Chapter 2
Conceptualizing Scientific Inquiry

2.1 Introduction

In order to develop a strategy for the assessment of scientific inquiry in a laboratory setting, a theoretical construct of the components of scientific inquiry needs to be developed. A basic principle of any assessment procedure is that the starting point of any project is the specification of the object that is to be assessed. In the case of active assessment the object to be assessed is scientific inquiry. Unfortunately, as discussed by Hofstein and Lunetta (2003) in their meta-analysis of 20 years of research concerning the use of the laboratory as a site for education, the term scientific inquiry has been described and defined in a variety of ways leading to the need for "greater precision and consistency" in the explanation of this term. The aim of the current chapter is to provide an understanding of some of the complexities within the educational context in defining scientific inquiry. The main problem that this chapter addresses is the definition of scientific inquiry as an object that can form the basis for the development of a program of assessment. The definition of scientific inquiry developed in this chapter posits a very significant role for the contextualized nature of scientific inquiry.

2.2 The Diversity of Scientific Inquiry

Since the widely referenced and acknowledged National Research Council (NRC, 1996) definition of *National Science Education Standards* there has been renewed recognition that the enhancement and propagation of scientific inquiry is one of the core elements of scientific education. The basic idea is that to learn science involves conducting activities that address the procedural and epistemological aspects of science. The National Science Education Standards (NRC, 1996) state that "scientific inquiry is at the heart of science and science learning" (p. 15). As conceptualized by the NRC, scientific inquiry includes a range of activities involved and related to the scientific process. Specifically the NRC defines inquiry in the following

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terms: “Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations” (1996, p. 23).

However, while there is broad agreement over the potential significance of scientific inquiry for science education, the definition of scientific inquiry has to a certain extent been quite elusive and on a practical level difficult to implement. Hodson (1996), in a historical overview and educational critique of the scientific inquiry movement, deconstructs the simplistic notion of scientific inquiry as a decontextualized set of abstract principles (such as those posed in the NRC definition) that can easily be transferred from one scientific context to another. Hodson (1996) points out that actual scientific inquiry is infused with specific theoretical knowledge and hence contextualized in very specific ways. As stated by Hodson, “The difficulty of an observational task depends crucially on what is being observed and what constitutes appropriate or significant observation. In other words, the task is governed by the nature of the concepts involved” (1996, p. 126). Meaningful scientific inquiry is contextualized within a specific and developed knowledge structure and not the abstract application of procedural knowledge.

A different direction of critique of the scientific inquiry movement comes from studies of in-school manifestations of scientific inquiry. Millar (1998) is skeptical about the ability of in-school laboratory experiments to provide alternative understandings of accepted substantive descriptions of scientific concepts. Millar (1998) describes this type of scientific inquiry as a rhetorical form designed to manipulate results in order to provide specific, historically defined answers. Nott and Smith (1995) show how teachers manipulate the actual classroom demonstrations so that they conform to the accepted position on how they are supposed to perform. Hanauer (2006) in a study of elementary school students reveals how under the heading of scientific inquiry a multimodal structure of oral, written, visual, and physical forms of communication direct students to required and predefined results. All these studies propose that scientific inquiry within the context of pedagogical discourse can become a persuasive communicative tool designed to convince students of the correctness of predefined scientific concepts rather than a tool of scientific discovery.

Several studies have analyzed the handbooks (manuals) that are used in schools to direct scientific inquiry laboratories. In an early study using a classification tool termed *The Laboratory Structure and Task Analysis Inventory* (Tamir & Lunetta, 1978; Lunetta & Tamir, 1979), Tamir and Lunetta (1981) coded three high school curricula in the disciplines of biology, physics, and chemistry. Their findings found that “almost all investigations were highly structured” and that “Seldom, if ever, are students asked to: (a) formulate a question to be investigated; (b) formulate an hypothesis to be tested; (c) predict experimental results; work according to their own design; (d) formulate new questions based on the investigation” (Tamir & Lunetta, 1981, p. 482). In addition these researchers point out that students are “often asked to perform a variety of manipulative and observational procedures and to interpret the results of their investigations" (Tamir and Lunetta, 1981, p. 482). In a later study using the same classification tool, Germann et al. (1996) studied nine biology laboratory manuals and found, once again, that biology laboratories are highly structured and that students were seldom provided with opportunities to "pose a question to be investigated; formulate a hypothesis to be tested; predict experimental results; design observation, measurement and experimental procedures; work according to their own design; or formulate a new question or apply an experimental technique based on the investigation they performed" (Germann, Haskins, & Auls, 1996, p. 493). The results of both these studies are strikingly similar and suggest that a wide range of in-school laboratory experiences emphasize physical manipulation over conceptualization and discovery.

