it, and create graphs or diagrams to reveal its patterns; (b) to identify all of the patterns in your data and consider their meaning and generality; and (c) to figure out which of your hypotheses are supported by their data and which are not. Each of these goals is the basis for an inquiry subtask that students carry out. The goals therefore link each inquiry process to a set of coordinated activities.

**Software Advisors**

To provide more detailed meta-knowledge for each inquiry process, the Web of Inquiry includes as resources a set of Inquiry-Task Advisors, one for each of the steps of the Inquiry Cycle. These advisors house knowledge of goals for that inquiry step, reasons why those goals are important, plans and strategies for accomplishing them, and criteria for monitoring their effectiveness. To make it easier for students to keep the advisors straight, each has a name, such as Sydney Synthesizer and Ivy Investigator. Sydney Synthesizer, for instance, can explain what a scientific model is: “Scientific models give you a way to express your ideas. For example, you could make a model to show how you think a spaceship moves through space, or to show the different types of arguments people have, or to show the factors that affect people's happiness, or to show how the human heart works. This can be done using words, pictures, graphs or diagrams to illustrate things.” He also has information about different kinds of models, including causal models, process models, stage models, structural models, and others, with examples of each for students to study. In addition, he can explain the goals for making models: a model “answers a research question,” “fits findings better than other models,” “seems reasonable,” and “is widely useful.”

The community of advisors also includes general-purpose cognitive, social, and metacognitive advisors. For instance Pablo Planner, a metacognitive advisor, has goals for creating a good plan such as “it outlines the goals to be pursued.” Taken together, the community of advisors portrays inquiry as a distributed process in which various
capabilities, like analysis and synthesis, come into play to meet the needs of the research. We personify the cognitive models of each of these processes in the form of advisors so that they can be thought of as roles students may take, or different hats to wear, at different times in their research. The idea is that students will learn to switch in and out of these different hats or roles as they engage in the complex process of scientific inquiry.

Reflection

Reflection involves looking back and evaluating both the process and the products of scientific inquiry. The Web of Inquiry assessment environment provides tools for students to use in reflecting on their own and others’ work as they carry out scientific inquiry projects. The assessments in the Web of Inquiry are called “goal assessments” because they are linked to the advisors’ goals for each inquiry process. The idea is for students to make self-assessments of their progress as they work, using “developmental” rubrics that give them guidance about how to proceed from one stage of accomplishment to the next. Some examples of goal assessment are shown in Figure 10.3.

The goal assessments include goals that encourage students to bring into play prior inquiry processes they have pursued, such as Theorizing and Analyzing, as appropriate. For example, in the Investigate step, they are asked whether their research design will enable them to test their competing hypotheses. In the Analyze step, they are asked whether they have tested each of their hypotheses. And in the Synthesize step, they are asked to construct a theory that generates predicted outcomes that cover their findings, and this can include findings that may not have been specifically hypothesized.

To foster use of such reflection in social practices of inquiry, we also include a discussion tool, which allows students to ask other groups to review their work and provide feedback to them in response to questions they have asked. Embedding reflective assessment into the inquiry process underscores for students that inquiry is a process of theory formation, testing, and revision, and that these processes are supported by getting feedback from others through collaborative discussions. The goal is to foster an intellectual climate in which students are valued as theory builders, and one in which knowledge is understood to be actively and collectively built, and always open to modification.

<table>
<thead>
<tr>
<th>Seems Convincing</th>
<th>Fits Findings</th>
</tr>
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<tbody>
<tr>
<td>Do your current best theory’s descriptions, predictions, and explanations seem believable and fit with everything else you know about your research topic?</td>
<td>Does your current best theory generate descriptions, predictions, and explanations that fit all of your research results?</td>
</tr>
<tr>
<td>◦ Not plausible This theory doesn’t seem believable. It doesn’t fit with some things we know about the topic.</td>
<td>◦ Doesn’t match This theory doesn’t fit our research results very well. Some of its descriptions, predictions, or explanations are different from what we found.</td>
</tr>
<tr>
<td>◦ Fairly plausible This theory seems pretty believable, and it’s consistent with most of the things we know about the topic.</td>
<td>◦ Partial match This theory is consistent with some of our research results, but it leaves some of them out.</td>
</tr>
<tr>
<td>◦ Highly plausible This theory seems very believable and is consistent with what is known about this topic.</td>
<td>◦ Good match This theory fits our research results well. Its predictions and explanations match what we found, and it covers everything that we discovered.</td>
</tr>
</tbody>
</table>

