10 The Interplay of Scientific Inquiry and Metacognition

More than a Marriage of Convenience

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The scientific enterprise is a form of collaborative learning that enables society to develop knowledge about the world—knowledge that is useful for predicting, controlling, and explaining what happens as events occur. Creating scientific communities in classrooms, by engaging young learners in theory-based empirical research, is a highly challenging yet important educational goal (Anderson, 2002; Blumenfeld, Soloway, Marx, Krajcik, Guzdial, & Palincsar, 1991; National Research Council, 1996, 2007; Schraw, Crippen, & Hartley, 2006). To achieve this goal, and enable students to learn about the nature and practices of scientific inquiry, the development of metacognitive knowledge and capabilities is crucial.

In this chapter we outline the metacognitive expertise that is needed to understand and regulate inquiry processes as students undertake research projects, and we elaborate why developing this type of expertise is important. We present evidence that students’ learning of scientific inquiry can be enhanced by providing them with explicit models of inquiry goals and strategies, while also teaching them self-regulatory processes. This approach is particularly effective for lower-achieving students.

Explicit models of inquiry and metacognitive expertise can be embodied in educational software as advisors, like the Theorizer and Reflector, which define and promote effective inquiry processes. For example, advisors can suggest appropriate goals and strategies to pursue, give examples of strategies in action, and provide criteria for monitoring their effectiveness. In addition to guiding students as they undertake research projects, the software advisors can be adopted, tested, and modified. For example, students can take on the role of an advisor in their research groups, so that one student becomes the Theory Manager, another the Reflection Manager, and so forth. Furthermore, students can undertake research projects in which they create and test competing models of their expertise.

They may, for instance, compare different strategies for generating theories or for reflecting on their inquiry processes. In this way, students invent and test their own conceptions of how to do various aspects of inquiry, how to learn through inquiry, and how to monitor and reflect on their progress. We provide evidence of the pedagogical utility of such role playing and “inquiry about inquiry,” which engages students in the recursive application of scientific inquiry and metacognition to foster the development of both types of expertise.
Metacognition and Scientific Inquiry

Ann Brown (1987) identifies two basic types of metacognitive expertise. The first is knowledge about cognition, which could be called self-understanding. It includes knowing what you know and don’t know, as well as how you learn, through processes like scientific inquiry, to increase your understanding of the world. The second type of metacognitive expertise is related to managing and improving your cognition and is often called self-regulation. It includes planning, monitoring, and reflecting, which includes being able to plan a research project, monitor your progress, and think about how you could do better next time.

**Knowing What You Know and Don’t Know**

Engaging in successful scientific inquiry requires developing metacognitive capabilities, such as being able to use conceptual models to generate explanations and check for understanding (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). Engaging in such practices not only facilitates students’ learning of inquiry, it also fosters their metacognitive development. If students are going to become proficient at scientific inquiry and learn how to understand a domain deeply, it is important that they be able to recognize gaps and inconsistencies in their conceptual models for understanding a particular domain. We have been struck by the finding that some students simply grab onto the first idea that occurs to them and stick with it, while others recognize the limitations in their understanding and pursue alternative ideas. Furthermore, figuring out how different ideas fit together, and whether in fact they do fit together, is critical. Unless students learn to recognize anomalies and contradictions, and are motivated to pursue them deeply enough to resolve such discrepancies, it is unlikely that they will be able to engage in successful scientific inquiry and build coherent conceptual models of complex domains.

**Knowing How You Learn Through Inquiry**

It is also important that students develop meta-knowledge about inquiry itself. Knowing about the nature and practices of scientific inquiry fosters proficiency in doing science, as well as in appreciating the role of science in the evolution of our societies (National Research Council, 2007). Such meta-level expertise includes knowing about the nature of scientific theories and questions, understanding the different types of investigations and data analyses that are possible, and appreciating the role that each type of investigation and analysis can play in testing hypotheses and in developing and refining models and theories.*

* Like many words in the English language, the terms “model” and “theory” have multiple meanings. When we use the term “model” or “conceptual model” as a noun, we mean a representation of a system that characterizes its structure or behavior, which can include rules, representations, and reasoning structures that allow one to predict and explain what happens as events occur. The scientific use of the word “theory” is similar to our definition of the term “model,” although theories may be thought of as more comprehensive and models as more specific. In this chapter, we argue that the goal for scientists and students is to create comprehensive theories, which include components of different types (such as concepts, predictive laws, and explanatory models), as well as interlinked models that embody different perspectives (such as macroscopic and microscopic). However, we also use the term “theory” to refer to initial, tentative ideas about the nature and causes of phenomena, particularly when we are referring to the theories that students are creating and testing. These typically include key variables (concepts), predictions, and explanations, but they are not necessarily comprehensive theories that have evolved to encompass and integrate different perspectives.
Managing Your Cognition

To engage in successful inquiry, it is also essential that students learn planning, monitoring, and reflection techniques (Azevedo & Cromley, 2004; Schunk & Zimmerman, 1998; Zimmerman & Schunk, 2001). Careful planning, for example, is crucial to many aspects of scientific inquiry, ranging from designing an investigation to determining how to analyze the resulting data. In designing an experiment, for instance, students must determine all of the steps that need to be completed. As part of their planning process, they need to learn to envision the possible outcomes for their experiment to make sure that it will enable them to determine which hypotheses are supported and which are not.