A different approach to the definition of scientific inquiry was developed by Chinn and Malhotra (2002). In these researchers work, the epistemological and reasoning aspects of professional science were compared with school manifestations of scientific inquiry. Using the technique of examining school textbooks for hands-on activities, these researchers differentiate between three types of simple inquiry tasks: simple experiments (a single factor experimental design), simple observations (the careful observation and description of an object), and simple illustrations (following a specific procedure). These types of scientific inquiry were compared to authentic scientific inquiry in relation to the cognitive process involved and the epistemological aspects of the tasks. In relation to the cognitive processes of generating research question, designing studies, making observations, developing theories, and studying research reports, the differences between in-school scientific inquiry and authentic inquiry are pronounced. In relation to question generation and study design, in-school scientific inquiry is teacher-directed with students following directions, whereas, scientists function much more as independent problem solvers. In relation to making observations, explaining results, and developing theories, in-school scientific inquiry thought processes are directed toward straightforwardly addressing research questions without addressing the problems of observer bias, data transformation, experimental flaws, generalizability, theory development, conflicting data and inconsistencies, and more extensive literature. In authentic science the complications and ontological status of any scientific statement is a consistent concern.

In Chinn and Malhotra's (2002) study the epistemological underpinnings of in-school scientific inquiry activities are differentiated from authentic scientific inquiry in relation to the purposes, nature of reasoning, and social construction of knowledge. Specifically authentic scientific inquiry is directed at the construction of knowledge through a variety of forms of argumentation and in the context of a community of researchers. In-school scientific inquiry does not develop knowledge, is limited in its forms of argumentation, and is not related to the wider community of scientific researchers. Zachos et al. (2000) extends this differentiation through the distinction between what they term "personal" and "cultural" discoveries. The discoveries of scientists have a historical and cultural aspect in that they constitute moments at which new knowledge is created. In this sense they are cultural discoveries. Personal discoveries involve the development of new knowledge for the individual – a moment in which an understanding of phenomena is achieved – but not a move forward for the wider scientific community. In this sense they are personal discoveries. As seen in Chinn and Malhorta (2002), in-school scientific inquiry is designed to produce personal and not cultural discoveries.

As exemplified in the studies reviewed above, a major aspect of the confusion over the concept of scientific inquiry results from the fact that under the heading of scientific inquiry a wide range of different activities are being conducted. Wenning (2005; 2007) provides a useful heuristic through which this range of scientific inquiry activities can be addressed. Wenning (2005; 2007) develops a continuum of types of scientific inquiry that differentiates forms and educational uses of inquiry in relation to the degree of teacher control and required intellectual sophistication. Wenning (2005; 2007) presents the following levels and types of scientific inquiry:

