown (1987) points out that discussion about the importance of what we presently refer to as “metacognition” and “theory of mind¹” goes back at least as far as Plato. In the past century, influential thinkers such as Dewey, Piaget, and Vygotsky have argued that knowledge and control of one’s own cognitive system play a key role in cognitive development. For example, Piaget (1976) argued that being aware of and reflecting on one’s cognition is an important capability that is one of the defining characteristics of the most advanced stages of cognitive development. Further, Vygotsky (1978) claimed that children progress from relying on others, such as teachers, to help regulate their cognition to being able to regulate it themselves, having internalized the regulation and control skills modeled by others.

Recent research adds additional theoretical and empirical support to arguments regarding the important role that metacognition plays in students’ academic performance and cognitive development (e.g., Baird, Fensham, Gunstone, & White, 1991; Chi, Bassock, Lewis, Reimann, & Glaser, 1989; Schauble & Glaser, 1990; Schoenfeld, 1987). Our own work, for example, indicates that enabling students to develop metacognitive expertise plays a major role in facilitating inquiry learning, particularly for academically disadvantaged students (White & Frederiksen, 1998). In addition, certain types of social interactions and activities, such as

¹ Developmental psychologists frequently use the term “theory of mind” to refer to children’s knowledge of other people’s beliefs and intentions (Astington, Harris, & Olson, 1988; Feldman, 1992). Here we focus on their knowledge of their own as well as others’ sociocognitive and metacognitive processes, particularly those related to problem solving, learning, reflection, and learning to learn.

collaborative work and peer tutoring, have been shown to facilitate learning and development (e.g., Brown & Palincsar, 1989; Driver et. al., 1994; Okada & Simon, 1997; Slavin, 1995), as have social structures introduced to create classroom communities that embody social constructivist approaches to learning (e.g., Bielaczyc & Collins, in press; Brown & Campione, 1996; Palincsar & Brown, 1989). Such findings support the view that social processes as well as cognitive processes play a major role in students' academic performance and cognitive development (Damon, 1990; Vygotsky 1978; Wertsch, 1991).

The above considerations lead us to a broad view of metacognition that encompasses: (1) "knowledge about knowledge," including knowledge of the form and content of cognitive and social expertise and when and why such expertise is useful; (2) "regulatory skills," including skills needed to employ sociocognitive expertise, such as planning and monitoring skills; and (3) "development expertise," including the ability to reflect on sociocognitive knowledge and its use to determine how to modify and improve both of these.

Given its importance, how can we enable young students to develop such meta-level expertise? We think one promising approach is to start by helping students learn about the nature and processes of scientific inquiry. It has long been argued that there may be correspondences between children's learning and cognitive development in the classroom and scientists' theory creation and revision processes in the scientific community (Dewey, 1910; Piaget, 1976; Vygotsky, 1978). For example, Piaget (1976) used the metaphor of "child as scientist" and argued that being able to consciously invent, test, and modify theories as well as talk about them with others is a characteristic of the most advanced stage of cognitive development, which he termed "formal operations." Further, a post-Piagetian paradigm is emerging, sometimes termed the "theory theory," in which it is argued that there are similarities between how young children develop theories and how theories evolve in science (e.g., Brewer & Samarapungavan, 1991; Nersessian, 1991) and, furthermore, that such theory formation and inquiry processes are central to children's learning (e.g., Dewey, 1938; Gopnik, 1996; Karmiloff-Smith & Inhelder, 1975; White, 1993). To develop these critical inquiry skills, some educational researchers have taken the approach of transforming classrooms into learning communities in which young students engage in scientific research (e.g., Brown & Campione, 1996; Scardamalia & Bereiter, 1994). We conjecture that taking the additional step of having students create and test explicit theories about their inquiry processes, making inquiry itself a topic of research, will further enhance the development of students' learning skills and metacognitive awareness.

Our hypothesis is that young students need to develop conscious, explicit theories of the cognitive and social processes needed for learning. Such awareness can enable them to engage in reflective conversations about the nature, purpose, and utility of these processes and to thereby come to understand them better, use them more effectively, and improve them. In particular, we argue that they need to develop widely applicable theories about collaborative inquiry and reflective learning. Enabling them to construct such theories should lead to improvements in their learning and reflection skills as well as to their metacognitive development in general.

Software can play a central role in such theory building processes. Our view is that complex performances, such as collaborative inquiry and reflective learning, can best be understood as the product of a social system of interacting agents, who each have expertise in accomplishing particular high-level goals. We have embedded this view of performance in a computer system, named SCI-WISE, that houses a community of software agents, such as an Inventor, an Analyzer, and a Collaborator. The agents give strategic advice and guide users as they undertake research projects and as they reflect on and revise their inquiry processes. SCI-WISE also enables users to modify the advisory system so that it expresses their own theories of how to engage in inquiry and how best to coach and scaffold the process.

Our goal is for young students to work with SCI-WISE to develop explicit theories of the social and cognitive processes needed for collaborative inquiry and reflective learning. To facilitate this, we are creating curricular activities in which middle school students engage in inquiry about their own inquiry learning processes, thereby making inquiry and metacognition themselves into objects of investigation. In these activities, students develop hypotheses about how best to support inquiry and use SCI-WISE as a modeling tool to represent their ideas.

They then carry out research to evaluate their hypotheses by following the advice given by their SCI-WISE models. For example, they use their version of SCI-WISE to guide them as they do a physics project and, as they do this, they also evaluate the helpfulness of their SCI-WISE system. While the students undertake this research, we investigate whether this form of inquiry about inquiry does indeed foster their sociocognitive and metacognitive development.

OUR PRIOR RESEARCH ON LEARNING ABOUT INQUIRY

The design and use of SCI-WISE builds on our earlier work in which we created and evaluated the ThinkerTools Inquiry Curriculum (White, 1993; White & Frederiksen, 1998). In this curriculum, students engage in inquiry using our ThinkerTools software as they formulate and test models of force-and-motion phenomena. The emphasis is on developing students' metacognitive expertise, particularly their knowledge about the processes of inquiry as well as their ability to monitor and reflect on these processes. The pedagogical strategies include having students make their inquiry goals, strategies, and conceptual models explicit, supplying materials to scaffold their inquiry, and introducing them to methods for monitoring and reflecting on these processes.

A goal structure for inquiry

The curriculum centers around a generic inquiry cycle, shown in Figure 1, which provides a top-level model of the inquiry process. This cycle is made explicit to students and is presented as a sequence of goals to be pursued:

- **QUESTION:** The students start by formulating a research question.
- **HYPOTHESIZE:** They then generate predictions and come up with alternative, competing hypotheses related to their question.
- **INVESTIGATE:** Next, they design and carry out experimental investigations in which they try to determine which of their hypotheses, if any, is accurate. (In our force-and-motion curriculum, they do their experiments in the context of both the ThinkerTools computer simulations and the real world. The computer simulations make it easy for them to conduct and see the results of their experiments. Experimentation in the real world is more difficult and is a good vehicle for enabling students to learn about problems that occur in the design and implementation of real-world experiments.)
- **ANALYZE:** After the students have completed their investigations, they analyze their data to see if there are any patterns.
- **MODEL:** Next they try to summarize and explain their findings by formulating a law and a causal model that characterize their conclusions in a form that is extensible to other situations. (Students' models typically take the form: "If A then B because ...". For example, "if there are no forces like friction acting on an object, then it will go forever at the same speed, because there is nothing to slow it down.")
- **EVALUATE:** Once the students have developed their laws and causal models, they then try to apply them to different real-world situations in order to investigate their utility and their limitations. They also examine the limits of their investigations. Determining the limitations of their conceptual models and investigations raises new research questions, and the students begin the Inquiry Cycle again.



Figure 1. The Inquiry Cycle which provides students with a goal structure for guiding their inquiry.

This Inquiry Cycle guides the students' research and is repeated with each module of the curriculum. As the curriculum progresses, the conceptual models that students are creating increase in complexity (e.g., they evolve to take into account the effects of variables such as friction, mass, and gravity). In addition, the inquiry that students are doing is less and less scaffolded. By the end of the curriculum, they are engaging in independent inquiry projects on research topics of their own choosing (e.g., circular motion, collisions, etc.). To guide them in writing their research reports, students are given the Project Outline, shown in Figure 2, which augments the Inquiry Cycle by unpacking the goals and subgoals associated with each step.

Question:

- ◆ Which general topic did you choose?
 - Explain why you choose that topic.
- ◆ What specific question(s) did you choose to investigate?
 - Why did you choose that question(s)?

Hypothesize:

- ◆ Write down some hypotheses, or predictions, that relate to your question.
 - You should have at least two different hypotheses.
- ◆ For each hypothesis, explain why someone might believe it.

Investigate:

- ◆ Describe how you did your investigation.
 - Give enough detail so that someone else could repeat what you did.
 - Include a list of the laboratory equipment, computer databases, questionnaires, or other information sources that you used.
 - If you did an experiment, draw a sketch of how you set it up.
- ◆ Justify why you did your investigation this way.
 - Explain how it allowed you to test your hypotheses.
- ◆ Show your data in a table, graph, or some other representation.

Analyze:

- ◆ Describe how you analyzed your data and show your work.
 - Be specific and refer to your table or other representations of your data.
- ◆ Describe any patterns in your data.
- ◆ Discuss parts of your data, if any, that do not make sense.
 - Could there have been any serious errors in your investigation?

Model:

- ◆ Summarize your conclusions.
 - State any laws or findings that you discovered.
 - Present your theory about why this happens.
- ◆ Illustrate how your data support your conclusions.
- ◆ How do your conclusions relate to your research question?
 - Which of your hypotheses, if any, do your data support?

Evaluate:

- ◆ Show how what you learned could be useful.
 - Can your model (laws & theory) be applied to new situations to predict and explain what will happen?
 - Give examples to illustrate.
- ◆ What are the limitations of your model?
 - Are there situations where your laws would make wrong predictions or your theory could not explain what happens?
- ◆ What are the limitations of your research?
 - What remains to be learned about your chosen topic?
 - What further investigations would you do if you had more time?

Figure 2. The Project Outline which students use for guidance as they write their research reports.

