The Multiple Meanings of Tentative Science

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Abstract: The notion that scientific knowledge is tentative is an important and emphasized concept within the nature of science. Its meaning, however, can be described in many different ways, even by scientists, educators, and philosophers. Of greater significance to us is that, when referring to science as being "changeable" or "tentative", our science students can have specific conceptions that contradict fundamental aspects of the nature of science. This research considers in-depth, qualitative case studies of 4 college learners enrolled in a physical science course that caters to the needs of preservice elementary teachers and emphasizes the nature of science, science process, and science teaching methods. These learners each describe various degrees to which science's knowledge can be tentative or changeable, yet they each describe different and misleading interpretations of this concept. We argue that students develop or apply differing forms of "tentative" to science in order for this definition to coincide with the epistemological standards they associate science to have. Thus, an apparently slight misinterpretation of science's tentativeness may be indicative of a more fundamental misunderstanding regarding science's way of knowing. Moreover, such misinterpretation has implications for what we believe we teach and what our students are actually learning, or failing to learn.

Scientific knowledge can, and does, change. This is one of the fundamental tenets of the nature of science as viewed by science educators, and it is a fundamental piece of understanding necessary in becoming scientifically literate (American Association for the Advancement of Science [AAAS] 1990; National Research Council [NRC] 1995; National Science Teachers Association [NSTA] 2000). Yet, to say that "science changes" or that science knowledge is "tentative" can have many different meanings and can highlight many various aspects of the process of science (Alters 1997; Lederman & O'Malley 1990). For the purposes of teaching and learning the nature of science this has deep implications. Our work investigates not just how philosophers conceptualize the changing of scientific knowledge, but how learners in an authentic context understand this concept. Our purpose is to elucidate more about the process of learning this philosophical tenet, and how this can ultimately inform teaching.

The AAAS succinctly describes the typical manner in which we envision the changing nature of scientific knowledge: "Change in knowledge is inevitable because new observations may challenge prevailing theories. No matter how well one theory explains a set of observations, it is possible that another theory may fit just as well or better . . ." (AAAS 1990, p. 2). As advocated by AAAS and other standards of science literacy, this concept is one that we hope our students eventually will learn during their educations in order to contribute to and understand society.

There is a subtlety in this concept that can be easily missed, however. If it is "possible that another theory may fit just as well or better," then theoretical knowledge itself must be a construction of humanity, rather than a simple set of direct observations. This is another piece of the nature of science that is essential to a literate science understanding. The very epistemology of science – how it comes to produce knowledge – is interwoven with its tentative nature. If tentativeness itself is a concept that is difficult to come by

(Lederman 1992; Lederman & O'Malley 1990), then the epistemological foundations of science should be even more difficult to grasp.

The great irony (and beauty) of scientific knowledge's tentativeness is that this very feature is what makes its knowledge so reliable and useful. Students may see a societal dependence upon scientific knowledge, but it is not obvious that this is a result of how science's knowledge must be continually be tested. The very nature of scientific practice is to continually reengage and refine theoretical constructs by collecting more data and testing current explanation. This continual testing is an inherent requirement of knowledge that is dependent upon the natural world and its empirical data, yet seeks to create explanation for the mechanics of the natural world. Science becomes more and more reliable as we continue to question all knowledge it has created.

And thus, understanding the process by which and reasons for which scientific knowledge can change is likely paramount to understanding the nature of science. Conversely, we may be tempted to assess students' understandings of the nature of science by determining whether or not they know that science knowledge changes. The issue that we illuminate in this paper, however, is that learners can know that scientific knowledge changes, and they can apply this to many specific situations and attribute multiple meanings to the same semantics. Our work shows how learners can vary not only in whether or not they conceive science knowledge to be tentative in nature, but can display a wide variety of significantly different meanings when stating that scientific knowledge is tentative. A student who claims, "science can change," may mean something far more superficial than what we, as science educators, strive for. The misconception, we argue, is deeply rooted to a learner's understanding of science's epistemological stance. The significant implications for how we come to learn about the nature of science are explored after the explication of our data. We preface these discussions with a brief consideration of the philosophy of science.