As learners carry out scientific inquiries, they need to monitor a range of things, including inquiry processes and products, progress at achieving goals, and metacognition itself. These can be monitored by getting students to ask themselves a variety of questions. For instance, Schoenfeld (1987) has students ask themselves three high-level metacognitive questions: (a) what are we trying to do; (b) why are we trying to do that; and (c) are we making progress? One can also ask students to monitor their achievement of widely applicable cognitive, social, and metacognitive goals, such as: Are we (a) reasoning carefully, (b) collaborating effectively, and (c) monitoring our progress sufficiently? It is also important for students to learn to monitor and evaluate their work using more focused criteria that characterize good work for each aspect of inquiry. For example, such self-assessment, in the context of arguing for a particular scientific explanation after doing an investigation, might include asking: (a) does our explanation address our research question; (b) does it seem convincing; and (c) does it fit the experimental findings? There are a large number of such monitoring questions that students should ask themselves as they engage in scientific inquiry, and doing so plays a role in carrying out good research and in coming to understand its nature and purpose.

Improving Your Cognition

Reflection can be used as an opportunity to improve the processes of inquiry, including the metacognitive practices it requires. Engaging in collaborative reflection, after students have completed a research project for example, can get them to think about how they could improve their processes for generating competing hypotheses or their processes for planning an investigation to test their hypotheses. In this way, students can become reflective practitioners (Schön, 1983) of scientific inquiry and gradually, over time, improve their inquiry practices and their understanding of their goals and purposes.

Metacognition and the Teaching of Scientific Inquiry

Unfortunately, not enough emphasis is placed on the development of metacognitive practices in the national curricular standards for science education. The standards put forward by the National Research Council (1996), for example, emphasize developing knowledge of a domain through inquiry, but they place far less emphasis on the need for metacognitive knowledge and skills. Yet increasingly, research has shown that metacognitive expertise is needed in developing knowledge through inquiry (Chinn & Malhotra, 2002; Frederiksen & White, 1997; Georghiades, 2004; Hogan, 1999; Kuhn & Pearsall, 1998; White & Frederiksen, 1998), and is critical in transferring one’s capabilities for learning in one domain to learning in new domains, as well as taking charge of one’s own learning (Bransford & Schwartz, 1999; Scardamalia & Bereiter, 1991). There is also evidence that feelings of self-efficacy in learning play a strong role in students’ motivation.
and interest in learning (Bandura, 1997; Pintrich & de Groot, 1990; Schunk & Schwart, 1993). Building metacognitive knowledge of oneself as a learner contributes to viewing oneself as an able learner (i.e., it develops self-efficacy), which influences not only success in learning, but also motivation to learn (Brown, 1988; Corno, 1986; Zimmerman, 1989; Zimmerman & Schunk, 2001).

Our basic thesis is that to become an effective inquirer, a person must develop the various types of metacognitive knowledge and capabilities that we outlined above. Science education needs to take metacognition seriously in order to educate students effectively (Baird, 1986; Baird & White, 1996; Schraw, Crippen, & Hartley, 2006; White & Gunstone, 1989; Yore, Pimm, & Tuan, 2007). To date, an emphasis on students' metacognitive development has been largely missing from the teaching of science in the vast majority of classrooms.

In recent years, however, educational researchers have been pursuing various approaches to addressing this need. For example, there have been a number of attempts to promote metacognition through computer scaffolding as students try to generate and refine scientific explanations (e.g., Graesser, McNamara, & VanLehn, 2003; Quintana, Zhang, & Krajcik, 2005; Sandolov & Reiser, 2004; Schwartz et al., this volume). Other researchers have investigated the utility of providing prompts, and other devices, to foster students' reflection and self-regulation as they work on science projects (e.g., Davis, 2003; Loh, Radinsky, Reiser, Gomez, Edelson, & Russell, 1997; Toth, Suthers, & Lesgold, 2002).

Some researchers have tried to make the nature of scientific theories more explicit to students (e.g., Lehrer & Schauble, 2005; Perkins & Grotzer, 2003; Schwarz & White, 2005; Slotta & Chi, 2006), while others have emphasized making inquiry processes more explicit (e.g., Blank, 2000; Linn, Davis, & Bell, 2004; Metz, 2004; Schauble, Glaser, Duschl, Schultz, & John, 1995; Smith, Maclain, Houghton, & Hennessey, 2000). Finally, some researchers have fostered students' understanding of the scientific enterprise by employing a “community of learners” approach, which emphasizes collaborative inquiry and knowledge building (e.g., Brown & Campione, 1996; Herrenkohl, Palincsar, Dewater, & Kawasaki, 1999; Hogan, 1999; Metz, 2000; Scardamalia & Bereiter, 1994). Such approaches can be highly successful at developing students' understanding of science, thereby meeting important goals for science education, while also symbiotically fostering students' metacognitive development.

In what follows, we outline some of the different types of meta-level knowledge and capabilities needed to understand and do scientific inquiry. Then we present examples of how such meta-level expertise can be fostered and utilized in science teaching, and explain, in more depth, why we think metacognition should be an integral component of science education.