Figure 10.3 Two examples of reflective assessments students can use while they are working on their Current Best Theory using the Web of Inquiry.
Managing Inquiry

Learning inquiry is complex, as it consists of a large repertoire of inquiry capabilities organized under linked inquiry processes, each with its underlying goals, strategies, and assessments. All of these are in play at various times in carrying out inquiry. If students are to be able to manage their own inquiry, they need to understand when, why, and how these capabilities are engaged in the course of their work. We have referred to this as “metacognitive knowledge for action,” that is, knowledge of how one organizes and manages one’s cognitive and metacognitive processes in the course of their application (White & Frederiks, 2005b). This involves using meta-knowledge of the processes of inquiry in controlling cognition.

The Web of Inquiry learning environment supports a number of approaches for developing metacognitive knowledge for action. First, aspects of planning and monitoring are represented in the structure of the system. For example, the Inquiry Cycle orders high-level inquiry processes and their sub-goals, so that students learn the logical purpose of the steps within the inquiry process and the value of keeping track of where they are within the Inquiry Cycle. Second, the Web of Inquiry includes metacognitive advisors who provide explicit cognitive models of planning, monitoring, revising, and reflecting, which students can use to guide their work. Third, as a further support for monitoring and reflection, the software provides formative assessments for each inquiry task. These enable students to monitor their progress in achieving the goals associated with each inquiry step as they work. The levels in the assessments are written to represent a developmental sequence and provide ideas for what the students should be thinking about to improve their work on that goal. Fourth, the inquiry tasks typically need the products created in the previous tasks to be available as a condition for that task to proceed. For example, the Investigator needs alternative hypotheses in order to proceed with designing an experiment. If a new task is attempted prematurely, the deficiencies in products of precursor tasks will become apparent, leading students to go back and do additional work on them so that they are good enough to proceed. These four approaches to controlling the flow of inquiry processes are based on a model incorporating distributed responsibility associated with different inquiry roles, coupled with a top-level inquiry goal structure and general habits of monitoring and evaluating one’s progress in relation to goals.

In several studies, we have tested this approach to developing students’ knowledge and use of scientific inquiry. Our most recent and largest study was designed to evaluate how the Web of Inquiry supports students in learning how to carry out scientific inquiry, and teachers in learning how to accurately assess students’ learning (Frederiksen et al., 2008). In this study, the participating teachers agreed to incorporate inquiry projects within their existing curriculum. The seven schools in which our participating teachers taught were chosen to represent a diverse population of students. In doing their inquiry projects, students worked in small groups, usually of two or three, to develop competing theories about some phenomena of interest to them, and then to design and carry out experiments to see which of their theories has the most empirical support.

As they did their research, the students carried out self-assessments and would also work with another group to provide feedback and have discussions about their work. The teachers chose project topics that were appropriate for their particular curriculum. Content areas of the projects included earth and ecological science, physical and materials science, biology, behavioral science, and health and nutrition. Most of the teachers included two projects in their class over a school year, but a few included only one. A total of 271 students’ projects were completed and scored, generally by two scorers. Scores were given for each of the numerous inquiry goals and for nine National Science Education Standards (National Research Council, 1996). The standards were rated on a
four-level scale using the categories (1) "Below Basic," (2) "Basic," (3) "Proficient," and (4) "Advanced." The mean scoring reliability (G-coefficient for two scorers) is 0.80 for the standards and 0.63 for goals.