Classroom Discussions of the Philosophy of Science

We must explain to the reader that we are approaching this work as *science educators*. Thus, while we appreciate the work of philosophers, we consider this work only for the purposes of science teaching and learning. That is, we are not pretending to contribute to the work of philosophers in what follows, but rather present some philosophical case studies that may make appropriate adaptations for classroom discussion.

Imagining any number of classrooms from the middle grades through the university, a class discussion may be directed to simply try to tackle the question, "Does scientific knowledge change?" Students at a variety of levels could be able to cite historical as well as current examples of such change. The Earth is no longer at the center of the universe. Species change. Continents shift. Time is variable. These "truths" were not always so. But quickly the conversation becomes more difficult. What is science's knowledge changing towards? Does it get closer to some absolute truth? How could we be sure? How is it that we know when to change our scientific knowledge? What mechanism is there for change? What kind of control do we have over this change? These questions ask about the very foundations of science and its knowledge production.

One view regarding science might be likened to natural selection: A scientific explanation is continually used as long as it successfully describes observation of the natural world. At the same time, the explanation is continually under trial, continually tested, to see if it fits with existing data. Explanations "survive" as long as they can account for data of the natural world, thus this accounting for data is a measure of the explanation's fitness, much like the ability to bear young is a measure of a species' fitness. Explanations die, and are replaced by a more fit explanation, whenever they cannot account for occurrences of the natural world. In this way, scientific knowledge evolves in small, ever progressing steps. Ironically enough, the manner in which such progress is attained is by falsification of the knowledge that is least correct. This view is a one-paragraph simplification of that which Karl Popper has advocated (1973; 1962).

Another view could still find significance in the testing of scientific explanation, but may suggest that it requires a greater upheaval before scientific knowledge can change. Instead of one falsification, it may take a great number of these. And furthermore, whole new ways of thinking about nature and about science itself may have to change in order for new explanations to be understood and realized. Change in science's knowledge, from this point of view, is largely painful. The world of science accomplishes much more – filling in the details and piecing together loose ends – when these radical shifts do *not* occur. Rather than being a welcome change, this view of changes in scientific knowledge suggests that it is a painful adjustment in which new ways of seeing and studying the world must be thought of in order for science to proceed. This view of revolutionary change in science is similar to that of Thomas Kuhn and many who would later build on these philosophical ideas (1970; 1962).

Still another view might be seen as an odd compromise between the previous two. Imagine scientific change as taking place in small, evolutionary increments. In fact, imagine that they occur with regularity, simply as a result of new scientists entering the discipline, and old scientists, along with their outdated ideas, dying off. Although similar to the proposition of Popper because such change could occur without changing the entire worldview of science, the idea is also similar to the notion of Kuhn in that the knowledge of science is determined by something other than the natural world. This position is often referred to as the *Planck Principle*, after the quantum physicist who remarked that scientists cannot often change their ideas and beliefs, but that it takes a new generation of scientists to support a new set of ideas. Holton and Brush (2001) pose how this plays out in the history of physics in certain circumstances. Hull and colleagues even show how this applies, in part, to the Darwinian revolution in the mid-1800's (Hull, Tessner, & Diamond 1978).

The point of teasing these different philosophical stances is this: Even if we barely scrape the surface of the issues within the philosophy and history of science, it is clear that tentativeness in science is not a simple concept. It entails a level of consideration that is much deeper than simply, "science can change." Even as we consider explicit, reflective instruction of the nature of science as advocated in the literature (e.g., Akerson, Abd-El-Khalick, & Lederman 2000) and engage students in the three discussions considered above, finding resolution to these philosophical debates would be difficult to come by, especially for those whose training is in elementary education rather than in the philosophy or science.

The views of science advocated by science education standards (AAAS 1990; NRC 1995; NSTA 2000) are relatively straightforward in that they paint science as an endeavor that is always trying to collect more evidence and construct more accurate explanations. Considering *how* to frame a classroom discussion or activity about this concept, though, is a much more complex problem. There are multiple ways in which science *could* change, and multiple causes for such changes; and as a result, simply teaching the standard "science is tentative" concept in an informed explicit, reflective manner, could fall short of giving students a fair shot at really understanding science. Given this, our research question is to consider how students actually conceptualize the process of scientific change, given the many implicit possibilities. We look to this research to help inform our own teaching and our curricular decisions, as well as the assessment of student learning.