Reflecting on the inquiry process

In addition to the Inquiry Cycle and Project Outline, which provide students with a goal structure for guiding their scientific inquiry, we also introduce students to a set of criteria for reflecting on their inquiry processes. These are shown in Figure 3 and include high-level goals such as “understanding the processes of inquiry,” cognitively-oriented goals such as “being inventive” and “reasoning carefully,” and socially-oriented goals such as “communicating well” and “teamwork.” The definitions for these criteria were designed to help students understand the nature and purpose of the cognitive and social processes involved in inquiry. Students are given functional characterizations of what it means to “be inventive,” “communicate well,” and so forth. For instance, “being systematic” is defined as: “Students are careful, organized, and logical in planning, carrying out, and evaluating their work. When problems come up, they are thoughtful in examining their progress and deciding whether to alter their approach or strategy.” Students are then asked to evaluate their own and each other’s inquiry using this set of criteria in a process we call Reflective Assessment (c.f., Frederiksen & Collins, 1989; Miller, 1991; Towler & Broadfoot, 1992). For example, in a typical self-assessment page in the students’ research books, a particular criterion, such as “understanding the processes of inquiry,” is defined and students are asked to rate the research they have just completed on that criterion (using a five point scale) and then to justify their rating by describing how their work deserves that score. The aim is to help students learn how to reflect on and improve their inquiry processes so that their future inquiry will have these functional characteristics and achieve these high-level, cognitive and social goals.

Our hypothesis is that this Reflective-Assessment Process will help students to better understand the purpose and steps of the Inquiry Cycle. It provides a metacognitive language for talking about goals and processes. Reflective Assessment should also motivate students in that their work will be constantly evaluated by themselves, their peers, and their teachers. This process encourages students to continually monitor and reflect on their work, which should improve their inquiry skills. Further, we hypothesize that this metacognitive Reflective-Assessment Process should be particularly important for disadvantaged, low-achieving students, since one reason these students are low achieving is that they lack metacognitive skills, such as monitoring and reflecting on their work (Campione, 1987; Nickerson, Perkins, & Smith, 1985). If this process is introduced and scaffolded as we illustrated, it should enable low-achieving students to learn these valuable metacognitive skills and their performance should therefore be closer to that of high-achieving students.

Instructional trials of the ThinkerTools Inquiry Curriculum

Instructional trials of the ThinkerTools Inquiry Curriculum provided an opportunity to conduct a controlled study concerning our hypotheses about the value of the Reflective-Assessment Process, in particular, and the development of metacognitive skills in general. The curriculum, centering around the Inquiry Cycle (in an earlier form: Question, Predict, Experiment, Model, Apply) and the Reflective-Assessment Process, was implemented by three teachers in their urban classrooms. For each of the participating teachers, half of his or her classes engaged in the Reflective-Assessment Process and the other half did not. Thus, all of the classes did the same ThinkerTools Inquiry Curriculum, but half of the classes included reflective assessment activities, whereas the Control Classes included alternative activities in which students commented on what they did and did not like about the curriculum.

These three teachers were teaching twelve classes in grades seven through nine. Two of the teachers had no prior formal physics education. They were all teaching in urban situations in which their class sizes averaged almost thirty students, two thirds of whom were minority students, and many were from highly disadvantaged backgrounds. The distribution of the students’ percentile scores on a standardized achievement test (i.e., the Comprehensive Test of Basic Skills – CTBS) was almost flat, so the sample was representative of the general population of students in those grades.

We will summarize the major findings from these instructional trials as they relate to our hypotheses about the value of the Reflective-Assessment Process and the development of metacognitive competence. In presenting the results, we focus on the students' learning of inquiry and the impact that the Reflective-Assessment Process had on that learning. For a more complete presentation of our findings, see White and Frederiksen (1998).

HIGH-LEVEL CRITERIA

	Understanding the Science. Students show that they understand the relevant science and can apply it in solving problems, in predicting and explaining phenomena, and in carrying out inquiry projects.
	Understanding the Processes of Inquiry. Students are thoughtful and effective in all phases of the inquiry process, including: raising questions for study, developing hypotheses, designing an investigation, collecting and analyzing data, drawing conclusions in the form of laws and models, and reflecting on the limitations of their investigation and their conclusions.
	Making Connections. Students see the big picture and have a clear overview of their work, its purposes, and how it relates to other ideas or situations. They relate new information, ideas, and findings to what they already know.

COGNITIVELY-ORIENTED CRITERIA

	Being Inventive. Students are creative and examine many possibilities in their work. They show originality and inventiveness in thinking of problems to investigate, in coming up with hypotheses, in designing experiments, in creating new laws or models, and in applying their models to new situations.
	Being Systematic. Students are careful, organized, and logical in planning, carrying out, and evaluating work. When problems come up, they are thoughtful in examining their progress and deciding whether to alter their approach or strategy.
	Using the Tools of Science. Students understand the representations and tools of science and use them appropriately in their investigations. These may include diagrams, graphs, tables, formulas, calculators, computers, and lab equipment.
	Reasoning Carefully. Students reason appropriately and carefully using scientific concepts and models. They can argue whether or not a prediction or law fits a model. They can show how their observations support or refute a model. And they can evaluate the strengths and limitations of a model.

SOCIALLY-ORIENTED CRITERIA

	Writing and Communicating Well. Students clearly express their ideas to each other or to an audience through writing, diagrams, and speaking so that others will understand their research and how they carried it out.
	Teamwork. Students work together as a team to make progress. They respect each other's contributions and support each other's learning. They divide their work fairly so that everyone has an important part.

Figure 3. The criteria for assessing inquiry which students use in the Reflective-Assessment Process.

The development of inquiry expertise

As part of the ThinkerTools Inquiry Curriculum, the students designed and carried out research projects. Their mean project scores, shown in Figure 4, indicate that students in the Reflective-Assessment Classes did significantly better projects than students in the Control Classes. In addition, the Reflective-Assessment Process appears to have been particularly beneficial for the low-achieving students: low-achieving students in the Reflective-Assessment Classes did almost as well as the high-achieving students. These findings were the same across all three teachers and all three grade levels.

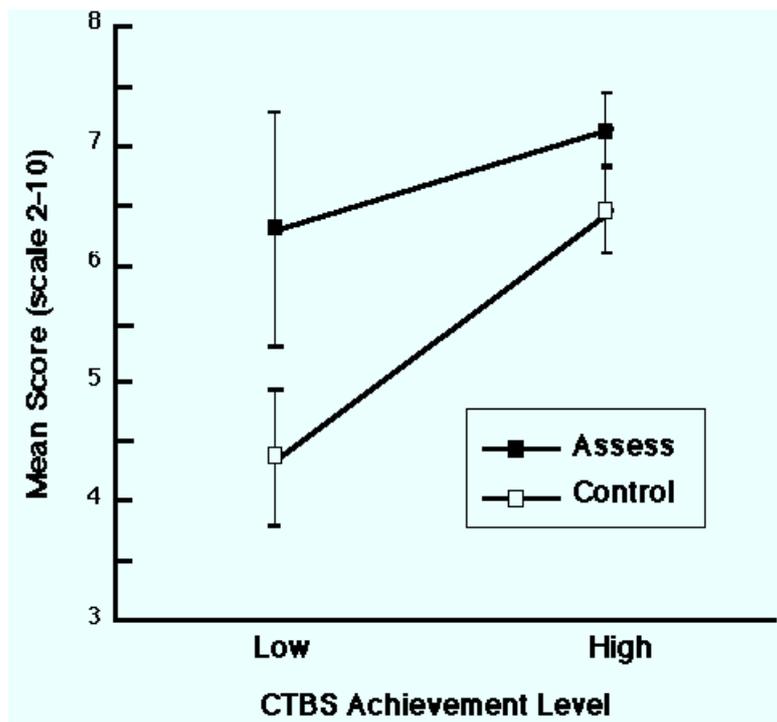


Figure 4. The mean combined score on two research projects (done at the middle and end of the curriculum) for students in the Reflective Assessment and Control Classes, plotted as a function of their achievement level.

To further assess students' inquiry expertise, we developed an inquiry test which was given both before and after the ThinkerTools curriculum. In this written test, the students were asked to investigate a specific research question: "What is the relationship between the weight of an object and the effect that sliding friction has on its motion?" The students were first asked to come up with alternative, competing hypotheses with regard to this question. Next, they had to design on paper an experiment that would determine what actually happens. Then they had to pretend to carry out their experiment. In other words, they had to conduct a thought experiment and make up the data that they thought they would get if they actually carried out their experiment. Finally, they had to analyze their made-up data to reach a conclusion and relate this conclusion back to their original, competing hypotheses. In scoring this test, the focus was entirely on the students' inquiry skills. Whether or not the students' theories embodied the correct physics was regarded as totally irrelevant.

Figure 5 presents the gain scores on this inquiry test for both low- and high-achieving students, and for students in the Reflective Assessment and Control Classes. Notice, firstly, that students in the Reflective-Assessment Classes gained more on this inquiry test. Secondly, notice that this was particularly true for the low-achieving students. These findings provide additional evidence that the metacognitive Reflective-Assessment Process is beneficial, particularly for academically disadvantaged students.

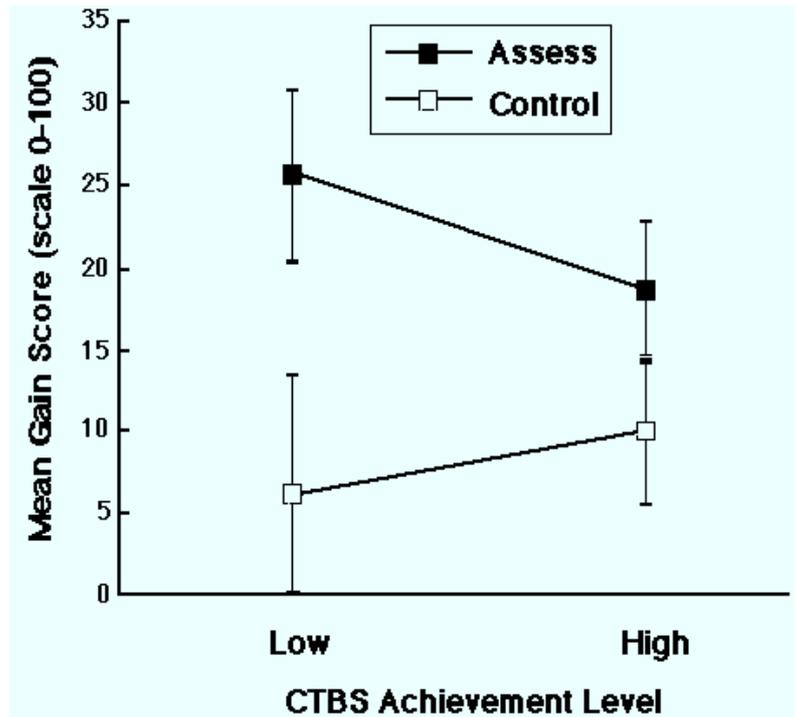


Figure 5. The mean gain scores on the Inquiry Test for students in the Reflective Assessment and Control Classes, plotted as a function of their achievement level.