Meta-Knowledge of Scientific Inquiry

Scientific inquiry can be viewed as a process of oscillating between theory and evidence, in a practice of competitive argumentation that leads to the development, testing, and elaboration of scientific laws, models, and theories. The ultimate goal is to create alternative theories and develop arguments that employ explanations and evidence to support or refute those theories (cf., Carey & Smith, 1993; Driver, Newton, & Osborne, 2000; Duschl, 2007; Duschl & Osborne, 2002; Kuhn, 1993; National Research Council, 2007). The transition from making theories to seeking evidence, through an investigation, is one where the generation of questions and hypotheses derived from theory is crucial. The transition from carrying out an investigation to the refinement of a theory is one in which data analysis and synthesis are central. This view leads to a basic model of
scientific inquiry that has four primary processes: (1) Theorizing, (2) Questioning and Hypothesizing, (3) Investigating, and (4) Analyzing and Synthesizing. Associated with each of these primary processes is a regulatory process that monitors how well the process is being carried out and whether another process should be invoked to deal with issues that arise.

In our earlier work on teaching scientific inquiry to young learners, we portrayed such a model as an Inquiry Cycle, which provides a scaffold for inquiry in the form of a series of steps that one undertakes in a never-ending cyclical process of generating, testing, and elaborating scientific principles and models, with the ultimate goal of developing a widely useful, accurate, and comprehensive theory for a given domain. This is, of course, a simplified view: mature scientific inquiry does not necessarily proceed in this step-wise fashion. For one thing, it is possible to start anywhere in the sequence. So, for example, one might start with vague questions that are not based on a particular theory, or one might start with an investigation or with existing data to generate theoretical ideas. Furthermore, one does not necessarily proceed through these “steps” in order. For instance, analyzing data can lead to the need to do further investigation. So the critical elements in the scientific enterprise are closely intertwined and any view of science education that underplays one of these elements fundamentally misleads students as to the nature of science (Chinn & Malhotra, 2002). Nonetheless, for pedagogical purposes, presenting students with an inquiry cycle, in which one starts with theorizing and questioning, is an effective initial model that can enable students to develop capabilities for inquiry, as well as an understanding of its constituent processes (White & Frederiksen, 1998, 2003a, 2003b).

In the next four sections, we briefly describe meta-scientific knowledge in terms of its four components: meta-theoretic knowledge, meta-questioning knowledge, meta-investigation knowledge, and meta-analysis knowledge (note that we do not mean “meta-analysis” in the statistical sense). We should emphasize though that meta-questioning knowledge includes meta-knowledge about forming both research questions and hypotheses, while meta-analysis knowledge includes meta-knowledge about data analysis, synthesis, and argumentation.

This model of scientific inquiry reflects the way most sciences include two camps: the theoreticians and the empiricists. Theory and empirical investigation form the two poles of science. Research questions form a bridge between these two poles, in which competing theories generate alternative hypotheses that are tested through empirical investigation. Analysis and synthesis form the other bridge between the poles by providing ways to represent and interpret data from the investigation to bear on the theories in competition.

**Meta-Theoretic Knowledge**

Meta-theoretic knowledge includes knowledge about the nature of scientific models and theories. In their work on epistemic forms and games, Collins & Ferguson (1993) characterized three types of models (or epistemic forms) that researchers use to guide their inquiry: structural, causal (or functional), and dynamic (or process) models. The different forms of structural models include hierarchies, cross-product tables (e.g., the periodic table), stage models, primitive elements (e.g., chemical elements), and comparison tables. Similarly there are different types of causal models, such as causal chains, form-function analysis, and multifactor models (as in medicine). Finally there are different dynamic model types, such as system-dynamics models, production systems (situation-action rules), and agent models. All of these representational forms have epistemic games (i.e., rules and
strategies) associated with them, which are practices scientists use as they construct models to characterize and theorize about different phenomena.

Different model types serve different purposes. Structural models highlight the relationships between different elements in the models. Causal models depict the causal and functional dependencies between elements in the models. Dynamic models allow one to “run” models to see the consequences of different assumptions and principles embodied in the models. These runnable models can unpack mechanisms that explain the causal relationships depicted in static causal models.

Scientific theories in our view are made up of a number of linked models. In chemistry, for example, the primitive elements (hydrogen, helium, etc.) are arranged in a cross-product table (i.e., the periodic table). There is an underlying atomic structural model of protons, neutrons, and electrons arranged in shells that accounts for the structure of the periodic table. There are also constraints that determine how different elements combine into molecules, based on their atomic structure. Hence the standard theory in chemistry is made up of different types of models linked together in systematic ways.

Frederiksen and White (2002; Frederiksen, White, & Gutwill, 1999) have shown how different models of electricity are linked together, in particular how circuit diagrams, constraint equations, local-flow models, and four other model types capture different aspects of the behavior of electrical systems. These models are linked in three different ways. First of all, models are linked vertically when the behavior of one model type is derivative or emergent from the behavior of another model type (Wilensky & Resnick, 1999). For example, Frederiksen and White (2002) describe how the behavior of constraint systems can be derived from the local-flow model of electricity they present. Secondly, models are linked horizontally when there is a “progression of models” (White & Frederiksen, 1990), such that a higher-order model is derived from a lower-order model by adding new rules or entities. For example, a simple local-flow model of circuit behavior allows people to solve problems about serial circuits, and an elaboration of the model allows people to solve problems about serial, parallel, and hybrid circuits. Finally, models are linked in a coordinated way when the models represent distinct characteristics, or perspectives, of a system in compatible ways (White & Frederiksen, 1990). For example, circuit diagrams and constraint equations represent different aspects of an electric circuit, but the two representations for any given circuit must be coordinated.