Methodology

In our research, 4 preservice elementary teachers' conceptions of science were investigated via qualitative case studies. These individuals all were enrolled in a university physical science course aimed at providing physics and chemistry content knowledge, teaching methods, and nature of science instruction. Teaching the course were two experienced science faculty from physics and chemistry, both with a dedication to undergraduate education, at a regional university in the western United States. Each case participant was selected from a pool of students who were dedicated to becoming elementary teachers and were willing to participate in the study. Even though each of these students had the same professional goals (to become elementary teachers) and educational background (high achieving, but minimal science coursework), each case study participant was selected in order to represent a different perspective regarding the nature of science. In order to select the 4 participants, a brief questionnaire about the definition of science (Abell & Smith 1994) and the Nature of Scientific Knowledge Scale (Rubba & Anderson 1978) were administered to all students in the course. Although these probes provided some data, their most important utility was to provide some clue regarding the initial nature of science views of students, and to give us the ability to select participants whose views were varied with respect to one another. (This deliberate sampling may have been more than what was necessary, due to the variability in responses across all students in the class.)

These 4 individuals each participated in 7 interviews (30-60 minutes) throughout the duration of the course's semester. Each interview was semi-structured and planned so that each student experienced the same interview theme and roughly the same time in the semester. The topics of each interview were as follows:

1. Science education background information is collected (e.g., what science classes have been taken, etc.). Questions about students' definitions of science and its purpose.
2. Review statements on the NSKS. Debrief class activity in which the volume of a penny was inferentially measured. Describe the teaching of science and the nature of knowledge in a science textbook.
3. Cart sort of terms relating to the processes of science ("fact", "theory", "experiment", "observation", "trials", "hypothesis", "law", and "variable" [Gess-Newsome 1999]; and additionally "religion", "science", truth", "known", "changeable", "progressive", "stable".)
4. Reaction to reading about Zuni Indian tribe's interpretation of NASA missions to the moon. Comparison of science to art, history, and writing. Description of trial and error method of designing a functional water wheel in class.
5. Describe the atom (review of class) and discuss how knowledge of the atom is obtained and how certain we are of it.
6. Critical Incidents (Nott & Wellington 1998) regarding how they would, as teachers, deal with various instances in which scientific knowledge seemed questionable in classroom experiments or in light of being controversial. Description of an ideal science lesson.
7. Revisit of the card sort. Questions about students' definitions of science and its purpose. Debriefing of the course and interview sessions and what has been learned by students.

Data, in the form of interview transcripts and field notes, were analyzed via grounded theory (Strauss & Corbin 1998) in order to find themes in the case study participants' responses that reflected their understandings of specific aspects of the nature of science. These themes were compared so as to trace any development of each participant's nature of science conceptions throughout the duration of the semester, as well as to show the distinctions between all participants' conceptions.

To make sense of each learner's conceptions of the nature of science as they developed, descriptive narratives and summative tables were created to document a researcher's interpretation of the data. These products and their explanations were then checked against the data in search of negative instances and elaboration. From this, the narratives and tables were revised. Then, the results of each case study could be compared to one another. Specifically for the purposes of this research, a comparison of how these four individuals described scientific knowledge in a variety of instances was made. This was done by isolating all data in which the tentative nature of scientific knowledge was described by case study participants and/or initiated in an interview probe. These data clips were accumulated in order to produce a summary of each learner's conception of the tentativeness of scientific knowledge. What resulted was a set of conceptions unique to each learner that could be compared and contrasted to the other learners' conceptions.