To study changes in individual students' performance brought about by engaging in Web of Inquiry projects, we analyzed the qualities of the students' initial Web of Inquiry projects, and the extent of improvement in students' performance between their first and second inquiry projects. Our idea was to identify, based on standards ratings, which aspects of the inquiry process are initially the most well developed, which are most in need of improvement, and how they improved when using the Web of Inquiry environment in carrying out their research.

Mean scores for the students' first projects for each of the standards are given in Table 10.1. For the most general of the standards, Designing and Conducting a Scientific Investigation, the mean rating on the four-point rating scale is 2.01, which corresponds to the "Basic" level. Only 25% of the projects were rated as "Proficient," and none were rated as "Advanced." Thus there was considerable room for improvement after they completed their first project. The mean ratings for three other standards are above this level, while the means for the remaining standards are all below the basic level of 2.0.

The weakest performance on the inquiry standards involves those that pertain to developing alternative theories and hypotheses that can be tested in an investigation, critically analyzing data to distinguish how well the evidence supports each theory, and considering how alternative theories may explain one's findings, all the while maintaining a skeptical attitude. Students also have difficulty in thinking through ways in which they could extend their work, which is essential if they are to regard inquiry as an ongoing process for improving their knowledge over time in their study of science. These are the areas of inquiry knowledge that are least developed in our sample of classrooms when students carry out a single inquiry project.

To evaluate students' learning through carrying out Web of Inquiry projects, we analyzed the changes that occurred in students' inquiry project scores from their first to their second project for four teachers who included two projects in their classes. We found that there is a significant improvement in scores for the overall standard of Designing and

<table>
<thead>
<tr>
<th>Inquiry standard</th>
<th>Mean</th>
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<tbody>
<tr>
<td>Overall—Designing and conducting a scientific investigation</td>
<td>2.01</td>
</tr>
<tr>
<td>Using tools and methods—Using research methods and tools to gather, analyze, and interpret data</td>
<td>2.34</td>
</tr>
<tr>
<td>Communicating science inquiry—Communicating scientific procedures and explanations</td>
<td>2.31</td>
</tr>
<tr>
<td>Asking scientific questions—Asking questions that can be answered through scientific investigations</td>
<td>2.32</td>
</tr>
<tr>
<td>Developing explanations and models—Developing descriptions, explanations, predictions, and models using evidence</td>
<td>1.95</td>
</tr>
<tr>
<td>Relating evidence and explanations—Thinking critically and logically to make the relationship between evidence and explanations</td>
<td>1.89</td>
</tr>
<tr>
<td>Analyzing alternative explanations—Recognizing and analyzing alternative explanations and predictions</td>
<td>1.76</td>
</tr>
<tr>
<td>Showing scientific skepticism—Science advances through legitimate skepticism</td>
<td>1.79</td>
</tr>
<tr>
<td>Extending the research—Generating new ideas and methods for extending your research</td>
<td>1.88</td>
</tr>
</tbody>
</table>
Conducting a Scientific Investigation with an effect size of 0.57σ. This effect size should be taken as an underestimate, because it does not reflect students' learning while they are engaged in their first inquiry project. For the first project, 47% of the projects from these four teachers' classes were judged to be proficient and none were judged to be advanced, while for the second project, 70% were judged to be proficient or advanced. This substantial improvement may be attributed to students' working with the Web of Inquiry and also to other aspects of teaching that occurred when the teachers incorporated the Web of Inquiry in their classrooms.

We also determined which standards are most amenable to learning, and which are more difficult for students. We found that there are improvements in project scores for six of the standards: (1) Asking scientific questions, (2) Developing descriptions, explanations, and models, (3) Analyzing alternative explanations, (4) Showing scientific skepticism, (5) Extending your research, and (6) Communicating science inquiry. One of the hallmarks of the Web of Inquiry is the emphasis on having students use their theories to guide their work as they create research questions and hypotheses, identify meaningful patterns in their data, and consider alternative theories in creating and supporting their "current best theory." These findings suggest that using the resources of the Web of Inquiry fosters the development of these abilities. Significant gains in students' communication scores suggest that they are also gaining mastery over the language and practices of scientific presentations and writing.

