DOCUMENT RESUME

ED 465 632		SE 066 354
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TITLE	Scientists' Conceptions of Scientific Inquiry: Voices from the Front.	
PUB DATE	2002-01-00	
NOTE	32p.; In: Proceedings of the Annual International Conference of the Association for the Education of Teachers in Science (Charlotte, NC, January 10-13, 2002); see SE 066 324.	
AVAILABLE FROM	For full text: http://aets.chem.pitt.edu.	
PUB TYPE	Reports - Research (143) -- Speeches/Meeting Papers (150)	
EDRS PRICE	MF01/PC02 Plus Postage.	
DESCRIPTORS	Higher Education; *Inquiry; Science Instruction; Science Teachers; *Scientific Concepts; Scientific Principles; *Scientists	

ABSTRACT

The National Research Council (NRC) (1996) refers to scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work." This could be paraphrased, as 'scientific inquiry is what scientists say it is.' Accepting this rephrasing at face value, a study has been crafted using a blended grounded theory approach to answer the question "what is scientific inquiry?" and determine what conceptions scientists have regarding the nature of scientific inquiry. The goal is to develop a set of research grounded characteristics of scientific inquiry that will be a guide for this work as well as that of other science education researchers and reformers. Interviews with 52 science faculty members at a large midwestern research university were conducted using a semi-structured interview protocol designed to probe the subject's conceptions of scientific inquiry. (Contains 31 references.) (MVL)

SCIENTISTS' CONCEPTIONS OF SCIENTIFIC INQUIRY: VOICES FROM THE FRONT

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Calls for reform in science instruction have occurred on several fronts (Anderson, 2001; Moore, 2001). At the same time there is a strong push for teachers to use inquiry methods of instruction (NRC 1996, 2000, and 2001; Keys & Bryan, 2001; Krajcik, et. al., 1998). The idea of teaching through inquiry has actually been around since the early 1900's (DeBoer, 1991), but implementing inquiry-based instruction into the classroom has proven to be a challenging task for teachers at all levels. It has been well established that teachers have difficulty developing their conception of inquiry (Hewson et al., 1999; NRC, 2000 and 2001). Reiff (in review) has found that many pre-service elementary teachers had difficulty conceptualizing inquiry because they had never experienced inquiry as a learner. If science teachers are expected to teach inquiry (NRC, 1996), developing a common conception of inquiry can assist them with teaching a method with which many are unfamiliar. Science educators have made significant progress in defining inquiry as a teaching method but a missing component of conceptualizing inquiry is articulating the process by which inquiry is conducted and the skills necessary to do scientific inquiries. The researchers interviewed scientists about their conceptions of scientific inquiry to enrich our understanding of not only how to teach inquiry but how to do inquiry.

Part of the confusion surrounding defining scientific inquiry is that inquiry has been associated as both a teaching method and as a method for doing science. By the 1960s, inquiry branched into separate dichotomies and had evolved into a word with separate meanings Rutherford (1964) tried to clarify this divergence by defining inquiry as a method of science termed "inquiry of content" and as a method of teaching called "inquiry of technique." Welch, Klopfer, Aikenhead, and Robin (1981) surveyed teachers' attitudes toward inquiry and discovered that teachers were using different meanings of inquiry and were unclear about the meaning. While current efforts have better defined inquiry as a teaching method, research concerning how to do inquiry provides a more holistic picture of the meaning of inquiry. Both aspects of inquiry are necessary for teachers to see that inquiry teaching methods teachers employ are providing the skills and building blocks to help their own students conduct inquiries.

We believe the challenge of implementing inquiry-based teaching into the classroom and practicing a school science that more closely resembles scientists' scientific endeavors hinges on developing a common understanding and language around the issues of scientific inquiry and inquiry-based instruction. In order to better investigate the teaching practices of scientists and their beliefs about teaching, we need to first understand scientists' conceptions of scientific inquiry. Bybee (2000) points out that there are multiple understandings regarding the term "inquiry" as applied to science education. It is not clear, however, what conception(s) academic research scientists hold regarding scientific inquiry. Yet, the idea of inquiry-based science instruction is embedded in national and state standards and needs to be incorporated into college science classroom experiences. Providing college and university science faculty with a research-based understanding of scientific inquiry may open the way to fruitful discussion regarding scientific inquiry in a classroom setting.

The National Research Council (1996) refers to scientific inquiry as "...the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work." This could be paraphrased, as 'scientific inquiry is what scientists say it is'. Accepting this rephrasing at face value we have crafted our study using a blended grounded theory approach to answer the question implied and determine what conceptions scientists have regarding the nature of scientific inquiry. We seek to develop a set of research grounded characteristics of scientific inquiry that will be a guide for our work as well as those of other science education researchers and reformers.