The impact of understanding the reflective assessment criteria

If we are to attribute these effects of introducing Reflective Assessment to students’ developing metacognitive competence, we need to show that the students developed an understanding of the assessment criteria and could use them to describe various aspects of their work. One way to evaluate their understanding is to compare their use of the criteria in rating their own work with the teachers’ evaluation of their work using the same criteria. If students have learned how to use the criteria, their self-assessment ratings should correlate with the teachers’ ratings for each of the criteria. We found that students in the Reflective-Assessment Classes, who worked with the criteria throughout the curriculum, showed significant agreement with the teachers in judging their work, while this was not the case for students in the Control Classes, who were given the criteria only at the end of the curriculum for judging their final projects. For example, students in the Reflective-Assessment Classes had a correlation of .58 between their ratings of Reasoning Carefully on their final projects and those of their teachers. The average correlation for these students over eight criteria was .48, which is twice that for students in the Control Classes.

If the Reflective-Assessment Criteria are acting as metacognitive tools to help students as they ponder the functions and outcomes of their inquiry processes, then the students’ performance in developing their inquiry projects should depend upon how well they have understood the assessment concepts. To evaluate their understanding, we rated whether the evidence they cited in justifying their self assessments was or was not relevant to the particular criterion they were considering. We then looked at the quality of the students’ final projects, comparing students who had developed an understanding of the set of assessment criteria by the end of the curriculum with those who did not. Our results, shown in Figure 6, indicate that students who had learned to use the interpretive concepts appropriately in judging their work produced higher quality projects than students who had not. And again we found that the benefit of learning to use the assessment criteria was greatest for the low-achieving students.

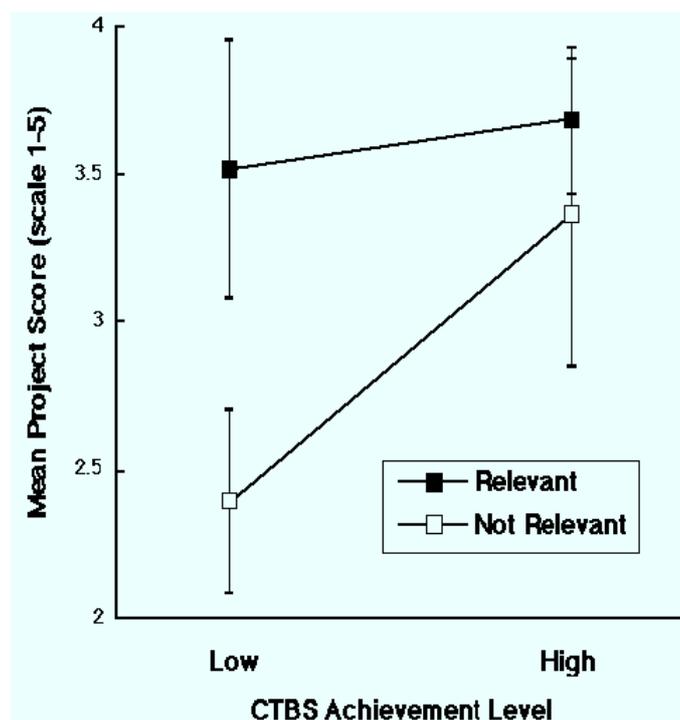


Figure 6. The mean scores on their Final Projects for students who did and did not provide relevant evidence when justifying their self-assessment scores, plotted as a function of their achievement level.

Implications and next steps

Taken together, these research findings clearly implicate the use of the assessment criteria as a reflective tool for learning to engage in inquiry and for developing metacognitive expertise. Students in the Reflective-Assessment Classes generated higher-scoring research projects than those in the Control Classes. Further, students who showed a clear understanding of the criteria produced higher quality investigations than those who showed less understanding. Thus, there are strong beneficial effects of introducing a metacognitive language to direct students' reflective explorations of their work in classroom conversations and in self assessment.

As we have illustrated, the ThinkerTools Inquiry Curriculum incorporates a number of pedagogical strategies that enable students to develop inquiry skills and metacognitive expertise. These include:

- making inquiry tasks and goals explicit using the Inquiry Cycle and Project Outline;
- scaffolding the inquiry process by recommending goals to pursue at each step and then, during the first few times through the cycle, suggesting methods for achieving those goals;
- introducing and defining criteria, like “reason carefully” and “be collaborative,” for talking about and evaluating cognitive and social processes related to inquiry;
- having students use the criteria to monitor their performance and reflect on their inquiry processes in order to determine how they could be improved.

The success of the curriculum, particularly the reflective-assessment component, supports our hypothesis that making students aware of cognitive and social processes related to inquiry will enable them to acquire metacognitive expertise, which will then play an important role in enabling them to learn via inquiry. In this approach, learning about inquiry is used not only to aid the learning of science and other school subjects, but also to help students develop theories about their own learning and self-regulation processes and thereby “learn how to learn.”

In our recent work, we are taking this approach a step further. We are exploring the hypothesis that one can enable students to “learn how to learn” by (1) creating models of social, cognitive, and metacognitive expertise related to inquiry, reflection, and self improvement, and by (2) engaging students in research in which they talk about, evaluate, and modify these models of inquiry learning expertise. To make this possible, we are creating a computer environment that reifies and supports key aspects of metacognition needed for learning via inquiry. This environment, called the ThinkerTools SCI-WISE system, advises users as they design and carry out research projects. It also enables them to modify the support system so that it expresses their own theories of how to do inquiry and how best to coach and scaffold the process. We are creating a variety of pedagogical activities that make use of this software, including engaging students in “inquiry about inquiry,” and are evaluating their effectiveness in urban middle school classrooms (i.e., with students aged 11-14).

GOALS FOR THE DESIGN AND USE OF SCI-WISE

SCI-WISE² represents a new genre of software that allows users to express their metacognitive ideas and sociocognitive practices as they undertake complex tasks. Such tasks include engaging in scientific inquiry by formulating research questions, generating hypotheses, designing investigations, analyzing evidence, constructing theories, and so forth. Such tasks also include higher-order activities like reflecting on and modifying one’s inquiry processes for the purpose of “learning how to learn” via inquiry. SCI-WISE is a system that, on the one hand, provides scaffolding and coaching to students as they undertake these various activities, while, on the other hand, provides a composing environment that enables students to represent their own ideas about how best to model and support inquiry.

The problem in designing such a system is determining a good method for representing ideas about how to carry out inquiry tasks, how to scaffold them, and how to talk about them. The system has to make explicit the purpose of the various tasks, strategies for carrying them out, and ways of monitoring and improving performance on them. Our hypothesis is that this complex set of cognitive and social activities can be made most understandable by representing them as a system of interacting agents, who each have particular areas of expertise. These agents, such as the Inventor and Collaborator, have goals that they pursue (e.g., inquiry goals and pedagogical goals), beliefs that they form (e.g., beliefs about the users and the context), advice that they can give (e.g., strategic advice and monitoring advice), and ways of communicating these goals, beliefs, and advice to other agents and users. This system of agents, working together, guides and counsels students as they engage in research and as they reflect on and revise their inquiry processes. Agents advise users concerning the development of goals and strategies, such as being inventive or collaborating effectively, but do not have enough expertise to carry out these tasks themselves without human partners. Thus the complexity of the goals, strategies, and monitoring behavior employed in doing inquiry emerges from interactions among human and computer agents.

Working with SCI-WISE introduces students to a model in which a research culture is portrayed as a community of agents who engage in collaborative inquiry and critical reflection, with members contributing their own particular expertise. This also potentially provides students with a way to view their own minds as a diverse community of expert advisors who work together to facilitate problem solving, learning, reflection, and self improvement. Such a modular, agent-based view of the mind is related to Minsky’s (1985) “Society of Mind” and Wertsch’s (1991) “Voices of the Mind” theories of cognition (although SCI-WISE advisors have a higher level of agency than either Minsky or Wertsch advocated). Development of such theories of individual minds and of research cultures should, we conjecture, facilitate students’ collaborative inquiry as well as their learning how to learn via inquiry.

² SCI-WISE is an acronym with alternative meanings that relate to different functions that the system can serve, such as (1) Scaffolding Collaborative Investigations Within an Inquiry Support Environment (here the emphasis is on supporting inquiry), and (2) Social and Cognitive Intelligences Working Interactively at Scientific Enquiry (here the emphasis is on presenting a theory of expertise).

SCI-WISE allows students to modify these agent-based theories about cognitive and social processes needed for inquiry and, in so doing, to conduct research on how best to model and support the inquiry process. They can modify SCI-WISE by creating new advisors or revising old ones, as well as by changing its pedagogy, such as modifying how much and what type of advice users get. In this way, students can create alternative versions of the system that house, for example, different sets of advisors with different forms of expertise. They can then conduct educational research to determine which versions of the system are most helpful and thereby test their conjectures regarding the characteristics of the most effective inquiry support environment. This type of “inquiry about inquiry” is carried out as students use their alternative versions of SCI-WISE to do research projects in various domains (such as physics and biology). This process of constructing competing theories of cognitive and social processes that support inquiry and then investigating their utility should help students develop, reflect on, revise, and internalize their theories and thereby develop increasingly powerful inquiry learning skills along with metacognitive expertise.

The instructional question is, how do we introduce students to such a novel form for expressing and experimenting with metacognitive ideas and sociocognitive practices? The idea is to provide a “seed system” that will acquaint them with what a SCI-WISE system can be like, what it can do, and how it can be changed. We are also creating curricula in which students modify and experiment with the inquiry support system, using our seed system as a starting point, with the aim of creating versions that better support their own and others’ inquiry learning.

In creating SCI-WISE, we are thus developing and enabling young students to develop a theory of metacognitive expertise related to learning via inquiry. The expertise for our seed system is being generated by our research group as it attempts to characterize and reflect on its collaborative inquiry processes. As part of this process, we are working with our graduate students to create a version of SCI-WISE that will be useful for young students as well as a version that will be useful to graduate students as they do their own research projects. Our middle-school curricula, in which students design alternative versions of the inquiry support system, ask young students to engage in a similar process. We are thus creating a genre of software and accompanying curricula that encourage the invention, exploration, and revision of sociocognitive practices and metacognitive expertise.

Our ambition is to develop a pedagogical approach, centered around this software environment, that enables young students to engage in such explorations and theory development in a way that is interesting and meaningful to them. As part of this process, they are introduced to a language and process for discussing and modeling metacognition. We conjecture that the language about metacognition will be meaningful to students if they can use it to talk about how they engage in and support inquiry. Further, the modeling process will be interesting to students if they can employ it to create helpful artifacts, such as their own customized inquiry support system, which they will continue to use and share with others. Introducing students to these discourse and design processes should enable them to develop and revise their metacognitive expertise. An important object is for them to acquire transferable skills for collaborative inquiry, so that they can apply their inquiry skills to any context they choose. Furthermore, we want them to develop an ability to reflect on their cognitive and social processes with the goal of improving them, so that they get better and better at learning via inquiry. Finally, we want to introduce them to understandable and useful models of how minds and communities work, which should facilitate the building of an effective research community within their classroom.