1. *Discovery Learning*: This is the most basic form of scientific inquiry and consists of a teacher-controlled activity through which students are directed to make specific observations and reach predefined conclusions.
2. *Interactive Demonstrations*: This consists of a teacher-controlled manipulation of a scientific demonstration and the request for a prediction or the explanation of the phenomena. The teacher is in complete control of the demonstration, questions, and responses. The emphasis is on the teacher's manipulation of scientific equipment.
3. *Inquiry Lessons*: This consists of a teacher-controlled demonstration of an experimental procedure. This demonstration of an experiment is accompanied by a verbalization of the conceptual and physical aspects of the experimental design. The teacher also asks leading questions and models the thought processes involved in scientific inquiry.
4. *Guided Inquiry Labs*: This consists of a teacher-directed student inquiry. Students conduct a scientific inquiry that is directed by a question presented by the teacher and lab procedures defined and guided by the teacher. Students are directed to find the answer to a specific question through the usage of a provided set of procedures (Herron, 1971).
5. *Bounded Inquiry Labs*: This consists of a student scientific inquiry that is directed by a question that is identified and posed by the teacher. The students are expected to design the experiment and conduct the scientific inquiry (Herron, 1971).
6. *Free Inquiry Labs*: This consists of a scientific inquiry that is directed by a question identified and posed by the student and an inquiry process designed and conducted by the student.
7. *Pure Hypothetical Inquiry*: This form of inquiry involves students developing hypothetical explanations of laws and explanations of physical phenomena based on empirical outcomes. This type of inquiry emphasizes pure hypothetical reasoning.
8. *Applied Hypothetical Inquiry*: This form of inquiry consists of problem-based learning in which a specific real-world problem is presented to the student and

through a process of hypothesis formulation on the basis of factual knowledge solutions and explanations are posed. Posed solutions are supported through logical argumentation and informed reasoning.

Wenning's (2005; 2007) conceptual scheme of types of scientific inquiry, building upon Herron's (1971) earlier work, clarifies the problem with the definition of scientific inquiry. Scientific inquiry is an umbrella term for a range of educational and professional activities within the sciences. While the rhetoric has tended to conflate scientific inquiry with authentic professional science, the majority of studies that consider in-school activity suggest that there are significant conceptual, physical, and epistemological differences between professional and educational scientific inquiry.

2.3 The Characteristics of Authentic Scientific Inquiry

The discussion in the previous section has brought us forward in the sense that it is clear that scientific inquiry covers a range of types of activity that are very different from what is usually done within professional science. However, this discussion does not solve the main problem that this chapter addresses – the definition of scientific inquiry as an object that can form the basis for the development of a program of assessment. The context of scientific inquiry that this book addresses is different from the ones that were discussed in the previous section. This book describes an approach to the development of assessment procedures for in-laboratory, educational scientific inquiry programs designed around authentic scientific research questions, directed by a real research agenda of interest to the wider scientific community and coordinated by an active research scientist. This context presents from an educational perspective a new configuration of the components of scientific inquiry. Using the concepts developed in the previous section, the description of this form of scientific inquiry can be characterized as follows:

1. *Development of Personal and Cultural Knowledge*: A central aspect of the type of in-laboratory educational scientific inquiry programs addressed in this book is that they are directed by the presence of an active scientist with an authentic, scientifically valuable research agenda. In other words, the research that is being conducted by the student-researcher is designed to provide both personal and cultural knowledge. The scientific inquiry process may be educational in that it provides the student with the experience of learning how research is conducted, but ultimately the aim of this research is not limited to the realm of education but rather has the goal of the creation of new scientific knowledge that is publishable.
2. *Contextualized Scientific Knowledge*: The development of a research agenda and the ability to identify what research needs to be conducted and is of value for the wider scientific community require a comprehensive and sophisticated understanding of the scientific knowledge that exists within the specific discipline. By definition, research that is conducted with the aim of producing cultural knowledge is contextualized within a specific knowledge structure. Accordingly,

students studying within a framework of this kind are exposed to contextualized scientific inquiry practices relevant to a specific body of knowledge and are not involved in the application of abstract concepts of scientific inquiry. In addition, the assumption of a program of this sort is that the knowledge that will be produced will be presented in the settings and formats that characterize scientific communication such as research articles, research reports, posters, and conference presentations.