Methodology

Interviews with 52 science faculty members at a large midwestern research university were conducted using a semi-structured interview protocol designed to probe the subject's conceptions of scientific inquiry (Appendix A). Interviews were tape-recorded and interviewers took field notes during the interview. Together, the transcripts and field notes represent our data. Purposive sampling was used and the academic research scientists interviewed were disbursed across nine science departments (anthropology, biology, chemistry, geography, geology, medical sciences, physics, applied health, and environmental affairs). The department name is not necessarily indicative of the type of science an individual is doing. For example, atmospheric chemistry is located in the Geography department. The disciplines and subdisciplines represented by our subjects are summarized in Table 1.

Table 1
Subject Disciplines and Subdisciplines

Department	Disciplines	Subdiscipline
Biology	Zoology, Botany, Limnology, Ecology	Molecular biology, genetics, botany, limnology, ecology
Kinesiology	Environment Kinesiology Muscle physiology	Env./man interactions, Biomechanics, biochemistry
Anthropology	Physical, biological, cultural	Biomedical, functional morphology, primatology, archaeology
Environmental Affairs	Environmental Science	Applied ecology, Atmospheric chemistry, Water Resources
Chemistry	Chemistry	Physical (experimental and theoretical), inorganic, organic, analytical, biochemistry
Physics	Physics	Solid state, condensed matter, high energy
Medical Sciences		Respiratory Physiology, Dermitology, Patholoogy, Pharmacology, Medical Physiology, Cancer Biology
Geology		Sentimentary, Geochemical, Paleotology, Geochemistry, Structural
Geography		Atmospheric science, Economics, Land Use/GIS, Developmental

We introduced the interview by letting subjects know that we were interested in their own understanding regarding scientific inquiry and that, therefore, there were no "wrong answers". Our first question was "what is your definition of scientific inquiry?" This direct question served as a way to focus our subject's attention on the issue and to get an insight into their broadest and most general initial conception of scientific inquiry. We expected that by the end of the interview many subjects would be more comfortable talking about scientific inquiry, would have found their own voice, and might therefore amend the initial response. Subjects were reassured that they would have the chance to revise or alter their answer to this first question at the end of the interview.

The method of analysis used for this study was grounded theory (Glaser & Strauss, 1967; Strauss & Corbin, 1990), which is a qualitative method that uses naturalistic techniques. Using these techniques, relationships emerge that are provisionally tested to further define boundaries and generalizability. The emergent categories, relationships, hypotheses, assertions, and theory are grounded in the data and are used to support, refute, add, or further define existing theory in the literature. Consistent with this methodology, the data were collected and coded systematically and categories and concepts began to emerge.

After conducting the interviews, we independently looked for patterns and connections in the science faculty members' responses to each of the eight interview questions. We noticed that concepts and descriptions from one interview would correspond to similar concepts in another interview. Descriptions emerged consistent with other science faculty members' responses in the interviews. If different science faculty members mentioned a concept more than once, we included that concept on a list of descriptors of scientific inquiry. These concepts resulted in a tally sheet that was used to identify when science faculty members mentioned the same or similar concepts. We compared our independent tally sheets and agreed on a single list of concepts with a consistent understanding among us as to how to classify items. We then independently read through the interviews a second time. When a concept was mentioned, the appropriate box on the tally sheet received a check mark. For example, several scientists mentioned "meticulous" as an important characteristic of an investigator in conducting scientific inquiry investigations. In other instances, descriptions such as "detail oriented" and "a careful recorder of data" were also included under the concept "meticulous".

Within each of the nine departments, we used tally sheets for individual faculty members. Each department's responses were pooled together to represent the frequency of concepts mentioned. The results from each science department were used to compare science departments to see if patterns of frequency developed. We accounted for validity by cross checking the tally results of each interview with the results of another member of the research team. When a discrepancy occurred, the results were discussed until a mutual agreement could be made (Tobin, 2000). In such cases, often one member had overlooked the concept in the interview.

Researcher Expectations

As a group of researchers we came to this study with certain expectations (Tobin, 2000). First, we expected to be able to identify a set of characteristics of scientific inquiry depicting scientific inquiry investigations. Second, we expected that there would be more than one conception of scientific inquiry with different sets of characteristics. Third, we expected that scientists from different disciplines would have unique conceptions of scientific inquiry. We asked our subjects for information about how they identified their field and subdiscipline (Table 1). Generally, however, we expected continuity of responses within science departments and discontinuity between most science departments.

One of the initial goals for this project was to describe groups of scientists that shared a similar conception of scientific inquiry. It was our initial belief that by clarifying the set of definitions of scientific inquiry, and then identifying which sets of scientists held which conception, reformers might be able to be more effective in engaging specific faculty groups in discussions regarding bringing inquiry-based instruction into college science classrooms.