Our approach, therefore, embodies both a constructivist (e.g., von Glasersfeld, 1995) and a constructionist (e.g., Harel & Papert, 1990; Kafai & Resnick, 1996) approach to education in that students create and revise theories by designing artifacts, namely intelligent advisors and their embodiment in an inquiry support environment. In this article, we provide an overview of our preliminary work regarding the creation and use of such sociocognitive tools – tools that are aimed at enabling students to develop metacognitive knowledge and skills as they create explicit theories of how best to model and support inquiry.

THE SCI-WISE SYSTEM ARCHITECTURE

In what follows, we describe the architecture and capabilities of our seed system. Our design decisions are important because they will constrain the ways in which students think about their own and the system's cognitive and social behavior as they carry out tasks. We are attempting to create a system that is as simple, transparent, and easy to understand as possible. Our design process is informed by research on metacognition, scientific inquiry, and social constructivism (e.g., Brown, 1987; Carey & Smith, 1993; Collins & Ferguson, 1993; Dunbar, 1995; Flavell, 1979; Palincsar, 1998; Salomon & Perkins, 1998; Scardamalia & Bereiter, 1991) as well as by research on the design of computer-based cognitive tools (e.g., Collins & Brown, 1988; de Jong & Rip, 1997; Derry, 1992; Dillenbourg, 1992; Kearsley, 1993; Lajoie, 1993; Schauble, Raghavan, & Glaser, 1993; Self, 1992). While the present system is limited to supporting work on tasks related to scientific inquiry, its architecture as well as the generic nature of its expertise will enable users to modify it so that it can support work on other tasks.

The programming platform being used to create a prototype of our seed system is Macromedia Director 6 and its Lingo code. While not as sophisticated a language as C++ or Lisp, it nonetheless allows an object-oriented, agent-based style of programming, and it can handle message passing and data tracking. More importantly, it provides multi-media authoring tools that allow for relatively quick interface design and prototyping. This is enabling us to conduct pilot studies with young students to see how they react to and benefit from a seed system that has some of the properties we envision. These results will enable us to improve the architecture and capabilities of subsequent versions of the system. In the next generation of SCI-WISE, which is currently under development, we are utilizing other languages, reasoning engines, communication protocols and interfaces, such as Java, JESS (Java Expert System Shell), KQML (Knowledge Query and Manipulation Language), and web browsers like Internet Explorer.

To illustrate how the system works, we will use examples from the prototype (see also Shimoda, White, & Frederiksen, 1999). We will also discuss some capabilities we envision that go beyond those that are presently implemented.

Task contexts

Within SCI-WISE there are a set of Task Contexts in which users work. We are presently creating four Task Contexts within our seed system, which correspond to authentic activities that scientists engage in as they do research. These include (1) designing and carrying out a research project, (2) preparing project presentations, (3) evaluating research reports, and (4) modifying the inquiry support system. In keeping with the idea that there are correspondences between scientists' inquiry processes and children's learning processes, these four tasks also correspond to important cognitive and metacognitive activities that children should engage in so that they "learn how to learn." These include (1) engaging in inquiry, (2) explaining their inquiry to others, (3) reflecting on their inquiry processes, and (4) revising them so that the next time they engage in inquiry, they can draw upon improved cognitive and social processes for assistance.

Task documents

Associated with each Task Context is a Task Document in which users do their work for that task. For example, there is a Project Journal, a Project Report, and a Project Evaluation, as well as a System Modification Journal (in which users record a history of their system modifications and the reasons for them). These documents are organized around a possible sequence of subtasks (or subgoals) for that task. For example, the Project Journal is organized around the Inquiry Cycle that we employ in our ThinkerTools curriculum (shown in Figure 1).

Task advisors

In addition to Task Documents, each Task Context has a set of advisors associated with it, including a Head Advisor and a set of Task Specialists. There is a Head Advisor for each Task Context; namely, the Inquirer for doing research projects, the Presenter for creating presentations, the Assessor for evaluating projects, and the Modifier for making changes to the SCI-WISE system. The Head Advisor gives advice regarding how to manage its associated task, suggests possible goal structures for that task, and puts together an appropriate team of advisors. For example, our version of the Inquirer follows the Inquiry Cycle shown in Figure 1. It suggests pursuing a sequence of subgoals, and each such subgoal has a Task Specialist associated with it, namely, a Questioner, Hypothesizer, Investigator, Analyzer, Modeler, and Evaluator. Figure 7 shows users consulting a Questioner who advises them about how to come up with a research question. Users can modify the team of advisors available to assist with any particular task by simply turning some off and/or creating new ones.

General purpose resources

In order for advisors and users to function within the various Task Contexts, SCI-WISE incorporates several General Purpose Resources, which can serve users and advisors no matter what task they are engaged in. These include memory systems for keeping track of what has happened, communication systems for communicating between advisors, users, and artifacts, and a set of General Purpose Advisors who can provide advice in almost any Task Context.

Memory systems

Memory systems are useful to both users and advisors. For example, they can be accessed by advisors to determine which aspects of the task the users have already completed, what the present context is, and so forth. They can also be accessed by students to help them recall and reflect on the processes they have gone through as they tried to accomplish a particular task.

Memory systems can include various types of work histories, like the Project Checklist which makes the proposed goal-structure for a task explicit and which students use to show what subgoals have and have not been accomplished. They can also include memories for things like user dispositions which could contain information about which types of advice a group of users prefers. These memory systems can be displayed or hidden according to the needs or preferences of the users.

Communication systems

Various communication systems allow advisor-to-advisor communication, advisor-to-user communication, and user-to-advisor communication. They can also allow advisors and users to get information from artifacts such as the Project Checklist. Three examples of interfaces that enable users to access and communicate with advisors are the Meeting Room, Project Journal, and Dialogue Box, all of which are shown in Figure 7. Students can go directly to an advisor for advice through the Meeting Room, which provides access to all of the advisors. They can also access advisors through Task Documents, such as the Project Journal, which provide access to advisors for that task. And, finally, students can use the Dialogue Box to send a message directly to any advisor. The advisor then checks the words in the message against its lexicon of key words. If a match is found, the advisor responds accordingly, taking into account the current context.

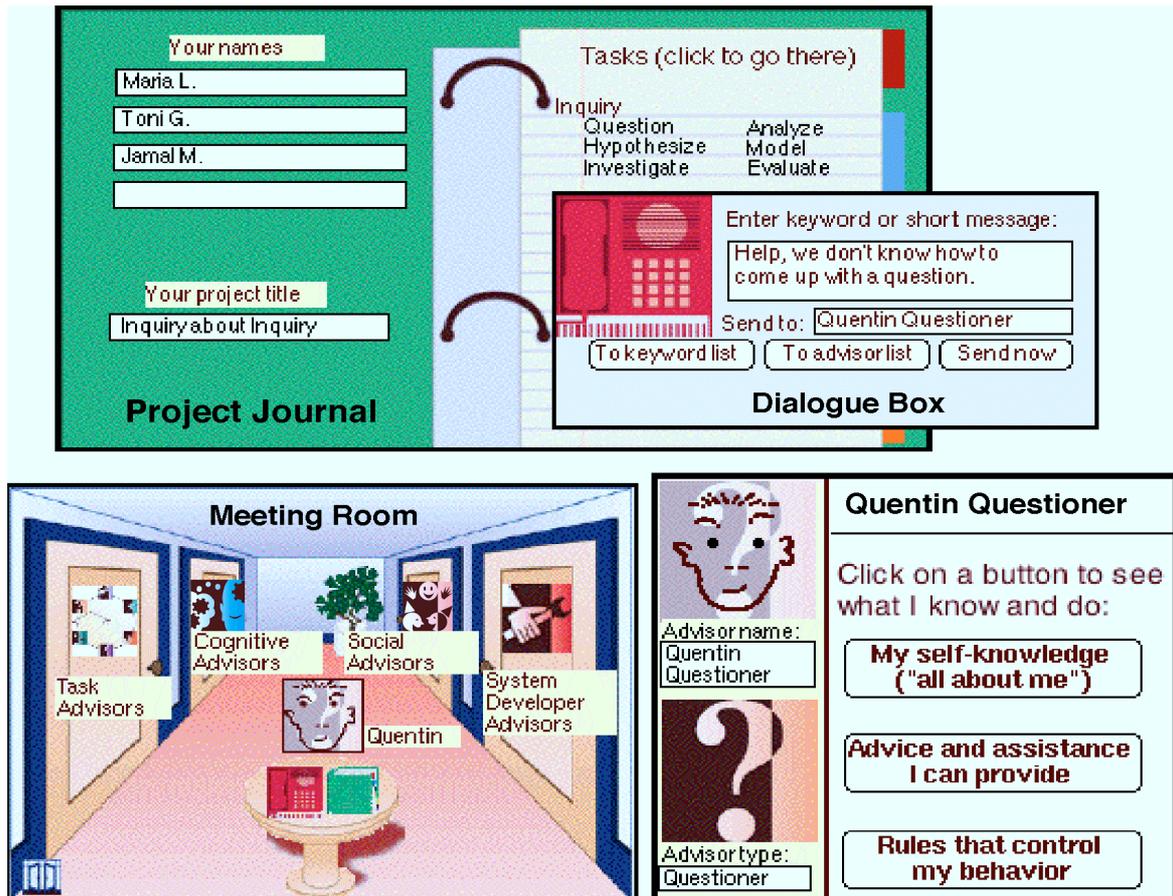


Figure 7. Students using SCI-WISE work in the context of various task documents, such as the Project Journal which serves to organize the task and house their work. Advisors can be called upon for help and can be accessed in a variety of ways. For example, they can be found in the Meeting Room, can be accessed via the Dialogue Box, or can simply pop up when appropriate. In the above figure, students have used the Dialogue Box to call upon Quentin Questionner for help in coming up with a research question.

General purpose advisors

In addition to General Purpose Memory and Communication Systems, SCI-WISE also makes available General Purpose Advisors, who can provide advice during any task or subtask. These advisors are based on the Reflective Assessment Criteria developed for our ThinkerTools Inquiry Curriculum (White & Frederiksen, 1998), which helped students understand the characteristics of successful inquiry processes and encouraged them to pursue high-level functional goals such as “being inventive” and “communicating well” (as described earlier). In SCI-WISE, these Reflective-Assessment Criteria have been cast as General Purpose Advisors whose purpose is enabling users to develop and employ widely applicable cognitive and social skills. Corresponding to the Cognitive Criteria shown in Figure 3, the Cognitive Advisors in our seed system include the Inventor, Planner, Representor, and Reasoner. The Social advisors include the Communicator, Collaborator, Debator, and Mediator. These General Purpose Advisors can pop up or be called upon whenever they might be useful. For example, “being inventive” is often a useful goal to pursue at the beginning of each step in the Inquiry Cycle and so the Inventor may pop up under such circumstances if it believes it can offer pertinent advice.