In contrast, students showed only small improvements for the standard Relating Evidence and Explanation, which is a standard that was also difficult for them in their first project. Relating Evidence and Explanation has three major components: testing how data patterns they have described support predictions from their theories, being careful to identify salient and consistent data patterns and not to overlook data patterns that might not fit their theories, and considering other plausible theories for explaining their findings. These skills for analyzing and interpreting data from multiple theoretical perspectives present a particularly difficult problem for teaching and learning, and will need to be addressed. Nonetheless, our overall conclusion is that even young students (as young as the fifth grade) can learn to carry out inquiry projects when they are taught, not by leading them step by step through the inquiry processes, but through developing a higher-level meta-knowledge of the structure, purposes, and goals of inquiry processes.

Learning Through Role Playing

We have described how carrying out scientific inquiry is a complex process in which interrelated processes are carried out, and not necessarily in a linear fashion. The decisions about when to move to a different inquiry process or sub-task depend upon active analysis of progress and the readiness of products for supporting future inquiry processes. Such active management depends upon having metacognitive capabilities like planning, monitoring, reflection, and revision. While these are represented in Inquiry Island (and in its web version, the Web of Inquiry) as general-purpose metacognitive advisors, these advisors, unlike the Inquiry-Task advisors, are not directly linked to work on inquiry goals. While their tie-in with accomplishing inquiry processes is implicit, it is not usually made explicit in the software (one example of an exception is when the Investigator refers you to the Planner to plan your investigation). This led us to study whether students' prior knowledge of such metacognitive processes, and whether providing students with additional ways to employ and internalize these metacognitive processes in their inquiry groups, will lead to greater learning using the Inquiry Island approach. We carried out two studies to investigate these questions.
The Interplay of Scientific Inquiry and Metacognition
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Effects of Students’ Prior Knowledge of Metacognitive Processes on Learning Inquiry

The objective of this first study was to evaluate whether students’ prior metacognitive knowledge contributes to their development of knowledge and skills in scientific inquiry. This study was carried out in three eighth-grade science classes in an urban school with a teacher who was familiar with inquiry teaching. To investigate this question, we used a test of metacognitive knowledge we developed which we call “Metacognition the Movie.” The test was designed to assess how well students understand the concept of metacognition, even with little formal instruction. In this assessment of metacognitive expertise, students watch a movie and then complete a written test. The movie shows two students doing a research project and, from time to time, one of them turns to the camera and expresses a metacognitive thought or sometimes indicates that she has a thought (which is not expressed). In the written assessment, the students are presented with excerpts from the movie’s script and are asked to respond to either a justified multiple-choice question or a free-response question about one of these occasions in the movie. The test questions ask students (a) to generate or select an appropriate metacognitive thought for the actor in the movie, (b) to characterize the type of metacognitive thought (planning, checking understanding, and so forth) expressed by the actor, or (c) to explain why that type of metacognition is important at that point in the actors’ dialogue.

Different versions of this assessment were given to students as pre-tests and post-tests, at the beginning and end of the school year. The versions were counterbalanced for the two occasions. Scoring was carried out using scoring rubrics that provide descriptions of three response levels. Level 3 responses give metacognitive interpretations of the students’ thinking in the movie, level 2 responses describe aspects that are related to the specific work of the students in the movie but do not exhibit metacognition, and level 1 responses are not reflections on the work issues facing the students in the movie. The inter-rater scoring reliability of scoring judgments ranged from 0.82 to 0.88 for the different items.