Table 2
Frequency of concepts in describing characteristics of the investigator and the investigation

Investigator		Investigation	
Make connections	33	Literature-based	38
Connected to other disciplines	29	Testable question	34
Focus on process	26	Meaningful question	24
Analytical	24	Repeatable	16
Persistant	20	Multiple Methods	15
Critical thinker	19	Systematic	15
Flexible/Openminded	18	Verifiable	13
Problem solving	18	Scientific Method	12
Observant	17	Serendipidy	8
Curious	17	Falsifiable	4
Meticulous	17		
Logical	17		
Decision maker	17		
Willingness to be wrong	17		
Collaborative	16		
Communicator	15		
Objective	14		
Creative	13		
Disciplined	12		
Skeptical	10		
Wired differently	9		
Think outside box	9		
Manual skills	8		
Patient	7		
Active searcher	7		
Organized	7		
Moral	5		
Enthusiasm	4		

Results and Discussion

We found that some of the scientists interviewed shared our expectation that scientific inquiry is understood differently by different groups of scientists. Many interviewees prefaced their response by informing the interviewer that they could only speak for themselves because other scientists would have a quite different perspective. In spite of the claims that they practiced science differently from scientists in other departments/field/perspectives, we found no significant difference among the characteristics associated with scientific inquiry. In analyzing the interviews, numerous similarities emerged instead of differences regarding how scientists believe they approach and do science. Our study quickly developed a focus on the commonalities that exist among disciplines and pulls these ideas together to enrich our understanding of scientists' conception of scientific inquiry.

We have arranged our results into three broad areas: The investigator, the investigation, and qualities of scientific inquiry. The characteristics of each of these areas are summarized in Table 2 (see previous page).

The Investigator

A key outcome from our study is a set of characteristics required of science investigators (Table 2). These characteristics have implications for the way in which teachers—both at the college and pre-college levels—present scientific inquiry to students. The most commonly mentioned characteristics of the investigator include the ability to make connections, connect different disciplines, focus on the process of the investigation, and have analytical skills. We found that 33 out of the 52 science faculty members identified "*making connections*" as an important skill for an investigator and, thus, became the most frequently mentioned description of what makes a good scientist.

Making connections refers to the ability to take pieces of information and to be able to look for patterns and connections within the data. In this case, the scientist is trying to make sense of the data. A scientist who is able to make connections has the ability to focus on the details of an investigation as well as to see the implications of the study and how the pieces fit together. The scientist must be able to keep track of details as well as be able to see the larger picture. A geographer used the metaphor "seeing the forest through the trees" to describe this skill set. The trees represent isolated facts of information, often disconnected, while the forest serves to connect the pieces of information into a living, breathing system.

Another scientist compared the process of making connections or synthesizing information, as other scientists described it, to assembling a puzzle. The scientist must try to figure out how the data fit together or how the pieces of a puzzle should be arranged. Through the process of making connections, eventually, a picture emerges that gives new meaning to the individual pieces.

Scientists identified the ability to make connections or to see patterns as valuable and characteristic of good scientists.

> The best scientists, I think, see connections where no one else saw. Most great discoveries are really new connections, transferring some knowledge to another situation.
>
> The heart of the matter is identifying patterns. Some people have it, other people don't. There is an enormous amount of information out there. Most of it irrelevant but guys like Watson and Crick were able to see the pattern.

The ability to synthesize information, to see things that others have not seen, to look at all possibilities, to keep track of the details of an investigation but also to see the larger picture are all attributes of making connections and are paramount in describing what makes a good scientist.

Another valued characteristic of an investigator is to be able to "*connect disciplines*". For example, a geologist described how techniques used in biology or chemistry could also be applied to a geology study. As might have been expected, math, statistics, and technical skills were also identified as benefiting the investigator. Knowing fields of study other than one's own seemed to enhance an investigator's ability to utilize resources and methods from different disciplines that could enhance a study.

Scientists also stressed the importance of writing skills, pointing to the importance of effectively communicating scientific ideas and discoveries.

> I think that anyone that gets into science as a whole and doesn't understand that they're also becoming a writer is fooling themselves, because a large part of the success in science relates directly to one's ability to convey that information to other people and that is a huge part of doing science. So I think you have to be a good writer.

A good scientist has the ability to "*focus on the process*" of an investigation without jumping to conclusions. Several scientists referred to Einstein and Newton as examples of scientists who spent time on the process of an investigation and not just the end result. "Einstein spent many years developing his ideas, they didn't just happen overnight." Another scientist in the same department explained how Newton was working with the building blocks that led to his result. He said the same is true with Einstein, "he didn't just wake up and say, 'Oh, $E=mc^2$'."

A geologist compared the process of scientific inquiry with that of putting together a mosaic. Sometimes in the process of making a mosaic, an artist or a scientist has to keep track of the individual building blocks while making the picture. In the process of the investigation, the scientist might find pieces of information that do not fit with the evidence. This information should not be discarded but may be useful in planning additional inquiry investigations. As one anthropologist explained,

> To me, it's very open ended, and the question that set out to investigate, in the course of your research may not turn out to be the most fruitful line of inquiry. That to me is a very strong feature of my work. It's often gone in different directions than what I originally intended. You have to be open to that, and not so invested in your ideas.

By focusing on the process of an investigation, the investigator can be more receptive to serendipitous moments. These flashes of insight can come day or night. Scientists stressed that science does not take place just in the laboratory. Reflecting and analyzing findings can happen in the shower or in bed. The investigator who is focused on the process of the investigation and not just on the end result will be more receptive to experiencing these realizations.