General Purpose Advisors have various types of expertise that are metacognitive in nature. For example, they can describe their goals along with the characteristics of performance that effectively accomplish those goals. They also make available evaluation rubrics that ask users to evaluate their performance against those characteristics. For instance, the Inventor’s goal is

to help users generate multiple possibilities that fit the constraints of a given situation. It can provide characterizations of what it means to be inventive, as in “you show originality and creativity in your work,” and it encourages users to evaluate whether they have been inventive. It then asks them to think of ways in which they could be more inventive. In addition, General Purpose Advisors can suggest heuristics for achieving their goals and can indicate when these heuristics might be useful as well as provide examples that illustrate their use. For example, the Inventor suggests heuristics such as “turn your mind loose” and “think of ideas and explore them.” It can also inform users that such ways of being inventive are often useful at the beginning of each step in the Inquiry Cycle and can provide specific examples to illustrate the process.

The introduction and use of these General Purpose Advisors within SCI-WISE embodies a key component of our theory of metacognitive expertise and its development. These advisors serve two important functions. First, they provide an initial, workable set of metacognitive categories that are useful in learning to talk about and develop theories of the characteristics of successful cognitive and social processes (Frederiksen & White, 1997; White & Frederiksen, 1998). Second, they provide a model of metacognitive expertise and of how such expertise can be employed as one engages in complex tasks like doing a research project.

System development tools and advisors

SCI-WISE also makes available System Development Tools and Advisors which aid students as they try to modify the system itself. These advisors can be called upon when the users’ goal is to revise the inquiry support system so that the next time they engage in inquiry, they will get better advice. Users work with the Head System Development Advisor, called the Modifier, to create alternative versions of the system that embody their own theories about the nature of inquiry and the best means of supporting it.

The Modifier’s goal is to help users talk about, reflect on, and revise inquiry support advisors, including possibly itself. It advises users as they make various types of changes to advisors,³ including minor revisions (like rewording aspects of their expertise), adding or deleting components of expertise (like adding a heuristic or strategy), and creating a new advisor (like adding a step to the Inquiry Cycle or adding a new General Purpose Advisor).

New advisors can be constructed for each class of advisors (i.e., Task, General Purpose, and System Development) through the use of advisor shells which inherit the structure and capabilities of advisors in that class. Systems that are inherited include the advisor’s memory system, its communication system, and its reasoning system. Users work with the Modifier to create alternative versions of an advisor so that they can experiment to find out which version users find most effective, or like best, and so forth. For this reason, advisors can be given proper names, like Quentin Questioner and Quincy Questioner, so that users can distinguish the various incarnations of an advisor. Helping users create, modify, and test advisors effectively may require that the system eventually include other types of advisors, such as a “Mind Modeler” and a “Community Creator,” who could provide information about Task Advisors and General Purpose Advisors and how they can work together to help users perform a task.

The Modifier can also work with users to alter when an advisor should give advice and what kind of advice it should give. How this can be done will become apparent in the sections on “Rules for Controlling Behavior” and “How Advisors Decide What to Do.” Enabling users to make this type of revision in a manner that actually improves the inquiry support system may require that the Modifier call on a Pedagogy Advisor who has information about theories of learning and coaching. For instance, the Pedagogue could present users with pedagogical principles like “give less and less advice each time so that users learn how to do the task

³ At present, advisors are the only components of the system that are modifiable by users. Future generations of SCI-WISE may enable users to change other components, such as giving them tools to create new types of Task Documents or Communication Interfaces. However, we are starting with tools for modifying an advisor’s knowledge and behavior, because the creation and modification of such pedagogical agents affords, we believe, the most powerful vehicle for fostering the development of metacognitive expertise.

without help” or “only give advice when users say they want it otherwise they may get annoyed at being told what to do all the time.” In this way, the Modifier could help users make changes to the inquiry support system that alter the amount and type of advice users have access to. For example, students could experiment with how much assistance the advisors provide to users, such as whether the advisors recommend subgoals to be pursued at each step in the Inquiry Cycle or instead require users to generate the subgoals for themselves. In this way, students could modify the system to represent their own theories of inquiry learning and how best to scaffold it. Furthermore, making such revisions should help them to realize that there are alternative theories of learning and that their own learning processes can be modified to embody different theories. Such a realization would help to combat innatist views of academic ability that limit student achievement (Dweck & Leggett, 1988).

Working with advisors

We have seen that there are three broad classes of advisors within the SCI-WISE system: (1) Task Advisors, who are specialized to help students achieve the subgoals associated with a given task, (2) General Purpose Advisors, who help in understanding and developing general cognitive and social skills needed for a wide range of tasks, and (3) System Development Advisors who help students construct alternatives to the seed system. This taxonomy of advisors is outlined in Figure 8. These classes of advisors are not the only ones that we could have created, but they satisfy our model of reflective, goal-driven inquiry (White & Frederiksen, 1998). They each play a role in helping students to develop a theory of how inquiry can be modeled and supported, and an understanding of how this theory can be refined through modification and experimentation with the inquiry support system.

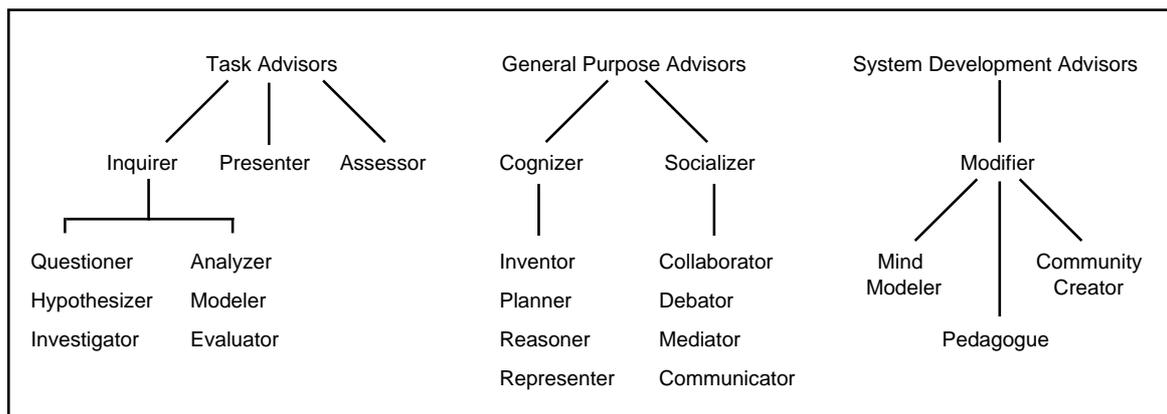


Figure 8. The SCI-WISE advisors are organized in a hierarchical taxonomy, which consists of the Advisor Class (top level), the Head Advisors (middle level), and the Specialists (bottom level).

We now provide an illustration of what it is like to interact with each of these three classes of advisors. What follows is a hypothetical example of students getting advice as they work in the Task Context of designing and carrying out a research project. The students are working in their Project Journal, which is organized around the Inquiry Cycle. They are just about to start work on their hypotheses and go to the Hypothesize section of their journal. At the top left of Figure 9, you can see that the appropriate Inquiry Task Advisor, Helena Hypothesizer, pops up to offer advice. She says, “Hi, I’m Helena Hypothesizer. I predict I can help you. Here are some things I can do for you: (1) I can describe the characteristics of good hypotheses; (2) I can suggest strategies for creating hypotheses and advisors who can assist; and (3) I can help you evaluate your hypotheses to see if they need revision.” The students click on “suggest strategies,” and Helena then says, “A good strategy to start with is to think of lots of ideas and then narrow them down to the good ones. For help in coming up with ideas, the Inventor might be worth checking out.”

The Hypothesizer has recommended that the students consult one of the General Purpose Advisors, namely the Inventor. The students decide to take her advice and so they click on the Inventor icon. As shown at the middle left of Figure 9, Ingrid Inventor pops up and offers two strategies “Fast and Loose” and “Control Freaks.” The students click on “Fast and Loose,” and Ingrid then says, “Good choice! Fast and loose is my favorite. Relax and turn your mind loose. Think of as many ideas as you can in five minutes. The ideas can be crazy or serious, it doesn’t matter.”

Now suppose that the students go to their Project Journal and write, “We still can’t come up with any ideas, so we think Ingrid gives lousy advice.” And they respond to Ingrid’s prompts to evaluate both their own performance and hers by giving low ratings. This causes Ingrid to say, “Please reflect on why you didn’t find me very helpful. Improve my advice so that next time I will be more useful to you.” So, the students decide to come up with a better strategy and want to give it to Ingrid.

In order to give their proposed new strategy to Ingrid, the students need the help of one of the System Development Advisors. So they go to the Meeting Room to find Marvin Modifier, because that is who they need to work with to give Ingrid a new strategy. They click on Marvin who then pops up and says (as shown at the bottom left of Figure 9), “I see that you last were working with Ingrid Inventor’s strategies for coming up with ideas. If you’d like to modify the strategies, click on Add or Edit. Otherwise click on Other Choices.” The students click on “Add” and the template for Ingrid pops up with a new, unmarked button on which they can enter the name of their new strategy. So they type “Ask a Friend,” and then they click on that button so that they can enter their strategy. A text box pops up in which they type (as shown at the bottom right of Figure 9), “Trade ideas with your friends. You give them an idea, then they give you one. You can get by with a little help from your friends.” In this way, the students have given Ingrid Inventor a new piece of strategic advice, which will now be available to all users of their inquiry support system whenever they consult Ingrid.

The preceding example illustrates how students can work with Inquiry Task and General Purpose Advisors as they carry out an inquiry project. It also illustrates how they can use System Development Advisors and Tools to modify such advisors.

What advisors know

What follows is a synopsis of the types of information and expertise that can be provided by the advisors in our seed system. To start with, they have “self knowledge”. For example they can inform users about what they know and when they might be useful. They also have Advice and Assistance to give, which includes knowledge about inquiry processes and products. For example, they can advise users about process goals, like generating hypotheses, as well as provide strategies for achieving those goals and referrals to other advisors who can help. And, they can provide information about the characteristics of good inquiry products, like hypotheses and experimental designs, and can give critiqued examples of good and bad inquiry products. Finally, advisors also have Advisor Behavior Rules, which they employ as they try to decide what to do in any given context. Users can modify all of these types of advisor expertise.

Self knowledge

One property of SCI-WISE’s advisors is that they have “self knowledge” which they can articulate when giving advice. By self knowledge we mean information an advisor has and can provide about its expertise. This information is put into its knowledge base by its creator. An advisor’s self knowledge includes answers to questions such as the following:

What expertise do I have?
Why is my expertise important?

What are my goals?
When might I be useful?

How do I get information?
How do I decide what to do?

How do I monitor my performance?
How do I improve myself?