Given the growing importance of modeling in science education (Gilbert, 1991; Halloun, 2004; Hestenes, 1987; Lehrer & Schauble, 2000; Mellar, Bliss, Boohan, Ogborn, & Tompsett, 1994; Schwarz & White, 2005; Smith, Snir, & Grosslight, 1992; Stewart, Cartier, & Passmore, 2005; White, 1993; Windschitl, Thompson, & Braaten, 2008), we think it is critical that students learn about the different forms that models can take and how different models can be linked together to form a coherent and powerful theory. Hence, the essential meta-theoretic knowledge that people need to learn is how theories and models are created, refined, and coordinated. We think these various pieces fit together to form the basis for the development of meta-theoretic knowledge in science.

Meta-Questioning Knowledge

In order to evaluate theories, it is necessary to turn elements of the theories into research questions that can be directly investigated. Sometimes research questions are quite vague (e.g., What are the precursors to heart disease?) and sometimes the questions are specific (e.g., Does taking a particular drug reduce one’s cholesterol level?). The hypotheses in any study are the different possible answers to a research question based on alternative theoretical positions or assumptions. Ideally, the different answers and their implications
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should be specified in advance of the investigation. However, if a research question is vague, this may not be possible.

The different epistemic forms (i.e., types of models) generate different types of research questions. For example, structural models generate questions such as: What are all the different types of X, and what stages does X go through as it evolves? Causal models generate questions such as: Does Y cause X? or What are all the factors that affect X? Dynamic models generate questions such as: What process produces X? and What are the rules of interaction between X and Y? These are some of the most common research questions that arise as scientists create models to express and develop their theoretical ideas.

Ideally research questions help to differentiate between possible theories. Finding crucial questions that in fact distinguish between alternative theories is very difficult. And when a crucial question is investigated, the researchers whose theories are not supported by the data usually can come up with some explanation that still preserves their theory, albeit in a modified form. But even in investigations that do not compare alternative theories, researchers have to come up with questions and data that enable them to differentiate their explanations for their findings from obvious alternative explanations that other researchers might generate.

When one research question is answered, it often raises a set of related questions. One way this occurs is when a particular structural pattern is found, as when Mendeleev discovered the periodic table, it raised the question of why the elements in a single column have similar properties. This question led eventually to the model of the atomic structure of atoms. Similarly a causal model, such as a multifactor model, raises questions about the mechanisms that lead each of the factors to have the given effects. These two examples show how answering one research question can lead researchers to generate related questions about underlying processes, structures, and mechanisms.

The metad-questioning knowledge that students need to acquire includes learning about the different types of research questions that can be asked, and how each type of question is related to particular epistemic forms. Students also need to develop an understanding of how questions can be created to distinguish between competing theories and how, in the process of creating a deeper, more coherent theory for a domain, one question leads to another.

**Meta-Investigation Knowledge**

The third element of scientific meta-knowledge is an understanding of the different forms that scientific investigations can take. There are many different investigation methods, but they generally fall into two basic types: (1) exploratory inductive investigations (often referred to as scientific induction) and (2) confirmatory investigations (often referred to as the hypothetico-deductive method). Exploratory inductive investigations are employed when one has broad research questions and some general theoretical ideas that suggest interesting data sources to study, but which are not specific enough to generate particular hypotheses. The goal is to obtain data that will constrain one’s efforts to develop more detailed theories. Confirmatory methods are used when one has a well-developed theory or set of theories in mind, which allow one to develop a set of theoretical hypotheses to test. The goal is to test each of the hypotheses to see if the findings are consistent with the theoretical predictions. This allows one to determine which theory or theories are most consistent with the data and which are not suitable for explaining the phenomena that have been investigated.
Inductive Investigations

Galileo is famous for developing exploratory inductive methods in science. In his experiments on pendulums and gravity, he systematically varied the elements that he thought might affect the period of the pendulum and the speed of a ball rolling down an incline. From these exploratory investigations, he derived equations for the motion of pendulums and falling bodies. The Framingham Heart Study is a modern variation on his method, using natural variation rather than controlled manipulation. The investigators in this study collected data from many people in Framingham, Massachusetts, on a large number of variables that they thought might influence the likelihood of getting heart disease. They then followed the people over many years to see if they developed heart disease and identified a number of variables that were precursors to heart disease.

In exploratory inductive investigations, different methods and data sources are often used to cover the phenomena of interest in order to construct a more robust theory. Dewey (1910, Chapter 7) suggested three principles for regulating the observation and collection of data in forming "explanatory conceptions or theories" that seem to be wise advice today: (1) Care must be taken in differentiating between what is observed and what is inferred, so as not to jump to hasty conclusions about one's theory. (2) One needs to look for multiple cases to see how general one's conclusion is, but one also needs to look for contrasting cases in order to determine the factors that are critical to the conclusion. (3) One needs to look for exceptions and contrasts that may challenge one's initial conclusions and suggest others. One often learns more from examining anomalous cases that don't have the expected features. (This principle is similar to having control conditions in a confirmatory investigation or experiment.)