To test whether students’ prior metacognitive knowledge contributes to students’ development of knowledge and skills in scientific inquiry, we compared the effects of inquiry instruction for students with low and high metacognition test scores. Our measure of inquiry knowledge is the total score on the Inquiry Test, which was described earlier. For students with low metacognition scores (total scores below the median), there was an increase in mean scores from the pre-test to the post-test with an effect size of 0.30, but this increase was not significant ($p = 0.09$). Carrying out the same comparison for students with high metacognition scores (scores above the median), we found there was a significant increase in mean scores ($p < 0.001$), with an effect size of 0.55. These results were the same when we controlled for the students’ CTBS scores. Thus there is evidence that students with higher pre-test metacognitive capabilities show greater gains in learning inquiry within the curriculum than do students with lower metacognitive capabilities. In other words, students’ level of metacognitive expertise predicts who will gain the most from our inquiry curriculum.

We also tested to see if the students’ scores on the metacognition test changed as a result of participating in the inquiry curriculum using Inquiry Island. In this case, we found that there were no significant increases in mean scores on the Metacognition the Movie test. This finding led us to the question, “How do we develop all students’ metacognitive abilities so that they would be better equipped to learn using a resource such as Inquiry Island (or the Web of Inquiry)?”

The Metacognition the Movie test asks students to explain, in the context of collaborative inquiry situations shown in the movie, how metacognition is playing a role in inquiry
and to provide relevant metacognitive thoughts for particular situations that are shown. In the students’ work with Inquiry Island, metacognition is practiced primarily through self-assessment using the goal assessments contained in the Inquiry Island software. We hypothesized that adding additional activities in which students engage in collaborative metacognition in their research groups, such as taking on the roles of the various cognitive, social, and metacognitive advisors, will enhance the impact of the inquiry curriculum on students’ developing metacognitive capabilities, making them more broadly applicable. We investigated this hypothesis in a second study.

**Providing Additional Experiences for Students in Using Metacognition Through Role Playing**

To foster students' collaborative inquiry and regulation, we created additional curricular activities in which we used role playing as a way for students to learn the metacognitive skills of planning, monitoring, reflecting, and revising, while practicing them in their group work. We then implemented these ideas in a fifth-grade classroom in an urban public school that was also using Inquiry Island in teaching science through inquiry (White & Frederiksen, 2005a, 2005b).

The students in this class carried out two inquiry projects, and in between doing these projects, they engaged in the role-playing unit in their literacy groups. The purpose of the literacy groups was to understand a fictionalized biography through group discussion. Their discussion was structured as a collaborative inquiry task (with five steps: question, theory, evidence, synthesis, and application). This task was designed to be similar to steps in the Inquiry Cycle they were using in science. Finally, for their second inquiry project, the students carried out research on roles in which they created competing hypotheses about how role playing impacts a group's performance and functioning, and then designed and carried out investigations to see which of their hypotheses were the most accurate. Again they used the Inquiry Island software to guide them through these research projects.

The roles the students played in their literacy groups included cognitive roles (Theory, Evidence, Synthesis, and Application Managers), social roles (Collaboration, Communication, Mediation, and Equity Managers), and metacognitive roles (Planning, Productivity, Reflection, and Revision Managers). The roles are coordinated with the cognitive, social, and metacognitive advisors in Inquiry Island. In their reading groups, students started by playing the cognitive roles, went on to focus on the social roles, and finally played the metacognitive roles.

One-page guides for each role provided students with descriptions of the goals and problems associated with their role, the strategies for achieving each goal and avoiding problems, and “things to say” to implement each strategy (see Figure 10.4 for a sample guide). The students kept journals in which they were asked to plan, monitor, and reflect on the playing of each of their assigned roles. In these journals, and in the curriculum in general, playing a role successfully is defined as getting your group to achieve your role's goals.

Our findings reveal that the students engaged in substantial amounts of role playing in their groups, and that each student became capable of playing multiple roles in a given session. Students not only learned to use the roles they were assigned (or had chosen) to play, they also began to play roles they had never been assigned, which they had seen other students play. This shows that students can transfer the knowledge and capabilities they have gained for one role to playing new roles. As the curriculum progressed, the students' role playing became less verbatim (sticking to the guides in deciding what they would say) and more adapted (using their own words, which fit the context well). This suggests that
Figure 10.4 The guide for the role of Planning Manager.