Results

The conceptions of tentativeness of the 4 learners probed turned out to be quite rich and elaborate. Although the views used were not completely consistent within each learner, there did exist very clear tendencies for each individual. The benefit (from the standpoint of a researcher) of having each learner with a different overall conception of science is twofold. First, it demonstrates quite nicely that there are many conceptions of science and its tentativeness to be had in the first place. After all, we only needed to look at 4 individuals in order to find 4 unique conceptions. Second, it allows us to demonstrate how a learner's conceptual framework is internally interactive; that is, the concepts that each learner considered were interdependent. This aspect of nature of science conceptions will be revisited in our discussion.

In the following sections, each of the 4 participants is described in detail, along with the general theme of her conceptions of how scientific knowledge changes. For each individual, a specific set of conceptions and their interactions are described.

LAURA: INCREMENTAL KNOWLEDGE BUILDING

Laura is like many of our university and high school students. While she looks forward to eventually teaching upper elementary grades, she has a fair amount of "science anxiety" and she has felt more alienated from than invited into science classrooms. She sees the processes and knowledge produced within science as being straightforward. Most of Laura's reflection regarding the nature of science portrays it to be an endeavor that simply builds upon itself, most knowledge being already well established. Science itself is mostly a large archive of "knowns".

Laura tends to sit in the back of the classroom, attentive but inconspicuous during class. She performs well in the course, maintaining a "B" average that matches the average scores of the entire class, but she has the low confidence in her abilities, especially in science. Reflecting on her previous experiences with science coursework, Laura admits that she can be "intimidated" (LaQ1) and "scared" (La1, p. 3) of the content covered in science courses and she implies that she generally hesitates to take such courses. (She is only enrolled in this particular course because it fulfills a requirement for the elementary education program.) On the other hand, she has also taken some geology courses that she enjoyed very much and felt successful in, making her think that she might be capable of incorporating some geology in her future elementary classes.

Responding in the written questionnaire before any interview sessions, Laura notes explicitly that she is taking this course so that she "will know how to teach my future students what science is and how it works" (LaQ1), but this is a rare instance in which Laura emphasizes anything about the processes of science and the definition of science. In most other cases, Laura describes science in terms of what it knows, describing it as "the earth and what it contains" or "what the world is made of and how it works". Laura is reflecting her own emphasis of science as being wholly summarized as the knowledge that is generated by science. Even more specifically, Laura shows her own bias towards learning about earth systems science rather than biological science or some other scientific discipline. These attitudes are similarly reflected in the first interview when Laura is asked to define science in an interview: "I always just think of the earth and how it's made" (La1, p. 6).

In an interview session, some statements regarding the tentative aspect of science were discussed briefly. Laura, sounding unsure of herself, begins to indicate that there are many pieces of scientific knowledge that we have yet to figure out: "[W]e just don't know everything" (La2, p. 8). She discusses the idea that there are things that science does not know, rather than discussing anything about errors or tentativeness in what scientists already claim to know.

Since it was difficult for Laura to describe the nature of scientific knowledge in general terms, we looked to a textbook written by her physics professor. The textbook in astrophysics is briefly described, and she is asked about how sure we are of the knowledge that is in it, specifically the knowledge that we claim regarding the temperature of the Sun. "It's probably . . . pretty sure, because it's in the book I guess" (La2, p. 8). Laura is less hesitant about making this statement than she was in describing scientific knowledge without any concrete examples. She suggests that having scientific knowledge written down makes it less likely to be changed than if it were not in a text. In general, Laura's descriptions suggest that, since we do not already "know everything", she still perceives scientific knowledge as something that could continue to look for new information. At the same time, she explains that the scientific knowledge that is currently written into textbooks must only be recorded because it is well known and not susceptible to revision. Her basic stance is that science can continue to add new information, but that the information that already has been gathered is largely static.

In a later interview session, Laura is asked to sort cards with terms (as described above) on them in any arrangement that makes sense to her, and then to explain her arrangement. One aspect of all of Laura's sorting tasks that is consistent is her omission of three terms: "stable", "progressive", and "changeable". The fact that Laura leaves them out suggests that she does not actively consider what these terms, or their implication of tentativeness, have to do with science. So, even if Laura were to show a conception that scientific knowledge is tentative, it seems that such a description for science is not one that Laura considers to be pivotal.