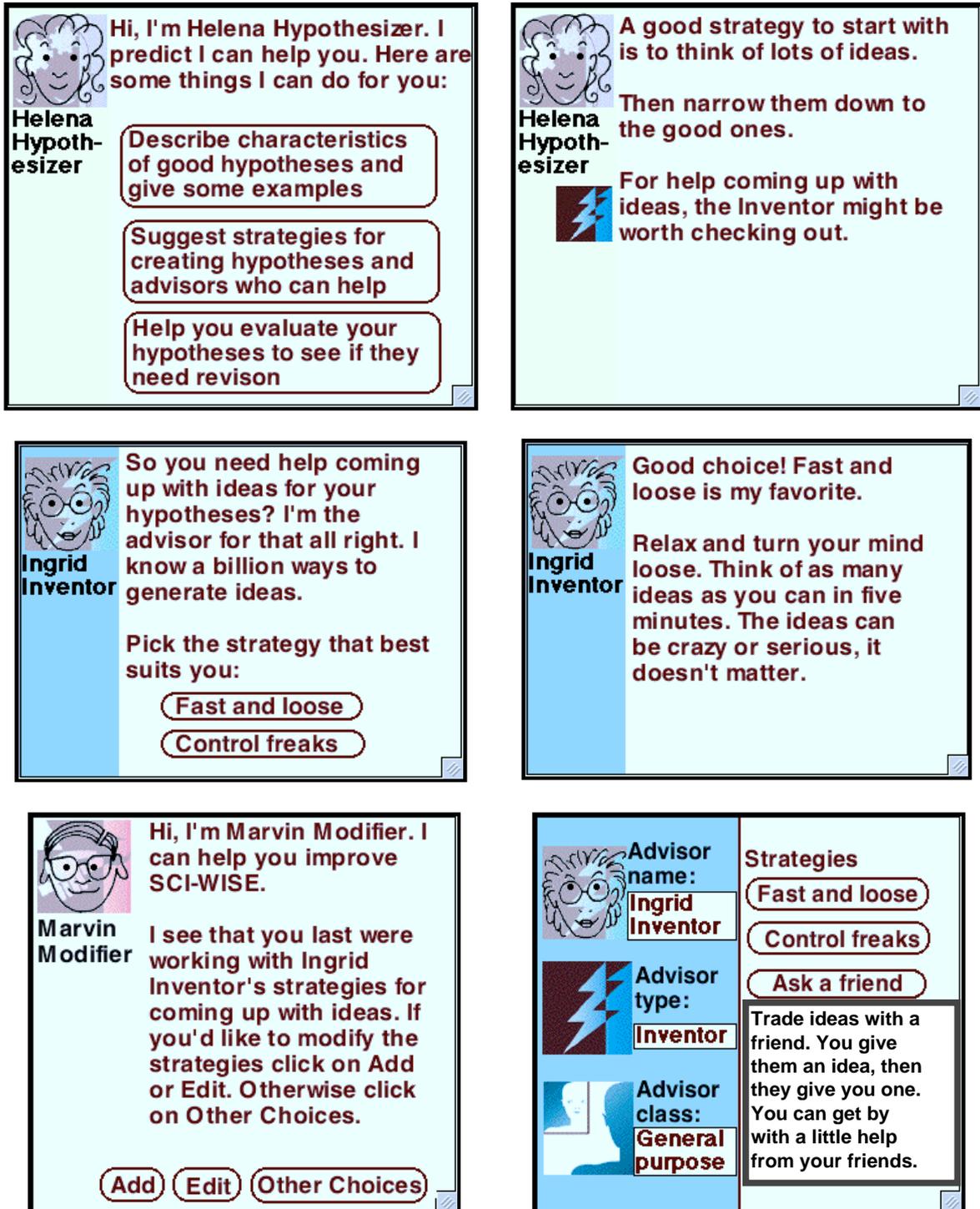


Figure 9. This sequence of illustrations (read from left to right) shows what it is like to interact with the three classes of SCI-WISE advisors. At the top, students start their research by consulting a Task Advisor. In the middle, they get advice from one of the General Purpose Advisors. At the bottom, they work with a System Development Advisor, called the Modifier, to try to improve the General Purpose Advisor.

Each advisor can thus provide characterizations of what it knows, when and why it is useful, how it decides what to do, and how it monitors and improves its performance. For example, the Assessor can say, “Hi, I’m the Assessor and I want to help you evaluate your work so that you can improve it. You might find me particularly helpful at the end of each task you undertake.” These characterizations of things such as an advisor’s expertise, its utility, and its functionality are linked to the actual advice and assistance that it can give, to its advisor behavior rules, or to its reasoning mechanisms (as appropriate) so that users can go from one to the other. Our conjecture is that these capabilities will help users to develop metacognitive expertise regarding the advisor’s purpose and functionality. They might also help users understand why it is useful to have such self knowledge and thereby motivate them to develop this type of meta-level knowledge regarding their own expertise.

Advice and assistance

All advisors have a knowledge base that houses their advice and assistance. This expertise is categorized in ways designed to help users find the advice they need, as well as to help the advisors select which piece of advice to give. The following illustrates one of the categorization schemes embedded in the Inquiry Task Advisors of our seed system:

Process Knowledge

- Task goals, subgoals, and their purposes
- Strategies for achieving goals
- Referrals to advisors who can help
- Assessment criteria for evaluating processes

Product Knowledge

- Characteristics of products
- Critiqued examples of good and bad products
- Assessment criteria for evaluating products

With their advice categorized in this way, Inquiry Task Advisors can support the inquiry process. For example, they can talk about goals that need to be pursued in order to accomplish a particular task, such as “come up with alternative hypotheses,” as well as about the purpose of achieving those goals within the overall inquiry process. They can also recommend strategies for achieving goals, such as “try being inventive,” and can suggest asking General Purpose Advisors, like the Inventor, for help. In addition, they can provide prompts to scaffold the process, such as “What hypotheses do you have about possible answers to your research question? And, explain the reasoning behind each of your hypotheses.” Finally, they can work with other task and system development advisors, like the Assessor and Modifier, to help students evaluate and refine their inquiry process.

With regard to inquiry products, like hypotheses and models, Inquiry Task Advisors can describe possible characteristics of inquiry products and can give critiqued examples of good and bad products, such as good and bad hypotheses. (All of the domain-specific examples used to illustrate inquiry products in various domains, like biology or physics, are scripted because the system has no domain-specific expertise.) They can also advise users as to how to evaluate inquiry products, such as how to critique their experimental designs in order to determine if they need revision.

By providing these types of advice and scaffolding, advisors introduce a model of how to talk about and employ theories about inquiry processes. For instance, they talk in terms of developing goals and strategies for achieving those goals, and discuss the need to monitor performance to see if the goals have been reached. This advice is in a form that is transferable and adaptable to a wide variety of situations. For instance, the Inventor provides generally applicable suggestions for how to be inventive as well as how to determine whether one’s inquiry process and products are indeed inventive. Interacting with a system that offers such generic advice concerning how to form goals, develop strategies, and monitor behavior should help users to develop and refine widely-applicable forms of metacognitive expertise.

Advisors also enable users to pay attention to the concerns of others and appreciate the role they play in the functioning of a scientific community. For instance, the Investigator might suggest that the users consider what type of model they are trying to create when planning their investigations. It can also recommend that they call upon the Modeler who may have expertise about such considerations. In this way, students should learn about the expertise of the various advisors as well as the relationships among them, which may help students in building their own communities.

Rules for controlling behavior

Advisors also have knowledge that enables them to decide when to pop up, which piece of advice to give, and when to keep silent. In the prototype version of SCI-WISE, this knowledge is encoded as a collection of condition-action rules such as those shown in Figure 10. Student designers⁴ of new versions of SCI-WISE can select which rules each advisor should follow from sets of alternative rules that relate to how the advisor should behave in different contexts. Figure 10 presents examples of such alternative rules. The rule set on the left determines how much advice the advisor should give, and the one on the right determines which type of advice it should give. Student designers select one rule from each such set of alternative rules. In this way, they can easily modify how an advisor or class of advisors behaves. (These rules can be set globally for all advisors, or for all advisors in a class, or locally for individual advisors.)

In future generations of SCI-WISE, we plan to provide a tool to enable student designers to actually compose these rules from sets of conditions and actions, rather than simply having them select from pre-made alternatives. This tool will enable student designers to conjoin both conditions and actions as well as to type in an explanation for why their rule should be followed. In this way, they could create more complex rules of the form “If *a* and if *b*, then do *x* and then *y*, because *c*.” For example, “If the users have limited experience and if they are at the beginning of a task, then explain the nature and purpose of the task and then suggest some strategies for doing the task, because they need to understand why a task is important before they try to do it.” With this tool, student designers will have the ability to create and justify rules and the advisor will have the capability to explain to users both how and why it selected a particular piece of advice.



Figure 10. Advisors have rules that control their behavior. The box on the left shows a set of rules for determining how much advice to give, and the one on the right shows a set for determining which type of advice to provide. Student designers can select one rule from each such set of alternative rules. In this way, they can easily modify how an advisor behaves and can create versions of SCI-WISE with widely varying properties, such as one in which the advisors are in control versus one in which the users are in control.

⁴ In this article, our focus is on characterizing SCI-WISE as a metacognitive tool that enables young students to embody and test their theories of the cognitive and social processes needed for inquiry and how best to support them. Thus we will use the term “student designers” even though designers can be anyone, including researchers and teachers.

How advisors work

SCI-WISE's advisors are agents who have certain reasoning capabilities that enable them to interpret information they acquire, decide on goals to adopt, and take actions in pursuit of their goals (Franklin & Graesser, 1997; Russell & Norvig, 1995). These capabilities are present only in limited forms in the present prototype.

Advisory agents have a wide variety of goals that they can pursue, including:

- Help students learn about the advisor's expertise;
- Help students understand the nature of the task being undertaken;
- Help students get the task done;
- Help students develop widely applicable cognitive and social skills;
- Help students learn how to assess, reflect on, and improve their inquiry processes.

Such goals are found in each agent's "self knowledge" and are linked to the "advice and assistance" that the agent can give. To enable advisors to decide which of its goals would be productive to pursue at a given time as well as what actions to take, the advisors have three subsystems. These subsystems enable them to acquire and interpret information, to decide what to do, and to monitor and improve their performance.

Ways of acquiring and interpreting information

An advisor has various means of getting information with help from the communication and memory systems. For example, it can get information from other advisors, from task documents and user histories, as well as from communicating with the users directly. In order to decide what goals to pursue and what actions to take, advisors use this information to form beliefs about the current conditions. These beliefs are formed through a process of inference and abstraction. This process transforms information into forms and categories that are useful for making advisory decisions. The categories of beliefs, along with examples of such beliefs, are illustrated below for the Hypothesizer.

Task context and status.

- These users are working on the hypothesize subtask.
- They are in the middle of the task and have just entered two hypotheses.