<table>
<thead>
<tr>
<th>Planning Manager</th>
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</thead>
<tbody>
<tr>
<td><strong>Goals:</strong> The planning manager tries to help the group (1) decide on its goals, (2) develop a plan for achieving the goals, and (3) figure out who will do what.</td>
</tr>
<tr>
<td><strong>Goal 1: Decide on its goals</strong></td>
</tr>
<tr>
<td><strong>Problem:</strong> The group can’t figure out what it wants to do</td>
</tr>
<tr>
<td><strong>Strategy:</strong> Get the group to discuss what its goals should be</td>
</tr>
<tr>
<td>• What are we trying to do?</td>
</tr>
<tr>
<td>• What are our priorities?</td>
</tr>
<tr>
<td><strong>Goal 2: Develop a plan for achieving the goals</strong></td>
</tr>
<tr>
<td><strong>Problem:</strong> We don’t have a plan for how to accomplish our goals</td>
</tr>
<tr>
<td><strong>Strategy:</strong> Break the task into a sequence of steps</td>
</tr>
<tr>
<td>• What should we do first?</td>
</tr>
<tr>
<td>• What’s the next step?</td>
</tr>
<tr>
<td>• How should we do that step?</td>
</tr>
<tr>
<td><strong>Goal 3: Figure out who will do what</strong></td>
</tr>
<tr>
<td><strong>Problem:</strong> We can’t agree on who should do what</td>
</tr>
<tr>
<td><strong>Strategy:</strong> Share the work fairly, considering everyone’s interests and strengths</td>
</tr>
<tr>
<td>• Should we do all the work together, or should we divide it up?</td>
</tr>
<tr>
<td>• Who wants to take charge of this task?</td>
</tr>
</tbody>
</table>

they were internalizing the roles and were able to adapt them to new situations. When students first undertook each set of roles (social, cognitive, or metacognitive), there was relatively more talk about the goals and strategies for those roles, but as they became more experienced with them, problems and “things to say” increased in relative frequency, with “things to say” being by far the most frequently used component of the guides. This indicates a shift from talking about how to play a role to actually playing the role. In tests of role understanding and interviews, the students were able to talk about the goals and purposes of each role, about how the different types of roles could be used in new contexts, and about why they would be useful. Their journal entries show a significant increase \((p = 0.004)\), over the course of the curriculum, in their understanding of how to get the group to achieve a role’s goals. Taken together, these findings suggest that introducing activities in which students play managerial roles can develop young learners’ understanding of cognitive, social, and metacognitive capabilities. Students also appreciated the usefulness of the roles in monitoring a group’s functioning and in intervening to improve it.

When our inquiry curriculum was expanded to include this type of role playing, we found that there was a significant increase in students’ Metacognition the Movie test scores. Fifth-grade students in the school were given this assessment of metacognition at the beginning and end of the school year. The students who undertook this sequence of
pedagogical activities, including Role Playing and the Research on Roles, showed significant gains on this assessment of metacognition \( (p = 0.01) \) with an effect size of \( \sigma = 1.1 \), whereas fifth-graders in the school who did not participate did not show a significant gain \( (p = 0.37) \) with an effect size of \( \sigma = 0.3 \). The metacognitive behaviors depicted in Metacognition the Movie are related to the metacognitive roles the students played in the classroom, so this provides an assessment of whether students can transfer their understanding of metacognition to this new context.

Our findings indicate that students are able to write an appropriate metacognitive remark for a character in the movie, to characterize the type of metacognitive thought expressed by the actor in the movie, and to explain why the metacognition remark is important at that point in the actors’ inquiry project. This finding, coupled with the students having demonstrated an ability to pick up roles from others and to adapt their roles to new situations, supports the conclusion that the metacognitive knowledge students have developed through role playing is generalizable. Remember that we did not find any improvements in scores on the Metacognition Test for students who learned inquiry by using Inquiry Island without the role playing. Enacting cognitive models of metacognitive capabilities through students’ role playing in groups engaged in collaborative inquiry, and then having them do research on the utility of the roles, appears to increase students’ understanding of metacognition and its purpose.