Even when following these principles, a limitation of such exploratory investigations is that the researchers may still have systematic biases in what data are collected and in how they are interpreted. This is why confirmatory studies are critical to the development and refinement of scientific models and theories. In carrying out exploratory research, it is important to be aware of how one employs one's theories in selecting and interpreting data. Confirmatory investigations that test hypotheses are needed to evaluate the accuracy of a theory's predictions and to resolve conflicts between different theories.

Confirmatory Investigations

Confirmatory investigations, which are designed to test theoretical hypotheses, can take many different forms. The most common is the randomized controlled trial, in which one or more proposed hypotheses are tested by comparing conditions that correspond to each of the hypotheses one is testing. Often such a test of a hypothesis contrasts an "experimental" condition, which includes some particular feature, with a control condition that lacks that feature. In order to ensure the generality of the findings, multiple experimental units (test trials, subjects tested) are assigned randomly to different conditions and then compared to see if differences in a dependent variable are consistent with what was predicted by the hypothesis. Often special efforts are made for controlling variables that one thinks might also affect the results. Confirmatory studies are also critical in determining the boundary conditions for a theory—that is, the range of situations over which a theory applies.

Studies designed to confirm or test hypotheses are best suited for situations where there are a small number of hypotheses and variables. When situations are complex, investigators may only be able to test a few specific predictions of a theory. Many confirmatory studies simplify or standardize the situation and collect a large amount of data, hoping
that factors that have not been controlled are contributing randomly to the effects being investigated and will not affect the group averages in any systematic way. Another way to deal with complexity is to use multivariate methods, such as regression or covariance analyses. The intent in these methods is to control complexity by taking into account, through statistical adjustments, factors other than those specified in the hypotheses that might have effects on the results.

We have argued that exploratory inductive studies help in constructing theories, whereas confirmatory investigations are used to test hypotheses that represent competing theories; however, the process is really cyclical. Often confirmatory studies, especially if they include collecting rich data, provide clues for further theory development through an embedded inductive investigation of those data. This can lead to theory refinement and suggest new confirmatory investigations that can further refine and test the theory. Thus in scientific inquiry, testing hypotheses deduced from theories, and interpreting patterns in data to construct new theories, are intertwined. This process is complex and depends on meta-knowledge of the forms of inquiry one is engaging in at a given time, and how they are interrelated as one moves from one form of investigation to another. Meta-investigational knowledge also makes one aware of the pitfalls and limitations of the forms of investigation one is using at any particular time.

**Meta-Knowledge for Data Analysis**

The main purpose of data analysis is to support the development of convincing arguments, which show how the findings from an investigation support particular conclusions and have implications for theories. Data analyses are systematic procedures for examining the information obtained in an investigation. These procedures can best be understood by the research functions they support: (a) the representation of data, (b) the confirmation or refutation of existing hypotheses, (c) the induction of new hypotheses, and (d) generalization.

**Representing Data to Reveal Patterns of Theoretical Interest**

Following the collection of data in an investigation, one needs to create useful data representations, which code and display data in ways that (a) reveal if patterns that are predicted by a theory are present, or (b) reveal new patterns that may require modifications or additions to the theory. In order to see patterns, data obtained in different situations need to be represented using similar measurements or coded qualitatively using similar categories. This makes it possible to make comparisons of data across different situations.

There are many kinds of patterns in data, paralleling the many kinds of relations among factors or variables that are generated by theories or models. In complex, multi-variable data sets, the number of pair-wise relations among variables can be great, and the possibility of interactions among variables increases the number of possible patterns even further. Experience in reading other investigators’ data analyses will lead to creating a “library” of forms for displaying data (cf., Giere, 1991). For instance, a graph of average values obtained before and after a treatment, shown for two different treatments, may be a good way to see if there is an interaction between treatment and effect.

Exhaustively searching for meaningful relationships is often impractical. The particular tools one uses in data analysis to reveal patterns are often guided by the epistemic forms of the models one has in mind. Here choices of epistemic forms and data analysis methods are entangled: you see data patterns through analyses that are themselves suggested by theories. In arguing for a particular interpretation of data, you need to be
cognizant of how other investigators with different theoretical orientations might interpret the data. One of the most difficult things in data analysis is to be able to "put on the hat" of a different theorist and consider alternative forms of analysis which that might entail.

Confiring (or Disconfirming) Hypotheses

To test hypotheses, one needs to obtain evidence of the soundness of each competing hypothesis. Patterns found in data provide evidence for whether a hypothesis is confirmed or disconfirmed. Confirming a hypothesis increases confidence in the theory's accuracy, but does not confirm the theory itself, because other theories might be constructed that lead to the same prediction and hypothesis. However, disconfirming a hypothesis can support an argument for rejecting the associated theory. Popper (1963) argues that strong theories are subject to refutation when tested, but can never be fully confirmed. Theories that are not fully specified are hard to disconfirm, because they can be augmented to account for facts that had been left out. Having meta-knowledge of the theoretical status of confirming and disconfirming evidence for a theory should help investigators to be careful in making inferences based on findings. It also motivates investigators to consider alternative hypotheses when they are designing their investigation.