3. *The Progression Toward High-Order Problem Solving*: The cognitive aspect of an educational scientific inquiry program that is designed to produce publishable knowledge involves the movement toward argumentation and problem solving that is used within professional science. In other words, all the complexities of real research, such as the coordination of data and theory, the design of research, the resolution of problems that occur, and the discussion of anomalous results, are part of the educational program. As argued by Hatfull et al. (2006) for this to be practical the educational scientific inquiry program has to have an accessible entry point and progressively move to more complex structures. This creates a scientific inquiry program that starts from a research process that is guided and directed by knowledge, questions, and procedures from the instructor to a situation in which the student-researcher works independently in coordination and discussion with other members of the laboratory. In the terms developed by Herron (1971) and Wenning (2005) this involves the movement from a guided inquiry laboratory to a free inquiry laboratory. It is important to note that the last stages of the research project are open ended and cannot be predicted. They evolve as a result of informed decisions made as the situations arise. One ramification of this progression is that the student cannot stay on the level of physical manipulation of laboratory equipment but rather must acquire the substantive and procedural knowledge relevant to the discipline within which the specific scientific inquiry is being conducted.
4. *Social Interaction for Scientific Goals*: Professional science is characterized by extensive social interaction with other scientists. Science is not done alone but rather is the result of a community. In educational, scientific inquiry programs designed to produce cultural knowledge the wider community of scientists within the laboratory and beyond the laboratory will be addressed. In the early stages of the educational program the scientific inquiry process is guided and directed which involves extensive interaction with professional faculty in order to facilitate the development of relevant knowledge; at later stages of the process there is also extensive interaction with professional scientists but at this stage this consists of working out how the research agenda of the whole laboratory can be moved forward. Within programs of this type, student-researchers who create cultural knowledge are expected to interact with the other scientists through the professional lines of communication such as professional conferences.
5. *Scientific Inquiry as a Multi-stage and Multi-representational Process*: A professional scientific research agenda is characterized by the presence of multiple stages of research over an extended period of time. A scientific inquiry progresses through a series of laboratory stages which often involve the

manipulation of various properties of the physical world. At each stage different physical outcomes are found and recorded in writing and visual formats. As described by Latour and Woolgar (1986), actions taken within the laboratory become meaningful when they are transformed into representational inscriptions. In this sense a lot of science is visual and representational. Accordingly, a scientific research process can be described as a series of stages each characterized by the development of a specific representational outcome.

2.4 An Analytical Framework for the Definition of Scientific Inquiry

Based on these characteristics of the educational scientific inquiry program presented above, a two-part analytical frame can be proposed to define scientific inquiry. However, before the model is described it should be remembered that the basic principle of this model is that this model is fully contextualized within the framework of a professional laboratory involved in an educational scientific inquiry designed to produce cultural knowledge. Accordingly, it is assumed that the actual definition of a scientific inquiry that will form the basis for the development of an assessment program results from the specific application of the proposed analytical framework to the definition of the specific scientific inquiry process that forms the basis for the educational program. The proposed model has two analytical parts: it proposes a series of types of knowledge that are significant for any scientific inquiry process and it then proposes an organizational structure comprised of two intersecting axes for these knowledge types.

In a study that was designed to produce assessment tools, Hanauer (2007) analyzed the scientific process of a particular educational in-laboratory scientific inquiry program from a multimodal information processing perspective (Hanauer, 2006). As presented by Hanauer (2007) the analysis of this scientific inquiry process involved four different types of information: *physical knowledge*, *representational knowledge*, *cognitive knowledge*, and *presentational knowledge*. These different types of knowledge are assumed to work together in a multimodal-layered construct and were each considered to be knowledge that needs to be assessed when considering whether scientific inquiry knowledge is being acquired. These knowledge types were defined as follows:

- *Physical knowledge* consists of knowledge required to actually perform the laboratory tasks involved in scientific inquiry.
- *Representational knowledge* consists of the written and visual representations used within the laboratory.
- *Cognitive knowledge* consists of background disciplinary knowledge of scientific content and thinking abilities such as problem solving, decision making, and calculation.

- *Presentational knowledge* consists of the ability to summarize understandings from research, to conceptualize these in manner that is valuable for the scientific community, and present them in the formats that are used by the scientific community.

The approach taken here is that in order to understand and operationally define the process of scientific inquiry, in addition to an analysis of the stages of a scientific process, scientific inquiry needs to be analyzed in terms of the types of knowledge that are utilized as part of the inquiry process. This type of analysis produces a description of the scientific inquiry process and allows assessment materials to be developed on this basis. The types of knowledge proposed by Hanauer (2007) are modeled in Fig. 2.1.