> The interesting experiments are always serendipity, I think. They come in the middle of doing something. If you aren't doing anything, you can't make discoveries.

About half of the science faculty members described the ability to stay focused on the process of investigation as a desirable characteristic of an investigator.

> It's really trying to get people to enjoy the process of learning not just the answer. Same with my students, try to enjoy the process of getting a degree, not just obtaining one.

This rush to get the right answer can mislead students into thinking that science has a right or wrong answer when, in fact, scientists described the process of finding evidence contrary to the expectation as leading to important discoveries. A scientist from the geology department explained, "A lot of scientific breakthroughs start when you find an exception to those supposed rules." This "*willingness to be wrong*" is an important feature of the inquiry investigator. This willingness to be wrong is described by Harding and Hare (2000) as open-minded realism. Surprising results should not be discarded because they can add to the existing evidence, lead the investigator in another direction, or can spark another investigation.

> I get really frustrated with people, including close associates, who set up what they want it to come out to. And I'm proud to say that most of my research hasn't come near to what I thought it would be...I like wrong answers.

The willingness to be wrong also was associated with personality traits and attitudes such as "having a certain amount of guts, the courage to go into something where there's a high probability that it won't work." The willingness to admit that the equipment failed or that the hypothesis was not supported leaves the possibility for unexpected discoveries. The willingness to be wrong is part of the process of conducting an investigation.

> Wrong hypothesis. That's the way it goes. Science doesn't guarantee that you're going to get the right answer. In fact, it almost guarantees that you will occasionally get wrong answers, sometimes more frequently than you expect. So much of what science is, [as] we do it in the laboratory, consists of getting the wrong answers because that's how we learn and refine our approach.

The ability to make connections, to connect disciplines, and to focus on the process was the most commonly mentioned characteristics of the investigator. In addition to these skills necessary to do scientific inquiry, science faculty members also discussed personality traits desirable of an investigator. These traits included persistence, open-mindedness, critical thinking, and curiosity.

Persistence was described as "the ability to concentrate over long periods of time," "attention to drudgery", "being disciplined," "the ability to tolerate frustration," and to have a "thick skin" or "emotional resilience" after being turned down for a grant the third time. When asked what are the skills needed to do scientific inquiry, one physicist responded, "Persistence, love of what you do, which leads to more persistence, and more persistence."

Genuine scientific inquiry can be frustrating. Equipment fails to work properly, procedures must be refined by trial and error, and many variables must be controlled. Inquiry in classroom settings often contains these and other sources of frustration (unfamiliarity with technique and/or materials, for example). What is not evident in most K-16 scientific inquiry is the solution to these circumstances used by real scientists: persistence. When scientists get unexpected or strange results or results indicate a mistake has been made, the scientists takes the time to rethink their investigation, make changes, and repeat the effort. Students in K-16 inquiry investigations rarely have the opportunity for this important reflection, change, re-do process. Yet, this develops as a key trait for investigators who persist with their inquiry and do not easily give up on an active investigation.

To think critically is another important attribute of a good scientist. Critical thinking is a trait needed to examine problems and to question findings. Scientific inquiry is viewed as a way to teach critical thinking skills (NRC, p.23). Ultimately, as one geologist explained, "What we are trying to do is teach people how to think." An anthropologist viewed critical thinking skills as applying holistically to many forms of expression.

> But having them [students] critically observe, critically write, critically express themselves, all of that is what, I think, is good science. I think that high school teachers tend to steer students away from some of that critically examining positions for whatever reasons and when they come to college they are very unfamiliar, very unprepared to begin to question, to begin to evaluate information for what it is and what it might not be.

Some scientists described children as scientists because of their strong sense of curiosity. In several instances, the scientists cited examples of their own children as little scientists who were full of questions. One medical scientist explained, "Young children, during the first three years of life have a natural curiosity; their brain goes in ten different directions. They ask questions we never think of." One biologist went as far to claim "the most scientific inquiries in anybody's life are undoubtedly those where they are three years old or two years old." This scientist went on to describe how,

> Children start out as scientists. We beat it out of them. How did they learn to walk, to run, to ride a bicycle? All of these, in fact, are inquiries into the forces of nature. Most people start out as curious. Somehow that curiosity disappears over time.

Another scientist reflected, "The difference between scientists and normal people is that as people mature, they lose that childish curiosity. Scientists, on the other hand, don't. The unfortunate thing is that they maintain all other childhood traits as well as curiosity."

Some scientists considered creativity as an important characteristic of an investigator. A scientist from the anthropology department compared cello playing and writing poetry to the creative process in science. She explained that playing the cello is not just playing the notes but it's about, "putting something of your own, yourself there." In writing poetry, one uses creativity to decide what structure or format will be used in much the same way a scientist decides which method to approach a problem. Another scientist viewed creativity as a means for advancing scientific thinking.

> If you don't have creativity and an imagination and a willingness to try new things or think outside of the box or however you want to put that, then all you're doing is repeating what other people have done and you're not necessarily going to make major new discoveries.