Induction: Exploring the Data to Uncover New or Unanticipated Phenomena

Often results reveal patterns that suggest new relationships among variables or factors that have interesting theoretical interpretations. If such a pattern is first noticed in a subset of the data (for example, in studying a particular case), one seeks to verify it by exploring its presence in other sets of data that are available. Finding unanticipated phenomena or relationships among variables may provide further support for one's current theory, or suggest ways to augment the theory, or require the invention of new theories. In searching for interpretable patterns, meta-theoretic knowledge can be very useful. For instance, one might think of a particular epistemic form, such as stage theory, as a way to look for patterns (Collins & Ferguson, 1993).

Generalizability: Establishing the Generality of the Findings

Theories are expressions of relationships that have general applicability across a range of situations. In scientific inquiry, establishing the generality of a theory is important. Commonly, one obtains data from a sample of different situations, or individuals, to provide evidence for the consistency of the results that are predicted by the theory across the range of circumstances to which it purportedly applies. However, a theoretical argument for the generalizability of a conclusion to other situations can also be made. This can take the form of specifying the conditions that are necessary for a conclusion to apply, with the implicit suggestion that other factors not mentioned are irrelevant.

All of these functions of data analysis are applicable and important, whether or not the data that are collected are quantitative measures of variables, detailed qualitative recordings or field notes, or a mixture. Data collected should allow researchers to test specific hypotheses, while at the same time supporting in-depth studies of the underlying processes. This is why many scientists keep extensive laboratory or field notes when they are conducting their investigation. Displaying data using multiple forms makes it possible to see different patterns. Ideally the researchers should be able to synthesize findings of all
their analyses to produce a coherent interpretation, or argument, that supports a particular theory, one which provides a better account than other, competing theories.

**Metacognitive Control of Inquiry Processes**

The inquiry process is complex. In carrying out research, one draws upon meta-knowledge of the top-level structure of inquiry and of its constituent processes: knowing about the forms that theories can take, developing questions and hypotheses that can test implications of theories, managing multiple goals and strategies for designing an investigation, analyzing data, and so forth. It is clear that inquiry involves the interplay of a large repertoire of processes, each with its underlying goals and strategies. To manage this system, one needs to understand when, why, and how the various processes are engaged in the course of carrying out an investigation, what are the products that are created by each process, and how those products are used as “inputs” for other processes. One also needs to have metacognitive expertise for controlling and improving inquiry, that is, knowledge and capabilities for self-regulation.

Zimmerman (1998) describes self-regulation as having three major phases: (a) forethought, (b) performance or vocational control, and (c) self-reflection. Forethought includes goal setting and strategic planning. Performance control has two aspects: (1) self-control, which includes deciding how to proceed in attending to and carrying out a task, and (2) self-monitoring, which is judging how well your processes for achieving the task’s goals are working. This helps you decide whether to try a different way to achieve the goal, and whether the products of your work are good enough to move on to another inquiry task or goal. Self-reflection refers to evaluating one’s performance of inquiry tasks, using particular criteria for each task, in order to identify ways to improve one’s inquiry products and processes. By choosing criteria carefully, students’ reflection can be directed towards developing inquiry meta-knowledge, which includes understanding the goals and purposes of the various inquiry processes as well as how they are interrelated. Self-reflection is useful as a basis for self-monitoring at all levels in the inquiry process, for instance in judging the quality of the design for your investigation, or in considering how well you have accomplished a sub-goal, such as choosing dependent and independent variables. This means that the self-regulatory system is used recursively throughout the sequential and hierarchical levels of inquiry (cf., Winne & Hadwin, 1998).

In general, we believe that for students to engage in self-regulated inquiry, they not only need to be provided with a means for developing the meta-knowledge of inquiry we have described, they also need to have explicit performance standards for each of the goal-directed processes in which they are engaged. Reflection is therefore central to both understanding and managing the movement through this network of inquiry processes. Participants in a classroom research community need to be involved explicitly in a reflective process in which they review their processes of working and the products of their investigation at every stage of their work. This reflective process should be a social one, so that students may see how multiple perspectives can be applied in viewing one’s own and others’ work as they carry out the processes of inquiry. This social process allows students to practice and internalize habits of reflection (Vygotsky, 1978).

The importance of such metacognitive behavior has been emphasized by researchers (e.g., Brown & Campione, 1996), who maintain that monitoring and reflecting on the process and products of one’s own learning are crucial to successful learning as well as to “learning how to learn.” Research on learning shows that many students, particularly lower-achieving students, have inadequate metacognitive processes and their learning suffers accordingly (Campione, 1984; Chi et al., 1989; Zohar & Dori, 2003). Thus,
if you introduce and support such reflective, metacognitive processes in the curriculum, the students’ learning and inquiry should improve, at the same time as they develop self-regulatory capabilities and meta-knowledge about scientific inquiry.