Science is an important endeavor in Laura's perspective, since "we wouldn't even know what was around us" if we did not do science (La4, p. 4). Asked why it is important to understand such things, Laura describes that "I don't know -- just, for me, it's important just to know about what God's created for us . . . It's hard to understand it all, but I think [that it's] important to learn" (p. 4). In this light, Laura does not just view science as one way of forming an understanding the world and our place in it, but as part of *the* way (in a singular sense) of understanding the world.

One interview probe simply asked Laura to describe the definitions of *fact*, *law*, and *theory*. To Laura, a "fact" is "just something that we've found that is true . . . just a 'fact'" (La4, p. 6). When asked what example she can think of, she refers to the current (as of this particular interview) content of the class: electric and magnetic fields. She justifies this by describing "that you see it and that's how it works" (p. 6). What Laura did see in lab and describes as seeing are the effects of electric fields (forces exerted on pieces of aluminum foil and light bulbs emitting light) and magnetic fields (the deflection of a compass needle), but she still describes the fields themselves as the facts that are known. A scientific law, Laura admits, she does not really have any idea of, other than it might be "something you have to follow", seemingly suggesting the more societal definition of a law (p. 6). A scientific theory, however, is some kind of a "new idea" (p. 6) that is different from a law in that "everyone didn't just believe because . . . I guess [it] wasn't fully developed enough" (p. 7). Throughout these descriptions, scientific knowledge is described as either pieces of information which are virtually self-evident, or are brand new pieces of information that are simply added on. Again, there is little depiction of change.

As a result of taking this physical science course, Laura notes that she sees science in more contexts than she did before. However, this perspective of science is consistently limited to the knowledge base of science rather than its process and way of knowing aspects. Science, to Laura, is the "things that we use everyday" (La7, p. 1) and "how the world works", including "how we move, live, and function" (LaQ2). In line with this idea, Laura's emphasis on what is important to know in science has to do primarily with scientific concepts and really understanding them.

Laura's primary view of the scientific change is that it builds incrementally, adding to the pile of knowledge that it already has at its disposal. In fact, Laura's view of science is much less a view of a means of knowing than it is a set of knowledge itself. Science, and the process of learning science, should simply be an accumulation of knowns that can be directly observed. This extended even to Laura's impression of scientific constructs that were much more inferred than observed (e.g., the temperature of the sun, electric fields, etc.).

Most likely, there were others in the same class as Laura who held similar views, even though they were enrolled in a class that described explicitly the nature of science and the tentative nature of its knowledge. Our other three case studies, on the other hand, each demonstrate an awareness that scientific knowledge can and does change. However, these conceptions are established upon very different bases.

JAMIE: TENTATIVENESS DUE TO ERROR

In general, Jamie is quiet, keeping a low profile both in and out of class. Her slight frame and careful persona enhance her quiet character. Jamie is careful in most everything that she says, often preparing her responses to interview questions with long pauses of thought. A consistent theme throughout Jamie's characterizations of science is that the process of science is analogous to learning. As such, Jamie sees the knowledge that science builds as being susceptible to error, just as humans are prone to be mistaken. Still, just as humans eventually learn from their mistakes and eliminate error in order to perform well on an exam, Jamie suggests that science eventually scores well on its final exams. That is, despite the fact that science can contain error, Jamie sees this as just part of a process that leads to immutable and correct knowledge in most cases.

Jamie was typically comfortable with the coursework, though she scored marks in the class that were slightly below the class average. In interacting with Jamie in interviews, however, she seemed to have a much greater capacity to understand difficult concepts than any of the other case study participants and certainly seemed to have more aptitude than her grade (a "B") would suggest. Jamie was certainly a dedicated student, often spending extra time after regular interview sessions to review course materials, or even to review math principles and music concepts from other courses.

Jamie's desire to be a teacher has been partially supported by her working with and observing an excellent teacher at the kindergarten level. She describes how in that particular classroom, science was presented as something that children can do for themselves and have fun with – in fact, investigations were integrated into their playtime. This is contrasted to the kind of science education that Jamie experienced herself in elementary school: "We read from the book and answered the questions. That's all we ever did" (Ja1, p. 4). Jamie realizes that there is more to science than this, and that there is merit in teaching science in an interactive and fun manner. She anticipates that the activities and portrayal of science advocated in this physical science class will be the kinds of things she would like to use in her own classroom.