Through questions in our interview such as "what are the characteristics of scientific inquiry" (Appendix A), scientists elaborated on what makes a successful scientist. Defining characteristics of a good scientist such as the ability to make connections, to connect different disciplines, to focus on the process of an investigation, to have critical and analytical thinking skills can help teachers to identify the many qualities of scientists and help students with the skills to carry out scientific inquiry investigations. Some of these characteristics of scientists may be unfamiliar to students who have images of scientists working in a lab with frizzy hair and glasses (Barnum, 1997). Some of the personality traits of scientists such as curiosity, persistence, creativity, and among others enhance the image of a scientist to one that seems more real. If students can relate to some of these qualities then they might consider themselves as scientists using similar skills to do scientific inquiry.

<u>The Investigation</u>

Scientists in our study also identified key characteristics of good scientific investigations (Table 2). The most important aspect of an investigation is that it is literature based. This result is consistent with Magnusson et al. (2000) in their exploration of the development of scientific reasoning through guided inquiry. To the scientists in our study, an investigation is only worthwhile—it is only truly a scientific inquiry—when crossing the boundary from the known to the unknown. A great deal of effort is expected from investigators to review and understand the published literature surrounding their question. From this reading, investigators are able to refine their central question to one that will address an exploration into the unknown. An anthropologist pointed out,

> A good bit of science is simply knowing and keeping track of where the knowledge base is. I think scientific review, literature review if you will, is the test of your credentials because what a good reviewer will then be able to detect is whether you are at that border, whether you are going to contribute anything beyond what is already known.

Along with this sense of the border, academic research scientists also view scientific inquiry as an accumulative process in which "we base our stuff on something that has been known and try to do something new based on the body of knowledge that already exists." A secondary benefit provided by an understanding of the literature is guidance regarding the details of the investigation. Scientists need to know what has been done and how it was done. This information can help a scientist develop a meaningful inquiry. An environmental scientist said,

> I studied the literature so instead of reinventing the wheel I was looking at if people had already answered that question. You will find that people have already answered other questions that are related so it gives you ideas about how to approach the study.

It is at the border between the known and the unknown where new knowledge is attained and the process of scientific inquiry is the bridge connecting the known with the unknown. The focus on pushing back the border is very strong and it is through understanding the literature that one can most easily identify questions of interest to the discipline. Part of moving from the known to the unknown is "starting with the certainty and then moving to the uncertainty."

A physicist cautioned that teachers and students, who may be uncomfortable with not knowing the answers, might be reluctant to ask questions. Some teachers may not encourage questions because he/she doesn't know the answer.

> If teachers just learn that asking questions without knowing the answers is wonderful. Kids love it and you could be doing it in the first grade. Why not have teachers help kids ask questions? That's scientific inquiry right there.

As mentioned earlier, knowing the literature is important to a proper scientific investigation. It is considered instrumental in developing good and interesting questions in the field. Scientists who are well informed as to what is known can stretch the boundary between the known and the unknown.

> It was hard to get the point where I could ask an original question, where I felt I knew enough to ask a good question. It takes awhile before you know the literature. I felt I could ask original questions because I knew what had been done.

Helping students to develop good questions seemed to be equated with the terms a *testable* and *meaningful* question. Scientists mentioned the importance of developing a good question as driving the investigation. This can take the form of a hypothesis but one scientist scoffed at the traditional hypothesis statement.

> The way that many of the textbooks force people to teach and the way my son was taught in schools is you must have a hypothesis, you must write down your predictions. It's absolute gibberish. That doesn't make sense. That's not science. So the answer is you have to have a question.

What is considered more valuable than stating a hypothesis is deriving good questions. As a medical scientist claimed, "The hardest thing to do is to teach students the ability to ask the right questions." Scientists used the term *meaningful* to describe questions that contribute new knowledge to the field of study or those that would lead to interesting results. *Testable* questions are those for which scientists have (or can imagine having) the resources to carry out the study.

To ask, 'What is the meaning of life?' is not considered a good question because it is not testable. The term "falsifiability" also emerged when describing a testable question. Falsifiability refers to whether a question is capable of being proven or disproven; that is, the question or the hypothesis/prediction can be proven false. The example given by an environmental scientist is the question 'What will happen if salt is placed in water?' and the prediction is that the salt will dissolve in water. Then this statement is falsifiable because it is possible to prove or disprove the whether the salt will dissolve in the water.

> Science, as I have been taught and as I teach and as I practice, is something that limits itself to those areas in which it is possible to know when you are wrong. That's the nature of falsifiability and it's really what sort of sets the limits for what scientists are willing to blunder around in.

In inquiry investigations, teaching students to question contrasts with the approach of telling students facts. Telling students facts is teaching them what we already know. If we teach students to question and provide them with the tools to do scientific inquiry, students will be better able to cross the border between the known and the unknown and contribute to scientific understandings. Two scientists spoke with distain about teaching facts:

> You are saying, here's a fact, here's the procedure you can use to demonstrate to yourself that the fact is true. That's not science. That's history. Science is finding out what we don't know.