**Approaches to Developing Students’ Meta-Knowledge in Science Education**

There is strong evidence that students and many adults have great difficulty in understanding the nature and relations among theories, hypotheses, and evidence (Carey & Smith, 1993; Smith & Wenk, 2006). This is viewed as a major handicap in understanding the nature of science, and it is also critical knowledge for carrying out scientific inquiry. Yet there is also evidence that young people can develop an understanding of the role that theories play in investigating and developing an understanding of the world (Smith et al., 2000). We believe that by bringing meta-knowledge about science and reflective metacognitive practices together within a rich learning environment, students will be able to develop these kinds of knowledge and capabilities and use them in inquiry.

There are a variety of ways to foster metacognitive knowledge and capabilities in students. Metacognitive thinking can be modeled so that students can see metacognition in action (Schoenfeld, 1983; 1987). Teachers can encourage and scaffold metacognitive practices. A common technique is to prompt students to do a metacognitive task, such as evaluating whether they have identified all possible outcomes to an experiment. Getting students to take time to reflect is also a productive way to encourage students to be more metacognitive. Sometimes metacognitive thinking is promoted and scaffolded by a metacognitive tool, such as a research journal, to prompt students to plan, monitor, and reflect on their work. In addition, as we will argue later, getting students to invent and investigate metacognitive processes themselves may be an effective way to foster metacognitive thinking and development. In all of these approaches, the aim is to introduce metacognitive practices into the culture of the classroom. This can include engaging students in collaborative planning, peer assessment, and collective reflection as they work together on research projects. In this way, students and teachers can model and support a range of metacognitive processes that facilitate scientific inquiry and learning. We argue that each of these methods can do this effectively if, in some way, it provides meta-theoretic information and insights about the inquiry processes in which students are engaged.

**Learning by Studying a Scientist’s Notebook**

One example of a metacognitive approach is Magnusson and Palincsar’s (2004) design and study of an innovative form of science text, which should help students in learning inquiry science while also promoting literacy. They first carried out an analysis, which revealed many parallels between the processes used in constructing knowledge in text comprehension and those used in learning through inquiry. However, they also found that that texts used in science instruction are more concerned with the presentation of information rather than with how scientific information is developed. In response to this mismatch, they developed a new type of text that is intended for use in inquiry-based science classes. It illustrates both the processes of scientific reasoning used in scientific inquiry, and the metacognitive skills needed to enlist appropriate learning strategies and monitor their success in constructing meaning.

The text is modeled after the notebook of a fictitious scientist, named Lesley, who uses her entries to (a) identify the phenomenon she is investigating, (b) think aloud about how she can accurately model the phenomenon for the purposes of investigation, (c) make decisions
about how she will most effectively represent the data that she is collecting, (d) share her data and the claims that she believes she can make from these data, (e) respond to the critical reactions of her colleagues as they weigh the evidence for her claims, and (f) revise her thinking as she gathers new data or considers alternative explanations. These kinds of entries in the notebook represent important forms of scientific meta-knowledge. For example, the notebook illustrates metacognitive practices that are used in carrying out inquiry through Lesley’s evaluations and revisions during the course of her investigations. In one illustration, Lesley has identified a set of claims based upon her preliminary evidence. Subsequently, with the urging of her peers, she collects more precise data, which lead her to revise her initial claim. This kind of modeling of a scientist’s metacognitive thinking shows learners how to monitor and reflect on their work as they carry out scientific investigations. The notebook also illustrates the social nature of scientific deliberation.

Magnusson and Palincsar carried out studies showing how using notebook texts, along with carrying out inquiry, facilitates students developing scientific concepts of knowledge construction, while also gaining a “critical stance” towards text comprehension and metacognitive capabilities, such as checking their sense-making and choosing strategies to improve their understanding. For example, in one class, students investigated how light interacts with objects while they were also reading Lesley’s notebook, and they compared their findings with Lesley’s findings. This led them to identify variables that might be different in Lesley’s and their investigations and that might have caused the different outcomes. The notebook texts also lead the students to reason about the design of their investigations, their measurement procedures, and the relations of claims and evidence.

Learning Using Guided Inquiry and Reflective Assessment

Another approach is to provide students with research notebooks that structure their work in carrying out an inquiry project, and to have students reflect on their work as they proceed. This is the approach we took in our earlier research with the ThinkerTools Inquiry Curriculum (White & Frederiksen, 1998) in which we first studied the effect of metacognitive reflection on students’ learning while they are engaging in collaborative inquiry. The research notebooks present a model that portrays the structure of the inquiry process, and incorporates self-assessments for each inquiry step to foster reflection. Students formulated and tested models of force-and-motion phenomena as they carried out a series of seven investigations. In each investigation (i.e., instructional module), students experienced all of the stages of inquiry (Question, Predict, Experiment, Model, Apply), while their overall research goal was to work to extend their theory of force and motion to cover more complex phenomena.

In this study, we had matched experimental and control classes for each of three teachers, so that we could compare their students’ learning. In the experimental or “Reflective Assessment” classes, metacognitive reflection was introduced by having students assess their work using a set of criteria that represent high-level cognitive and social goals, such as reasoning carefully and collaborating effectively. When students evaluated the research they had just completed, they were asked to write a justification for their score. Students in the control classes did not engage in reflective assessment, but spent an equivalent time commenting, at the end of each module, on what they did and did not like about that module, as opposed to the experimental classes who reflected, as described above, on their own research processes and products.