In the earliest interview sessions, Jamie begins to lay out her ideas about science and how it changes. From the beginning, her analogy of science-as-learning is explicitly stated. Jamie will readily agree that scientific knowledge could have error in it because, for her, this is all part of the learning process: "That's the first step, probably. You have an idea and then you go and share it with other people . . . And then they can work together as a group and somehow make that knowledge into a law . . ." (Ja2, p. 4). Once such knowledge attains that status of "law", Jamie feels that it should not have any errors. The idea of scientific knowledge as tentative is agreeable with Jamie, so long as the knowledge itself is somehow still under development. Once it reaches some mature stage – what she refers to as a "law" – it should no longer be mistaken.

In a later interview session where she is describing her card sort, Jamie discusses the process of science and how such a process involves laws and theories. She sees these two concepts as being different steps along a progression:

> *Jamie*: So you can have a theory and it becomes law.
> *Adam*: Okay. Once you get to a law, then what can happen? Or is it done?
> *Jamie*: I thought it was done . . . because you have to, he said, you have to go to a board of scientists or whatever and they decide. (Ja3, p. 5)

In class it had been suggested that laws and theories were similar to one another in that they were testable but represented a very strong statement (rather than a speculative one) about how nature operates, based on evidence. Jamie recites what was stated in class but adds a statement: "A theory becomes a law", as though it is a different kind of entity or stage. Further, Jamie suggests that laws are not tentative, referring to some board of scientists that decide what becomes scientific law. In class, it was noted that science was not a process of one individual, but was pursued by many individuals who communicated with each other via journals, conferences, etc. in what is referred to as a "communal experience" (FN03.1). Jamie pictures this scenario as some committee of scientists who pass judgement on explanations, deciding whether to grant them the status of "law", and thus something that is no longer tested. As she organizes the cards with terms on them, Jamie makes a conscious distinction between scientific "laws" and other constructs: "Ohhhh . . . I should have put this [law] over there" (p. 6), away from anything that is associated with changeable.

It is interesting that Jamie associates "changeable" with science, but considers "law" to be so static. It appears that science does change and progress, but at some point Jamie sees this as reaching an ending, what she calls a scientific "law". In this probe and others that analyze a learner's distinction between "law" and "theory", it is less important that the participants know all the details regarding the exact distinction between these terms, but very informative to see what other conceptions the specific uses of these terms can reveal. Her constructions and uses of "law" and "theory" are not simply impromptu descriptions, for she uses them repeatedly throughout the semester.

Throughout the entire semester of interview sessions, and reemphasized in the final interview, Jamie says that the purpose of science is basically to produce knowledge, providing explanations for those who want to know (Ja7, p. 7). In addition to this, Jamie suggests that the importance behind teaching science is not only to provide explanations and knowledge, but to give students skills in thinking and asking questions. These skills become valuable not just for conducting science, but in all thinking and problem solving. In sharp contrast to the 2 case studies yet to be described, Jamie's views of the purpose of science never refer to anything utilitarian. In contrast to Laura, who sees science knowledge as what can be directly observed, Jamie describes science as a process of explanation of the observables. Again, using the analogy that science is a process of learning, Jamie sees science as a great tool for figuring things out. Although such a tool could occasionally be used incorrectly or give false results, eventually these mistakes are corrected. With constant effort, eventually science should understand the correct answers. The assumption Jamie is making is that the natural world is explained directly via our observations (rather than by constructing explanations based on such data). Although we could mislead ourselves, eventually nature herself will simply be uncovered.