Prior interactions with the agent.

- They always ignore my advice to evaluate their work to see if it needs revision.
- They give me a low performance rating whenever I ask them to evaluate their work.

Users' history and characteristics.

- These users have done five projects already and have never modified the system.
- They recently gave themselves a low rating on "being reflective."

Users' goals and desires.

- These users say that their goal is to get the task done.
- They say that they want me to help them.

Agent's own goals and priorities.

- My highest priority is to help users learn how to assess, reflect on, and improve their inquiry processes.

This set of beliefs is then used, as described below, to determine the advisor's goals as well as to select appropriate actions aimed at achieving those goals.

Mechanisms for deciding what to do

Agents need to have a mechanism for deciding what to do. To accomplish this, we employ a simple, forward-reasoning, inference engine. In the SCI-WISE prototype, this decision making is done using condition-action rules. These take as inputs the beliefs that the agent currently holds (described above). These beliefs form the conditions that determine which rules get activated. This decision making process is done in stages. The agent first uses its beliefs about the current conditions to form a set of conjectures about which goal(s) it should pursue. It then goes on to decide which of these goals to pursue and what actions to take in pursuit of those goals, such as which piece of advice to give and what form the advice should be in. Associated with each step in this decision process, is a rule or set of rules that were specified by the student designers as they selected or created the Rules that Control Advisor Behavior. These rules enable the advisor to answer questions related to deciding how it should behave in the present context. These questions include: Am I relevant, should I give advice, and what advice should I give?

As a simple example, we illustrate the decision making process of Helena Hypothesizer in the context of working with novice users. Imagine that she has formed the beliefs that the users are working on their first research project and that they have just advanced to the hypothesize step of the Inquiry Cycle. Her belief that the users are in the hypothesize step causes her Advisor Behavior Rules to conjecture that she has relevant advice to give. Since Helena's creators also selected the rule "If you have relevant advice, pop up and show the advice," this leads to the conjecture that she should give advice. Imagine that Helena's creators also gave her the rule that "if the task status is 'haven't started' and if the users have 'no prior experience,' then the goal should be to inform the users about the nature and purpose of the task." Since her beliefs also match this rule's conditions, Helena forms another conjecture, namely that her goal should be to "inform the users about the nature and purpose of the task." Since all of her conjectures about which goals she should pursue are compatible, she decides to adopt the goal of giving advice that will inform the users about the nature and purpose of the task. She then accesses and gives the appropriate advice (i.e., the advice that is linked to this goal in her "advice and assistance" knowledge base).

The decision making process is not always as simple and straightforward as in the preceding example. It is possible for an advisor to have a set of beliefs and behavior rules that lead to conflicts about which goals the advisor should pursue. In fact, the set of beliefs illustrated for the Hypothesizer in the preceding section is highly likely to produce such a conflict. In that example, the users said they wanted help and that their goal was to get the task done; yet, the Hypothesizer's priority was to get them to reflect on their work, which was reinforced by the fact that they had rarely done this in the past. As such problems occur, they are articulated by the advisor who asks the users for assistance. For example, in cases of such goal-setting conflicts, it asks users to determine which of the proposed conflicting goals should have priority. (Alternatively, one could enable student designers to select from a set of conflict resolution rules, such as "always adopt the goal that has the highest priority for the advisor" versus "always accede to the desires of the users.") Such articulation of cognitive conflicts and user involvement in the decision making process might lead students to be more able to think of their own cognitive processes in terms of setting goals, developing strategies, and monitoring progress. In this way, limitations of the system can be used as opportunities for discussions about metacognition.

Methods for monitoring and improving performance

Advisors work with students to monitor and reflect on both the advisors' and the students' performance. They help users monitor whether they have achieved their goals and, if they have not, can give advice concerning how to proceed or can refer them to other advisors who can help. Advisors also need to do this for their own behaviors. That is, they should adopt the goal

of improving their own performance. To accomplish this, they need to monitor whether they have achieved their own goals and, if not, they should modify their knowledge and behavior accordingly.

In the prototype, this monitoring and improvement is done by asking the users for assistance. The Hypothesizer, for example, can ask if its advice was helpful. If the users give its performance a low rating, the Hypothesizer says, "I'm sorry my advice didn't help you to achieve your goal of creating hypotheses. Here are the different types of advice I can offer you. Why don't you select some advice that you think might be more helpful to you." At the end of a task, users are also encouraged to modify advisors to make them more effective. For instance, the Hypothesizer can ask, "Please reflect on why you didn't find me very helpful. Improve my advice and my behavior rules so that next time I will be more useful to you." As part of this reflective process, students might decide, for instance, that the Hypothesizer's feature of constantly asking them to evaluate their performance is no longer useful and has become downright annoying. They could then work with the Modifier to alter the Hypothesizer's behavior rules so that it no longer prompts for such evaluations. Subsequently they could experiment with this new version of the Hypothesizer to see if it improves their performance. In this way, students can not only be introduced to reflective processes, they can also develop and test theories concerning their utility.

Our conjecture is that encouraging students to monitor advisors' usefulness and to improve them when necessary will serve a role in enabling students to monitor, reflect on, and improve their own performance. In future generations of SCI-WISE, we plan to experiment with giving advisors learning capabilities that will enable them to improve their own knowledge and performance. Thus, ultimately advisors will include additional expertise in self regulation and self improvement. In this way, they can provide more sophisticated models of these important metacognitive processes and may better enable students to "learn how to learn."

How the community of advisors behaves

Can students create a community of advisors who work together so that their advice appears coordinated and coherent to users, or will the behavior of their SCI-WISE systems be disjointed and confusing? Coordination is facilitated, as described previously, by the communications system. For instance, advisors can get information from the inquiry environment, from other advisors, as well as from users so that they are informed about the present context. Given such information, how do advisors coordinate (or not coordinate) their behavior?

Coordination of advisors' behaviors is related to how advisors get activated. Within SCI-WISE, advisors can get activated in a variety of different ways. For example, users can seek out an advisor either because they know it is relevant or because their perusal of its self knowledge (i.e., its information about what it knows and when it might be useful) indicates that it should be helpful in the present context. An advisor can also be called upon when another advisor indicates that it might be useful. This happens either because the presently active advisor has the knowledge that the other advisor is relevant in the present context or because the other advisor sends a message informing the presently active advisor of its relevance. In addition, advisors can decide to pop up themselves because they know they are relevant based on the task context and/or something the users did such as give themselves a low rating in their area of expertise, which might be, say, "inventiveness" or "collaboration."

Student designers have control over whether advisors have to be sought out, or recommended by other advisors, or can just pop up whenever they want. This is done by selecting alternative options in the Advisor Behavior Rules, particularly those that govern when the agent should intervene. Choosing different options produces systems with different characteristics, ranging from total user control to total system control of sequentially presented advice. It can also produce hybrid systems such as one in which multiple advisors pop up and users control which ones they consult, or one in which different advisors behave in different ways such as some popping up and some having to be invoked. Alternative versions of SCI-WISE can thus have very different emergent properties, depending on the choices made by its student designers and users. This capability to easily make modifications that produce widely varying system behaviors provides a vehicle for students to engage in research on the design of

the system itself. For instance, they could engage in educational research regarding how best to support the inquiry process with sequential or parallel advice or with user or system control.

Summary of SCI-WISE architecture

To summarize, SCI-WISE provides an environment in which students create a variety of artifacts in the form of Task Documents, such as the Project Journal and Project Report. Each Task Document has a set of Task Advisors associated with it. The system also makes available General Purpose Advisors, such as the Inventor and the Collaborator, and communication and memory systems that are intended to be useful across a wide range of contexts. The expertise and behavior of the different types of advisors are easily modifiable by student designers using System Development Tools and Advisors. This control over what advisors know and how they behave enables students to engage in educational research regarding how best to model and support the processes of collaborative inquiry and reflective learning.

USING SCI-WISE TO FOSTER METACOGNITIVE DEVELOPMENT

SCI-WISE integrates cognitive and social aspects of cognition within a social framework that takes the form of a community of advisors who work together to guide and support reflective inquiry. To support the pedagogical value of SCI-WISE as a tool for fostering students' metacognitive development, we argue that metacognitive processes are most easily understood and observed in such a multi-agent social system. After all, in a social context, one is concerned about what others are doing and why. Social systems provide a natural context for focusing on goals and motives, as well as for monitoring and reflecting on others' behavior and expertise. SCI-WISE models these types of metacognitive concerns as its advisors interact with one another and with users. It also allows students to create and represent this type of expertise as they work to improve the advisors.

In order to provide a richer social system that better illustrates the need for and use of metacognitive expertise, SCI-WISE could be augmented in various ways. For example, in the version of the system we have described, advisor-to-advisor interactions are limited to exchanging beliefs about the current context, deciding which advisor(s) should pop up, and little else. One can imagine augmenting advisors' capabilities so that they can engage in a richer array of social behaviors. For example, the Rules that Control Advisor Behavior could include sets of alternative rules for governing social interactions, such as "talk whenever you want" versus "let other advisors talk" versus "yield only to the Head Advisor." Student Designers could then examine these explicit representations of social principles and could make decisions about which rules each advisor should follow. Furthermore, advisors could be augmented so that they formulate a richer set of beliefs about others and engage in more types of interactions. For instance, one can imagine advisors forming beliefs about who it is that they agree and disagree with, and this could trigger collaboration or debate among advisors. One could then envision agents arguing publicly with one another about who has the most relevant advice to give in the present context. Further, one can imagine social advisors, such as a Mediator, being consulted by users to help resolve such disputes among the advisors. Through such augmentations, the social behavior of SCI-WISE could be enhanced, thereby making its metacognitive behavior more prevalent, necessary, and explicit.

Pedagogical approaches to fostering metacognitive development

Our primary approach to supporting students' metacognitive development is to reify meta-level expertise within a social system of advisory agents, namely SCI-WISE, and then to enable students to interact with this system in ways that foster the internalization of its expertise. How then can we enable students to internalize the expertise? That is, how can we enable individuals to appropriate external, social entities (the advisors) as internal, cognitive processes (Vygotsky, 1978)? As we have described, the meta-level processes are embodied within a system of agents who talk about their capabilities and concerns, and who are cued as functional

units within a variety of application contexts. In this way, they are capable of having modularity and transferability. Our claim is that an agent's meta-level expertise can be internalized by students and then consciously invoked if, through a process of reflected abstraction (Piaget, 1976), it has been identified, explicitly labeled, and interacted with as a functional unit. By internalizing expertise as a system of such functional units in the form of advisors, they become accessible to reflected abstraction and conscious control, enabling students to "put on different hats" and "invoke different voices" when needed as they solve problems or engage in inquiry learning.⁵

We are working with our collaborating teacher/researchers to develop a variety of pedagogical activities designed to foster the development of such metacognitive expertise. Students engage in these activities as they work with the inquiry support system to conduct research across a number of domains throughout the school year(s). The activities include having students put together advisory teams, act out the roles of the different advisors, and engage in inquiry about inquiry. Undertaking these activities should also serve to facilitate the functioning of the classroom as a research community. An important objective is to help teachers cultivate a community in which students engage in inquiry and, by so doing, develop expertise that enables them to learn via inquiry in any domain that they choose.