And,

> I mean simply telling people this is the name of this, this, this, this, doesn't really strike me as science. But having students make inferences about what happens when you cross this one with this one strikes me as having something to do with science.

Our subjects conceptualized the process by which scientists accomplish scientific inquiry as a set of interactive stages. The fact that these scientists framed their work in a common conception of the investigation process was a surprise. Based on our data of scientists' conceptions of the scientific method, however, it is readily apparent that the commonly used version of the 'scientific method' found in science textbooks needs to be revised and restated to fit a broader view of the way science is done. Several science textbooks surveyed depicted a linear progression of conducting science where the end result is either a theory or a law. Many scientists interviewed indicated that the process of conducting a scientific investigation is not linear but iterative. It is one where questions are asked along the way and emphasis is given to the process, not the end result.

> We all practice science to a degree, whether we are driving our cars and eating our dinners…I think there are moments at which we are in fact presented with alternatives and dilemmas and we proceed to go through some decision making. Now will they always follow along a scientific protocol or step-by-step methodology? I don't think so but then science doesn't either. Hypothesis, methodology, testing results, conclusions. Things don't move around in quite that progression; things get bumped around a bit and, I think, in everyday life I think it's the same way.

Thus, scientific inquiry does not follow in a linear path where each stage is completed before moving to the next stage. Scientists described the process of investigation as messier with stages that do not necessarily follow a particular order. For our subjects, the process of conducting a scientific inquiry can be viewed as a set of stages that answer and generate questions. These questions and their answers are the force that moves the investigation forward. In this model, scientists have the flexibility to generate questions along each stage and to revisit previous stages whenever needed. This fluid approach better portrays how science is practiced among scientists than the standard "check-list" found in textbooks.

<u>Qualities of Scientific Inquiry</u>

<u>Scientific inquiry is fueled by questions, which drive the investigation.</u>

The importance scientists place on questions in driving the scientific investigation is also evident from our data. Scientific inquiry is described as concerned with "asking questions in hopes of learning the next question." Questions are at the heart of any scientific investigation and serve to fuel an investigation. Lederman (1998) defines scientific inquiry as "the systematic set of approaches used by scientists in an effort to answer their questions of interest." The scientists in our study reinforce this view. Questions serve as the foundation for the bridge of knowledge to be built. A geographer echoed the central role of questions,

> You should question everything. Question, question, question. Why, why, why? If nothing else, science is important for that. It keeps everybody on his or her toes. If there were more scientists, we would be on our toes. We are not on our toes.

<u>Scientific inquiry is a process that focuses on the investigation and not the end result.</u>

An important feature of inquiry investigations is staying focused on the process of an investigation. Scientists who are primarily concerned with proving a hypothesis may overlook data in the rush to communicate findings to peers. An anthropologist described, "Inquiry is what keeps you from jumping to conclusions." The process of conducting an inquiry investigation involves forming questions, reviewing the literature, articulating an expectation, designing and conducting the study, interpreting and reflecting on the results, and communicating the findings. By following these stages with the ability to repeat previous stages better ensures that investigations are thorough and contain higher levels of internal validity.

Scientists emphasized the importance of helping students to focus on the process of an investigation and not just on getting the right answer. Scientists may take many months or years to reach conclusions and then may decide to repeat one of the earlier stages. If students are primarily concerned with getting an answer, they may associate science as a linear progression of steps that leads directly to a theory. As a medical scientist explained:

It's really about trying to get people to enjoy the process of learning and not just the answer. Same with my students, try to enjoy the process of getting a degree, not just obtaining one.

Scientific inquiry is an approach used in problem solving.

Some scientists related scientific inquiry to solving problems in their everyday lives. In fact, 39 out of 52 scientists connected inquiry with activities outside of the realm of science. "Let me put it this way, I can't think of many things that scientific inquiry doesn't one way or another play a role in a person's life. They are doing it but they don't know it's scientific inquiry." Trying to figure out why the car won't start, why an appliance has stopped working, or how to get the lights to come on involves using skills in inquiry to help find solutions to these problems.

People can approach and solve problems in ways similar to scientists solving a scientific problem. "I think science is just day to day problem solving, maybe in a different arena but the same process." Some scientists compared the act of farming or gardening to scientific inquiry. For example, a farmer is questioning the type of fertilizer that is best suited for planting a particular crop. Similar to a scientist, the farmer may ask experts about the problem or review information concerning different types of fertilizer and then designing an experiment to test the hypothesis. If further studies are needed, the farmer may repeat any of the stages mentioned earlier and redesign the experiment using different controls. The farmer can then decide to communicate the findings to his peers (farmers) or to the community. Scientific inquiry results in enhancing understanding of problems and in coming up with solutions to these problems.

Scientific inquiry is a natural way of thinking.

Scientists stressed that people do inquiry in their everyday lives without realizing it. Some scientists went so far as to insist that inquiry is a part of what it means to be human and that humans could not survive without it. The skills of identifying a problem, forming a question, searching for an answer, and making improvements are scientific skills that can be applied in everyday life. In fact, without these skills, some scientists insisted we would die. "You've been doing scientific inquiry since you were old enough to recognize patterns; you can't stay alive without doing it."