As represented in Fig. 2.1, the process of scientific inquiry is a multimodal and multilayered phenomenon that integrates four different types of knowledge. Cognitive knowledge provides the background scientific information that is crucial to the actual understanding of the science involved in the scientific inquiry process. Cognitive knowledge also involves the ability to make informed decisions, interpret physical and visual results, and make calculations. This information source feeds into the physical activities that are actually conducted in the wet laboratory. The results of the laboratory process are in the form of visual and written representations that are stored in most cases within the framework of the laboratory notebook and as physical outputs from the laboratory work itself (such as plates or gels). To understand the visual representations that were produced, cognitive knowledge is

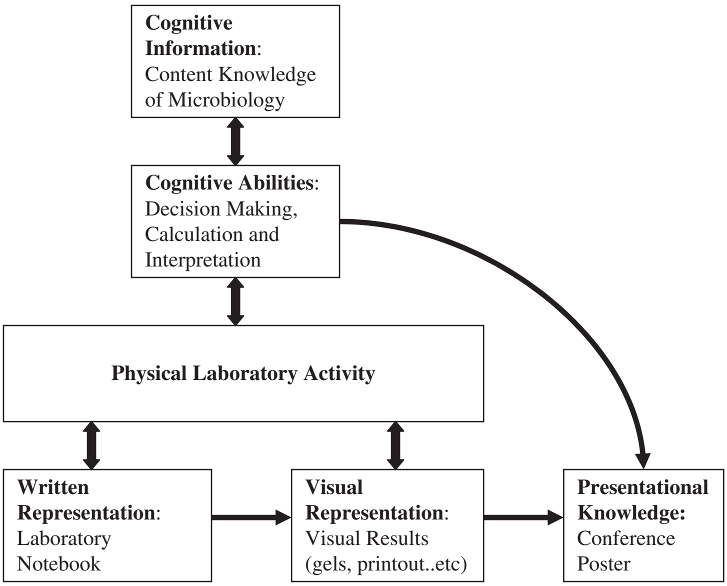

Fig. 2.1 A Schematic Representation of the Types of Knowledge Involved in a Scientific Inquiry Process

applied and decisions are made as to the future directions that need to be taken. Finally, presentational knowledge is to be considered the ability to produce a product that is useful for the wider scientific community to gain access to the research that was conducted. Presentational knowledge consists of the public presentation of conference posters (or perhaps written research papers or oral presentations) at professional conferences or within educational settings. The production of a poster integrates knowledge that comes from the notebook entries and other visual representations. The actual creation of a poster (or written/oral paper) involves the summarization and reconceptualization of the actual research that was conducted and the decision as to what makes this information important for the wider scientific community. As such to create a poster requires both the representational and cognitive knowledge sources used during the scientific inquiry. It should be noted that all the knowledge types presented above are of significance within the educational scientific inquiry program. It is the interaction between the different knowledge types that creates some of the complexity in assessing and understanding the scientific inquiry process.

The development of an assessment strategy for scientific inquiry requires a basic description of the components of scientific inquiry and the way these components are organized. The organizational approach used here specifies that scientific inquiry can be defined by two theoretical axes: the axis of knowledge source and the axis of stages of a specific scientific inquiry process. The basic idea behind this organizational structure is that scientific inquiry is a multi-stage process that involves the development of a series of in-lab outcomes (representations) over an extended period of time. Accordingly the definition of a scientific inquiry process consists of understanding the specific aspects of each knowledge source and how they develop over a period of time. Another way of understanding this model is to think of an extended scientific inquiry as a collection of much smaller scientific inquiries each of which produces a definable outcome and that collectively develop toward a research finding. For each specific stage, cognitive, physical, and representational knowledge is applied in order to reach the desired outcome, so that at different stages of the scientific inquiry different knowledge is required. Accordingly as the student progresses through the educational program knowledge will develop in relation to all the types of knowledge. From an assessment perspective, as will be discussed in later chapters, in the process of active assessment each of these axes requires a detailed analysis by the prime scientist-educator of the specific research project that is being utilized. Together the definition of knowledge for each of these two axes provides a detailed and operative description of a scientific process that can be used to generate a comprehensive assessment strategy. Figure 2.2 presents a schematic representation of the scientific inquiry process.