Students carried out two independent research projects, one about halfway through the curriculum and the other at the end (these were less scaffolded than the other five modules of the curriculum). To study the effects of students’ prior academic background, we
compared students who were in the lowest, middle, and highest thirds in their scores on a standardized test (the CTBS) used in the school districts. For the sake of brevity, we have added the scores for the two research projects together in showing our findings (see Figure 10.1). These results reveal that students in the reflective assessment classes have higher-rated research projects than students in the control classes. The results also show that reflective assessment is particularly beneficial for the lower-achieving students. The differences among mean project scores for the reflective assessment group are statistically indistinguishable for the three levels of CTBS scores, while those for the control group differ significantly.

We also tested students’ understanding of inquiry using an individually administered written assessment called the Inquiry Test. This test asks students to engage in a thought experiment. It provides them with a research question (i.e., what is the effect of varying the weight of an object on what sliding friction does to its motion) and asks them to do the following: (a) generate and justify two alternative hypotheses about the answer to the question, (b) design an experiment to test these hypotheses, (c) make up data that are consistent with their design, (d) analyze their made-up data and reach a conclusion, and (e) explain which hypothesis, if any, is supported by their research. The Inquiry Test was scored solely with regard to inquiry skills. In other words, students were assessed on their understanding of the inquiry processes not for their conceptual understanding of physics.

This Inquiry Test was given to students before and after the ThinkerTools Inquiry Curriculum was completed. Comparing these scores allowed us to see if the gains in inquiry knowledge were greater for students who engaged in reflective assessment than for those in the control group, who did not. It also allowed us to see if the students who had lower CTBS scores showed greater gains than students with higher CTBS scores. We found that for the low-CTBS students, the average gain was 25.6 in the reflective assessment classes (an effect size of 1.3σ) and 6.2 in the control classes (an effect size of 0.3σ), a significant difference (p = 0.02). In contrast, for the high-CTBS students, the average gain was 18.7 (1.0σ) in the reflective assessment classes and 9.9 (0.5σ) in the control classes, a difference that is only marginally significant (p = 0.08). Thus the reflective assessment process, while

![Figure 10.1](image-url)  
*Figure 10.1* Mean scores on their research projects for students in the Reflective Assessment and Control classes, plotted as a function of CTBS achievement level.
beneficial for all students, has the effect of bringing the low-CTBS students up to a level that is closer to that of the high-CTBS students. These results, and those of others (Black & William, 1998), show that reflection on one’s performance is an important part of complex learning, such as mastering scientific inquiry.

**Learning Using Explicit Models of Inquiry Meta-Knowledge**

Another approach we have taken for developing meta-knowledge and metacognitive practices for inquiry is to have students carry out inquiry projects with the support of a web-based resource called the Web of Inquiry, which provides a model of inquiry goals and fosters metacognitive practices that are intertwined in supporting students’ inquiries (Eslinger, 2004; Shimoda, White, & Frederiksen, 2002; White & Frederiksen, 2005a, 2005b; Frederiksen, White, Li, Herrenkohl, & Shimoda, 2008). This resource, and its precursor called “Inquiry Island,” provides students with explicit models of inquiry processes, their purposes, and how they are used together in carrying out inquiry. These models are infused with meta-knowledge of science and inquiry.

In addition, we promote metacognitive practices through the use of reflective assessment resources, which students use throughout their research in formatively assessing their progress in accomplishing inquiry goals. These resources include self-assessment tools for formatively evaluating their progress, and a threaded dialogue facility that supports students in asking for and receiving guidance from other students. These assessments are closely aligned with the meta-knowledge that is presented in the models of inquiry processes found in the Web of Inquiry. Our hypothesis is that students can acquire an understanding of the meta-knowledge of scientific inquiry by explicitly using this knowledge as they undertake, and help each other undertake, research projects. In the following, we illustrate how meta-knowledge has been presented in the Web of Inquiry.

**The Inquiry Cycle**

The Web of Inquiry learning environment includes a top-level structure for inquiry, called the Inquiry Cycle, a research notebook, which scaffolds the goals for each inquiry step, and a community of software “advisors” who “live” on “Inquiry Island.” The Inquiry Cycle (see Figure 10.2) depicts the meta-knowledge of inquiry as a cyclical journey from Questioning and Theorizing, through Hypothesizing, to Investigating, and from there to Analyzing Data, Synthesizing a new “Current Best Theory” and providing evidence to support it, and Extending what has been learned. Thus, the inquiry process cycles between a plane of ideas and theories, and a plane of investigations and observations.

Students begin with curiosity about some phenomena and use their current theories and ideas to develop researchable questions and competing hypotheses to investigate. Using these as a guide, they develop plans for an investigation that will provide data, which will allow them to test their hypotheses. Through analyses of their data, they synthesize their theories and findings to come up with their “Current Best Theory” and provide evidence to support it. They then consider ways in which they might extend their theory and suggest further research that needs to be done.

**Inquiry Processes, Goals, and Activities**

The Inquiry Cycle involves a set of six steps representing processes that are abstract, and which derive their meaning from sets of related activities or subtasks. Each subtask serves as an important goal of that inquiry process. For instance, the inquiry process called “Analyzing Our Data” has three goals for students: (a) to organize your data, summarize