Scientific inquiry involves skills children possess.

A large group of scientists (38 of 52) indicated that the skills necessary to do scientific inquiry should be presented to children at a young age. When asked what age should people do scientific inquiry, a chemist responded, "Zero, I mean immediately because one of the keys is asking questions." Several scientists described how developing skills in scientific inquiry could start at an early age, even two and three year olds. Perhaps children would not be able to synthesize the information or analyze the results but the fundamental skills involved in scientific investigations such as making observations and conducting a test can be practiced at an early age. Even though scientific inquiry is considered a natural process of thinking and approaching the world, scientists recognized that children could develop the skills and learn about the tools necessary to carry out investigations. A natural curiosity about the world may be innate but in order to put the building blocks together to see the bigger picture takes analytical skills that may take time to develop. Some people do not move beyond the basic level of making observations. A chemist explained,

> I think it [scientific inquiry] starts at three years old. It's just different. It changes so at the earliest stage is probably purely observational. Let's categorize butterflies and let's look at the flowers and the shape of things. I think that is the earliest stage. It's purely observational, then classification but then, of course, I think it shouldn't stop at that stage. I think that for too many people that's what science is and that's a little tragic.

Scientists agreed that scientific inquiry skills could be refined with children. A geologist described skills such as observation occurring within a structured experiment beginning in kindergarten.

> You can say to a small child, let's see what animals come to the door if we put a can of tuna there. Let's see what animals come to our door if we put a banana out there. What about other things like Jell-O? A kindergartener can discover that raccoons eat anything, ants eat Jell-O and it's inquiry-based. It's what happens if…?

A geologist agreed that scientific inquiry could start with children because they are naturally curious. Perhaps they wouldn't be at the point to synthesize information or to make connections but children can start learning about the building blocks and then put the blocks together when they get older. A chemist elucidates this point "…but you can start with the first elements, say observation and then as they get older, you can build on some of the other elements."

Though children are not contributing original pieces of work, they are still working on the building blocks to do scientific inquiry. Through experience, these blocks can be constructed into an original piece of work.

> If you define science as a set of questions and answers tied together with logic than a toddler could do it but that's a very simple building block of scientific inquiry. If you define science as producing original work that needs to be founded on previous knowledge to identify what is original then it depends on your definition of inquiry. I think they're both right…the second one was more scientific work that leads to original work and the first one was sort of a building block on how to do scientific inquiry.

The scientists felt that everyone has questions and that scientific inquiry is a very effective process to get answers to many questions. Thus, there was a strong theme to provide people, especially children, with the skills and habits of mind to conduct scientific inquiry. Almost all the scientists felt that it was very important for everyone to understand the process of scientific inquiry. "If people understand more about science instead of being afraid of it then they would discover how to use scientific discovery wisely." Another scientist responded, "How do people make progress? How do we get where we are? There are lots of people that ask questions." Thus, asking questions builds on the knowledge base and progresses science from the unknown to the known (see below).

Scientific inquiry is the bridge that takes us from the known to the unknown.

Questions are the driving force required to cross this bridge. These are the questions that require us to learn what is known and then develop new knowledge in order to gain an answer. The new understanding will provide the basis for further questions. The answers to these questions refine our understanding of the world and the way it works. Here, then, is a connection between scientists' conceptions of scientific inquiry and their conception of the nature of science. For example, the scientists in our study understand that the "known" is not static. That is, science understanding is mutable and changes with time. New evidence and new models improve our understanding and supplant or adjust earlier ideas. Scientific inquiry provides a continual process of asking questions that challenge the existing knowledge base. Summing up this idea, one scientist informs the class he teachers as the following:

> What I'm going to tell you in this class are things that I think are true. I wouldn't lie to you intentionally. But, you know, twenty years from now you may look back on this class and say that everything I told you was garbage. Hey, if that is the case, then I'm sorry but that is the nature of science. My job is to train my students to prove me wrong. Of all people, my students shouldn't trust anything I say.

The idea of science extending the borders of the known into the unknown was viewed as being the key defining issue for good science. However, scientists also felt that extending *personal* knowledge and understanding of the world is also important. In particular, the role of children in taking an approach to knowing that develops the skills and habits of mind inherent in scientists' conception of scientific inquiry was strongly encouraged almost all of our subjects. They felt that children's exploration could be a model for genuine scientific inquiry, where the community's knowledge and understanding is increased. The focus of children in pushing back their personal borders between the known and the unknown can be aided with the tools and techniques of science.

Implications

This study provides an insight into scientists' beliefs regarding scientific inquiry; that is, what scientists believe they do and the general approach they believe they use. It adds to the literature regarding the nature of science as it applies to the issue of scientific inquiry. Lederman (1998) indicates that the conventional wisdom is that approaches to scientific inquiry vary widely within and across scientific disciplines and fields. Our results suggest that the approach to scientific inquiry is common to this group of scientists regardless of discipline. The tools and techniques that scientists' use in a particular study will, of course, vary with the goals of the study.