**Learning Through Inquiry About Inquiry**

Perhaps our most important pedagogical goal in developing inquiry and metacognitive expertise is to transform students and classroom environments into self-aware, self-improving systems. We want students to become learners who create theories of their own practices—about what they are doing and why—as they engage in cycles of planning, monitoring, reflecting, and improving. There are a number of ways to enable students to do this, and they all involve an interesting metacognitive move: the recursive application of their inquiry and metacognitive processes in order to improve them.

When we work with students, we call this “inquiry about inquiry” or “research on learning.” Research on inquiry is often carried out around another inquiry that is going on in a group. In other words, two inquiries are going on at the same time: inquiry in the domain of study, and inquiry about how you develop knowledge through inquiry.

Inquiry about inquiry can take a number of forms, which can range from simply reflecting on weaknesses and thinking about how to improve, all the way to fully-fledged scientific inquiry, in which, for example, one invents new strategies and carries out controlled comparisons to determine which are the most effective. For instance, students may focus on a particular advisor's strategies, such as those of Molly Monitor, and evaluate them to see if they are helpful. If they are not, they can then modify them, perhaps by adding some new strategies to make the advice better. They could then test the new strategies as they do their next project, or have other groups try out the new strategies and study how well the strategies work for them. In doing experiments with advisors, they would be developing hypotheses, designing an investigation (thinking of data they will collect), and interpreting their findings in ways that will enable them to improve the advisor’s strategies. Testing the strategies on themselves is an example of reflective learning. Testing the strategies on others is essentially doing educational research.

The instructional idea, associated with this example of inquiry about inquiry, is to have students represent their ideas in the form of cognitive models that are embedded in the advisors. To test these ideas, they follow the advisor’s advice, or take on its role in their group, while the group undertakes an inquiry project. Students evaluate the group’s
ability to use the advisor's advice in various task situations and its usefulness in doing the tasks. They then use this information to revise the advisor, or to change their ideas for where it is useful. There is a built-in validity check to this process for improvement: if their ideas can't be enacted or aren't understandable, or if they are not functionally effective for the task at hand, students will have evidence that their ideas need to be revised. Thus they are applying their knowledge of inquiry to their own cognitive, social, and metacognitive processes needed for inquiry in order to improve them. White and Frederiksen (2005a, 2005b) provide examples of engaging fifth-graders in such inquiry about inquiry.

This notion of inquiry about inquiry is consistent with Schraw and Moshman's (1995) claim that it would be beneficial for students to develop explicit formal theories of their cognitive processes, as well as with Bandura's (1997) idea of self-experimentation and Scardamalia and Bereiter's (1983) notion of children as co-investigators who work with researchers to investigate cognitive processes (in Scardamalia and Bereiter's work, it was the cognitive processes needed for writing). Advocating for inquiry about inquiry represents an extreme position, arguing that not only will children benefit from developing explicit models of their own cognitive and metacognitive capabilities, but also that they will benefit from conducting theory-based, empirical research in which they test competing hypotheses about these capabilities and how to improve them. Our research indicates that this is possible and beneficial for young students (White & Frederiksen, 2005a, 2005b).

Concluding Thoughts

Due to the inherent complexities of scientific inquiry, students need to acquire meta-level expertise in order to engage successfully in the scientific enterprise. Unfortunately, the knowledge and capabilities needed to understand and regulate the processes associated with effective inquiry are often found lacking in students (Kuhn, Black, Keselman, & Kaplan, 2000). Thus it is imperative that we develop tools and teaching methods that emphasize critical metacognitive knowledge and processes. As we have illustrated, this can be accomplished by (a) defining and modeling these processes by providing software advisors that suggest appropriate goals and strategies to pursue, (b) giving students the opportunity to practice using and controlling these processes as they engage in authentic inquiry, (c) having students monitor and reflect on their performance using goal-related criteria, and (d) enabling students to investigate and refine these practices by conducting inquiry into their own inquiry-related processes and practices.