As an operational tool the two axes provide active researchers or observers of a scientific inquiry process a terminology and a conceptual heuristic with which to describe a scientific project in terms that are useful for assessment and educational design. The particular aspects and operational definitions of this framework are presented in Chap. 5. As seen in Fig. 2.2 the first axis divides a scientific inquiry process into representational "milestones." The idea is that a scientific process can

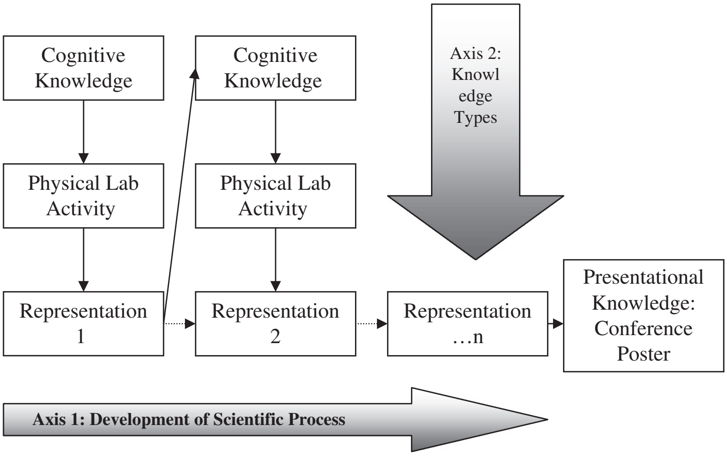

Fig. 2.2 A Schematic Representation of the Scientific Inquiry Process (*see* Color Insert)

be divided into stages according to the laboratory products that need to be produced. These products are termed representations in that they fulfill a representational role as the actual outcome of both a thinking process and physical laboratory activities. By analyzing the first axis a series of stages with specific outcomes can be defined and the overall process of scientific inquiry can be explicated. The second axis considers the types of knowledge that are required in order to produce the required laboratory representational "milestones". Every laboratory product results from the application of cognitive, representational, and physical knowledge sources. The analysis that needs to be done here is of exactly what knowledge is required to produce and comprehend each representation. This knowledge should be defined under the heading of cognitive, physical, and representational knowledge types. If both axes 1 and 2 are analyzed a detailed and operationally functional description of a specific scientific process should emerge. The detailed description of a specific scientific inquiry process is the basis upon which a comprehensive assessment program can be designed. In broad terms every assessment of an inquiry process would want to address the four knowledge sources of cognitive, physical, representational, and presentational knowledge and do so in relation to the different stages of the process itself.

2.5 Chapter Summary

The aim of this chapter was to provide an understanding of the concept of scientific inquiry that is applicable as a basis for the development of an assessment program. The following ideas and concepts were defined:

- The term scientific inquiry as manifest in different educational settings covers a wide range of diverse activities.
- The differences in types of scientific inquiry can be organized along a continuum according to the degree of teacher control and intellectual sophistication involved in each type of inquiry.
- Types of scientific inquiry can also be defined according to whether they produce cultural knowledge or personal knowledge.
- Authentic scientific inquiry is defined according to five characteristics: development of personal and cultural knowledge; contextualized scientific knowledge; the progression toward high-order problem solving; social interaction for scientific goals; and scientific inquiry as a multi-stage and multi-representational process.
- The definition of scientific inquiry that forms the basis for the development of an assessment program consists of a two-part analytical frame: the definition of knowledge types relevant to scientific inquiry and the definition of an organizational frame for these knowledge types.
- Four types of knowledge are significant for the definition of a specific scientific inquiry program: cognitive knowledge, physical knowledge, representational knowledge, and presentational knowledge. All four of these knowledge types are considered significant.
- These four types of knowledge are organized in a framework that consists of two intersecting axes: the axis of knowledge types and the axis of stages of a specific scientific inquiry. This framework describes scientific inquiry as multi-stage process that involves the development of a series of in-lab outcomes (representations) over an extended period of time.
- The definition of a scientific inquiry is contextualized within the framework of a specific research agenda in a particular scientific field that is directed by an active researcher.

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