The set of characteristics for scientific inquiry determined in this study support those listed in the National Standards (p. 23):

> 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; communicating the results. Inquiry requires a clarification of assumptions, use of critical and logical thinking, and consideration of alternative explanations.

Additionally, we define the key goal of scientific inquiry as pushing back the border between the known and the unknown. Moreover, that scientific inquiry can be viewed through the lens of six over-arching qualities of scientific inquiry. Scientific inquiry

1. is fueled by questions, which drive the investigation.
2. is a process which focuses on the investigation and not the end result.
3. is an approach used in problem solving.
4. is a natural way of thinking.
5. involves skills children possess.
6. is the bridge that connects the known to the unknown.

These six qualities are gathered together into a conceptual model for scientific inquiry that is consistent across disciplines. This model contains the elements identified in the National Standards quote above, but captures these and other elements into distinct stages that can be visited and revisited as often as necessary in the course of a scientific inquiry.

An implication of this conceptual model of scientific inquiry is that teachers of science need to expand on the step-wise version of a scientific method as outlined in textbooks. Moreover, that reflection is an important part of a scientific inquiry. Students need to be presented with the opportunity to reflect on results critically with the goal of improving their experiment, rather than simply noting that they achieved a "right" or "wrong" result. Scientists rarely categorized results of their inquiries as correct or incorrect. Rather, they looked on their results as confirming their expectations or providing information to improve either their question, their model or experiment, or their understanding of the topic. Scientists in our study indicated that they work hard at thinking about their ideas and results, examining and re-examining them many times.

This implies that research is needed to explore the value and practice that university scientists place on modeling scientific inquiry in their college science courses (Gess-Newsome, et. al., in review; Southerland, Gess-Newsome, & Johnston, in review). How many college science courses, provide opportunities to do experiments, evaluate the results, and repeat or extend the experiments as necessary? The set piece right/wrong sort of laboratory is easy to grade, but not indicative of what scientists believe they do in their own inquiry. DeBoer (p. 192) points out that:

> It has long been a goal of science educators to develop in students ways of thinking that mirrored the way scientists think about the natural world. Development of these intellectual skills was important for two reasons. First, anyone who might become a scientist had to learn how to think like a scientist, and second, for those who would not become scientists, scientific thinking provided an effective way of dealing with their everyday world.

Conclusion

The combination of responses in defining scientific inquiry from nine science departments greatly enriches our understanding of scientific inquiry and provides intriguing insights into how scientists believe they do science. Scientists' conceptions of scientific inquiry did not seem to be influenced by the department to which they belonged. Instead, scientists across disciplines shared a common understanding of scientific inquiry that is not often elucidated to the general public. The most salient differences among our set of scientists appears to be the types of question scientists ask, the tools used to resolve the question, and the styles expected for formal reporting of the outcome. The general process of investigating their inquiries was consistent across all disciplines.

A key feature of scientific inquiry, as described by they scientists in our study, is a focus on scientific inquiry as a process. The process of scientific inquiry is fueled by questions, the answers to which provide a bridge between the known and the unknown. Moreover the process of scientific inquiry is grounded in appreciating two key aspects of the nature of science. These are that scientific knowledge builds upon and extends previous knowledge. That is, that scientific knowledge is accumulative. Along with this, that scientific knowledge is mutable and changes over time as the results of scientific inquiries are obtained.

This study is limited in that it examines scientists' conceptions of scientific inquiry and not their actual practice. Avenues of future research would include developing a better understanding of scientists' actual practice and whether or how it relates to the conceptual model provided here. Many of the scientists in this study indicated their feeling that young people should be involved in scientific inquiry in classroom or course settings. This also provides an important avenue for research and instructional development. Do scientists take their conception of scientific inquiry into classroom settings? An exploration of many issues raised by this question would help the science educators and scientists interested in science education reform to be more effective in their efforts.

The emerging patterns from our study provide an interesting array of possibilities and directions that lead us to further our understanding of scientific inquiry. Through this understanding, it is hoped that we can improve science education for students at all levels. A common conception of scientific inquiry is essential to aligning teaching practices with the National Science Education Standards. If teachers do not understand inquiry or have never been modeled scientific inquiry then they are unlikely to inculcate students with the skills and practice to conduct inquiry investigations. Scientists can help to better define scientific inquiry so that teaching inquiry really becomes the standard.

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Appendix A

Scientists' Conceptions of Scientific Inquiry Protocol, 2001

1. What is your definition of scientific inquiry?

2. What are the characteristics of scientific inquiry?

3. Describe the earliest scientific inquiry experience that you had?

4. What kinds of skills are necessary to do good scientific inquiry?

5. In what ways does scientific inquiry require higher order thinking skills?

   (Does doing science require skills such as application, synthesis, analysis, and evaluation?)

6. Can you provide an example of an activity that requires doing scientific inquiry?

7. Is scientific inquiry valuable? Who should do scientific inquiry? At what age?

8. Would you like to add to or make changes to your definition of inquiry?

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Organization: Association for the Education of Teachers in Science

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