We have argued throughout this chapter that teaching scientific inquiry, infused with metacognitive knowledge and practices, enhances both science education and students' metacognitive development. Such an infusion of metacognition is crucial to effective science education, not only because it facilitates the learning of scientific inquiry, but also because it:

1. Fosters the learning of science and learning how to learn in general.
2. Builds an understanding of the nature of science and its methods.
3. Develops widely useful cognitive, social, and metacognitive capabilities.
4. Improves students' self-regulatory capabilities.
5. Fosters students' abilities to work together.
6. Helps develop students' theories of mind and community.
7. Leads to autonomous learners and learning communities.

Metacognitive practices such as self-explanation, in which students create explicit
conceptual models of scientific phenomena, play a role in the generation, understanding, and evaluation of scientific theories (Chi et al., 1989). Meta-representational expertise (diSessa, 2002, 2004) is needed to understand and use different epistemic forms to embody these theories, as well as to represent data in ways that enable students to evaluate and test their theories. Self-regulatory capabilities foster the learning and management of complex inquiry, which also develops students’ self-regulatory capabilities in general. For example, self-assessment practices can encourage students to monitor and reflect on how well they are testing their theories and considering alternatives. As we have shown, such self-assessment practices develop students’ understanding of inquiry processes, as well as motivating and guiding their improvement (White & Frederiksens, 1998, 2005a, 2005b). Taken together, such metacognitive practices improve students’ self-regulatory capabilities and foster their learning of science and learning how to learn in general.

Being exposed to and internalizing explicit models of the cognitive, social, and metacognitive capabilities needed for collaborative inquiry and reflective learning develops skills such as theorizing, investigating, and reflecting (White & Frederiksens, 2005a, 2005b). These models can be embodied by software advisors, like the Investigator and Reflector, or they can become roles that students play, like the Evidence Manager and Reflection Manager (White & Frederiksens, 2005a, 2005b). Alternatively, they can be embedded in scientists’ journals that have been created to illustrate these processes in action (Magnusson & Palincsar, 2004). Acquisition of such cognitive and metacognitive skills creates capable individuals, who can engage successfully in generating theories, evidence and arguments as they employ processes that are useful, not only for scientific inquiry, but for learning, problem solving, and critical thinking in general. In addition, getting students to undertake research projects, in which they investigate alternative models for such inquiry processes and metacognitive practices, not only enhances students’ awareness of these capabilities, but also provides a path to their development and improvement.

Students learn how to approximate a scientific community as they work together on research projects, engaging in many of the practices of a scientific community (Brown & Campione, 1996). The intertwining of metacognition and inquiry helps to develop a classroom community that is highly aware of the status of its theories and methods, can employ and manage them productively, and is constantly trying to improve all of these. This not only helps students learn how to collaborate, it also leads to a better understanding of the nature of science and its methods, and to an understanding of mind and community in general. Extended immersion in such a learning environment should result in a classroom community that is composed of capable, autonomous learners, who have greater feelings of self-efficacy (Bereiter & Scardamalia, 1987) and can collaborate effectively (Borge, 2007).

The vision is to create students and classrooms that are self-aware, self-improving systems, who create theories about what they are doing and why, as they constantly engage in cycles of planning, monitoring, reflecting, and improving. This can include science classrooms in which students develop and test theories about themselves and their social systems, as well as about the physical and biological world. Conducting research into their own metacognitive practices, for example, is a route to enabling students to learn about scientific theorizing and inquiry, while also fostering their metacognitive development.

Furthermore, introducing students to the idea that they and their communities can be improved, and teaching them how to do this through scientific inquiry intertwined with metacognition, should lead them to an important realization: You don’t have to be “born smart.” Instead, students can learn how to become more capable individuals and better functioning communities of learners (Dweck & Leggett, 1988). Such a realization should further increase students’ feelings of self-efficacy and motivate them to develop the
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...ing, expertise needed for collaborative inquiry and reflective learning, which should serve them well throughout their lives.

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