Creating teams of advisors

In this activity, students are encouraged to think about the roles and utilities of the different advisors. Students are asked to put together a team of advisors who will guide them in a research project or inquiry task that they are about to undertake. They start by discussing and trying to decide which advisors they think would be needed. They then work with SCI-WISE to create an advisory team designed to suit the needs of their task. For instance, students could decide that they want to engage in some exploratory research and that the Inquiry Cycle shown in Figure 1 is not well suited to their present goals. So they modify the Head Advisor for this task, namely the Inquirer, so that it has a more appropriate goal structure, such as (1) investigate, (2) analyze, and (3) hypothesize. They then put together an advisory team that is headed by the Inquirer and that includes the Investigator, Analyzer, and Hypothesizer as well as some of the General Purpose Advisors. In this way, students are encouraged to think about the structure of tasks as well as the expertise of the different advisors.

Playing roles: Research groups as communities of advisors

Creating a classroom research community in which sociocognitive processes are represented as areas of expertise associated with particular individuals, such as an Inventor and a Planner, should enable students to recognize, talk about, and take on the role of those experts in carrying out inquiry within the classroom. We developed a pedagogical activity in which students play such roles in a process we term "social enactment." In this activity, research groups work with SCI-WISE to design and carry out a research project. Individual students within the group work in partnership with and take on the roles of one of its Cognitive and one of its Social Advisors. So, for example, one student is the Planner and Collaborator, another is the Inventor and Communicator, and so on. Students switch roles from time to time so that each gets an opportunity to be in charge of the different components of cognitive and social expertise that are needed when carrying out a complex task like scientific inquiry. As the group does its project, the student who is embodying a particular advisor works with that advisor to see what it would do, to act out its behavior, and to modify it when the group thinks its behavior needs improvement.

This activity enables students to apply the cognitive and social processes embedded within SCI-WISE to the actual functioning of their research group. In this way, students can

⁵ Suggesting that students need to internalize SCI-WISE in its entirety is an extreme position to take (c.f., White & Frederiksen, 1990). Important questions that we plan to address in our future research are how much of SCI-WISE is appropriated by students, in what forms do they internalize its expertise, and how much and what forms are needed to facilitate their sociocognitive and metacognitive development.

investigate the utility of the advisors for enhancing their group's functioning. Playing the different roles may also serve to help students internalize the expertise of the different advisors (Vygotsky, 1978). Pedagogical activities of this type utilize SCI-WISE as a tool for supporting collaborative inquiry among the students themselves and may help teachers to transform their classrooms into more effective learning communities.

Engaging in inquiry about inquiry

To further students' awareness of sociocognitive and metacognitive processes related to collaborative inquiry and reflective learning, we are also developing activities in which students engage in inquiry about inquiry. That is, they create and experiment with explicit theories of processes needed to support inquiry learning. Students embed their various theories in alternative versions of SCI-WISE and then experiment with them to assess the utility of their theories. For example, a class might be interested in investigating the utility of reflectively assessing their work. Students could work with the Modifier to revise the Assessor so that it embodies their own theories of this reflective process. In this way, different groups of students could develop alternative, competing models of how to be reflective. The class could then conduct empirical research to determine which are the most useful by finding out which models produce the most helpful inquiry support environment. This type of metacognitive research is carried out as students use their alternative versions of the inquiry support environment to design and conduct research projects on whatever topic they are presently studying.

In these inquiry-about-inquiry activities, students collaborate as they work to improve SCI-WISE by developing and refining the expertise of its advisors. The advisors, in turn, collaborate with the students as they engage in these processes of reflection and improvement. We argue that such pedagogical activities, in which students become both members of and developers of this multi-agent social system, should be particularly effective in fostering metacognitive development.

The vision and its obstacles

Our hope is that by modifying the system to test their own theories of collaborative inquiry and reflective learning, by working with the system to conduct research on a wide variety of topics, and by enacting the roles of the different advisors within their research groups, students will internalize the advisors' expertise and will be able to generalize the use of their expertise to different contexts. Furthermore, we hope that they may even come to view both their minds and their research groups as a community of advisors who collaborate as they engage in inquiry and reflection. However, much more nightmarish scenarios are possible. For instance, it is relatively easy to create versions of SCI-WISE that many would find annoying and confusing – annoying in that the system provides too much advice and structure, and confusing in that there are too many agents who are indistinguishable from one another. In fact, in developing our seed system, we keep heading toward this more nightmarish scenario by creating complex systems whose behavior is potentially mysterious. So, how can we possibly expect young students to create versions of the system that successfully model and support collaborative inquiry and reflective learning and, by so doing, enable them to develop powerful metacognitive expertise as well as productive theories of mind and community?

Students as educational researchers

To achieve these challenging goals, we build on the idea of engaging students in inquiry about inquiry. We are experimenting with having students become cognitive scientists and educational researchers, who address many of the same research questions that we investigate in our own work. One such question is, what makes a good advisor? In other words, what characteristics does an advisor need to possess to be effective? For example:

- Would giving advisors distinct personalities make them more appealing to users, or would all that unnecessary chatter just be annoying?

- Do advisors need to be “metacognitively articulate” and talk about their goals and strategies, or is it better if they just tell users what to do?
- Does it help if advisors make their expertise available for inspection and modification by users, or will that just waste users’ time and degrade the advisors?
- Is an advisor’s expertise more useful if it is generic and applies to many contexts, or does it need to be context specific to be useful?

Students could also investigate aspects of system design that relate to long standing issues in the field of computers and education. For example:

- Which is more important, providing a system’s users with autonomy and freedom or with guidance and support?
- Should the system adapt to individual differences, or is it better to treat all students the same?
- Should one worry more about developing a system that keeps students motivated or that makes sure they learn?
- Which “seed system” provides the best starting point for pedagogical purposes, one that is complex and rich, or one that is simple and more easily understood?
- Does the modelling of social processes, like collaboration, play a useful role in students’ social and cognitive development (such as enabling them to develop collaboration skills and metacognitive expertise)?

We are putting together a collection of such research questions that meet two important criteria: (1) they are interesting to young students, and (2) they are productive in terms of fostering their metacognitive development. In our pilot work, we have found that issues that relate to control and to social factors can be highly motivating for middle school students. For example, one such control issue is that of autonomy versus guidance. More specifically, how do you give users control while also providing sufficient guidance? Investigating alternative positions with respect to this question involves making design decisions, such as:

- Do users have to ask for advice or is it given automatically?
- Are users required to follow the advice or can they ignore it?
- Are users stuck with a given version of the system, or can they modify it?

To enable students to engage in investigating such questions, we are creating curricula to accompany the SCI-WISE software that are aimed at facilitating this type of inquiry about inquiry. In these curricula, students conduct educational research on issues such as those mentioned above, like autonomy versus guidance. Our collaborating teachers are overlaying this inquiry about inquiry onto their regular science curriculum, which includes group work and inquiry activities in domains such as physics, ecology, and nutrition. So, for example, their students are conducting research on “the best strategies for collaboration” as they do their ThinkerTools physics projects.

Engaging young students in such inquiry about inquiry will, we conjecture, be effective for a variety of reasons. First of all, the topics addressed, like collaboration and autonomy, can be highly motivating, more so for many middle school students than, say, Newton’s laws of motion. Furthermore, such inquiry can enable young students to do “publishable” research on, for instance, their findings regarding alternative collaboration strategies. Also, this research is potentially useful to themselves, their teachers, and future students. It can enable a teacher to work with her students to develop, for instance, a set of collaboration strategies that she can recommend to her classes in the future. Finally, as we have argued throughout this article, it can enable students to develop metacognitive expertise related to collaborative inquiry, reflection, and “learning how to learn.”

After conducting such research, students could publish their research reports along with their inquiry support systems (or particularly interesting and effective components of them) on the World Wide Web. For instance, as part of their research, a class might create a set of advisors that are useful for a particular task such as reflective assessment or system modification. In this way, classrooms around the world could share and build on one another's work.

Our future work could investigate how SCI-WISE could be modified to better support interactions between different research groups as they work together as part of a research community (either in the same or different classrooms). Community tasks that relate to the Inquiry Cycle (see Figure 1) include:

- **QUESTION:** Developing a common research question, or set of related questions, and deciding which group should pursue which question.
- **HYPOTHESIZE:** Creating a space of possible hypotheses that contains those generated by the various groups.
- **INVESTIGATE:** Collaborating in the design of investigations, such as assessing one another's experimental designs to determine if they have confoundings or if they fail to test competing hypotheses.
- **ANALYZE:** Sharing research findings through the creation of common databases (which makes meta-analysis possible).
- **MODEL:** Engaging in debates using theory and evidence to determine the best models.
- **EVALUATE:** Annotating and evaluating one another's projects to point out the utility and limitations of each other's research, and engaging in discussions about which evaluation criteria to use.

SCI-WISE could be modified to better support these community processes by, for example, making it possible for different research groups to put their work in a common space, introducing an annotation system for commenting on each other's research, and providing software for engaging in debates and discussions (e.g., Bell & Linn, 1997; Cavelli-Sforza, Weiner, & Lesgold, 1994; Scardamalia & Bereiter, 1994). Such enhanced versions of our software system could serve to play a greater role in fostering the development of inquiry-learning communities. A similar process could occur with professional researchers. For example, the graduate students in our research group are working with us to create versions of SCI-WISE that are useful to themselves and their peers as they do their masters and doctoral research projects. Such software can thus provide widely-applicable tools for fostering the development and dissemination of expert practices as well as computer-based models of how best to develop and support those practices.

CONCLUSION

In this article, we have argued that the types of sociocognitive modeling tools found in SCI-WISE are needed in order to make metacognition itself an object of thought and investigation. Furthermore, we have argued that, to be effective, such tools need to be embedded in curricula that engage students in inquiry about their own inquiry learning processes. In this way, students can develop theories about their own skills, such as collaboration and reflection, which should enable them to develop and refine widely-useful cognitive and social skills. The architecture and capabilities of SCI-WISE will undoubtedly evolve as we gain experience with students' ideas regarding how best to model and support sociocognitive processes. In addition, there is the intriguing possibility that the students' own research on inquiry learning and metacognitive expertise could make significant contributions to educational research. With the support of a system such as SCI-WISE for reifying and testing their theories, students and their teachers could collaborate with educational researchers to address some of the difficult issues

related to the nature of lifelong learning skills and the design of effective learning environments.

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