MICHELLE: HISTORICAL TENTATIVENESS

Michelle walks into class and promptly and quietly takes her usual seat towards the back of the classroom. Armed with a cup of hot chocolate from the student union, she looks prepared but casual, composed but flexible. Michelle is soft spoken and never speaks out in class. In fact, other than a single streak of bleached hair, Michelle draws little attention to herself. Yet, her capacity and awareness of her capacity for science are very clear and perhaps worthy of some attention. Michelle "love[s] math", and she professes a joy in taking calculus exams in high school (Mi1, p. 1). Likely the least apprehensive about science of all of the case study participants, Michelle sometimes notes that she is bored in class since she is familiar and confident with much of the material.

Such boredom, rather than the result of Michelle's *not* wanting to think about scientific issues, is the result of her desiring to better understand many wonders of nature. Michelle shows fascination for the natural world, revealing her intrigue for certain concepts during the interview sessions. These interests stem more from other media (mostly TV) than from the course. For example, when discussing the surface temperature of the Sun, Michelle segued into a question about lightening, asking if it could really be hotter than the surface of the Sun. Such a fact amazed her and piqued her interest, as do other facts that she comes across. Michelle finds a great deal of merit in what science states for its knowledge: "I pretty much believe everything science says" (Mi2, p. 2). Many of Michelle's interests in science are related to biology, though many of her greatest fascinations are with natural disasters, such as earthquakes and the possibility of earthly asteroid collisions.

As she describes in the first interview, Michelle uses her previous experiences in science classes as well as her experience during the 1st week of this class to define what science is: "using data, experiments, and experience to determine how the world works around me" (MiQ1). In a subsequent interview, Michelle continues to describe science as a process. Like before, Michelle claims that science is all about "finding out about the world around you . . . using all of your senses, thinking a lot, figuring out things" (Mi1, p. 4). Asked, "Why do we do science?" Michelle begins to hit on a theme that will become familiar throughout her interviews. The theme is that of *utility* – that, even though science is done because we are curious about the world and want to obtain a better understanding of it, ultimately such an understanding should be of some important human use. Quite justifiably, Michelle points out that there is "tons we don't know"(Mi2, p. 1). The "tons" to which she is referring and most concerned about, however, have to do with "like if something is going to come and hit the earth, we should know about it – you know, to survive things" (p.1). For subsequent probes, Michelle is asked to describe more about science and some of its attributes. When asked, "What is the importance of science?" Michelle, in typical form, says that science is "understanding the world around us, so that we can become more and more advanced" (Mi4, p. 3). As she explains her statement, Michelle describes becoming more "advanced" as meaning that we will be able to better survive – to fight disease, prevent disasters, and increase our ease of living. Michelle even emphasizes this as part of what she would advocate in her own classroom as the reason we need to do science: "[S]cience does everything in the world. . . . learning about diseases and everything like that, I think it's really important to find cures . . . also I don't want to get hit with some asteroid or have some huge ol' earthquake that no one knew about" (Mi6, p. 7).

In a majority of instances, Michelle shows a very strong tendency towards suggesting that scientific knowledge is tentative. This view of tentativeness is quite specific, however. Although consistently suggesting that science "is always changing" (Mi2, p. 3), Michelle considers this tentativeness to be a dying attribute of science. "I think [scientific theories] are changing, but I don't think they're changing as much, because we have much more technology" (Mi2, p. 5). Thus, it would seem that Michelle sees science as something that can and does converge on the truth of nature. Michelle further exemplifies this when she describes how creativity applies to explanations in science:

> I don't really agree with that [the idea that a scientific law expresses creativity]. I think that the . . . actual law doesn't come across to me as being creative. But when I think about what went on behind it, like uh, just the main thought that brought it up – the hypothesis or whatever – that seems creative to me. But when I look at a scientific law, I don't think creative. It's a fact (Mi2, p. 3).

Michelle separates the scientific product from the scientific process by suggesting that only one of them, the process, is a human creation. The products of science, while before suggested to be tentative, are given to us by nature. One would suspect that such gifts must also be correct, or as Michelle refers to them, "facts".

In her card sort, Michelle makes special mention of the following terms: "changeable", "progressive", and "fact". As Michelle describes the terms, science is both changeable and progressive, and she implies that the two are synonymous. That is, if any change is to take place, it must be a progressive change: "If something's changeable, then it's going to progress – become bigger and better" (Mi3, p. 2). Becoming more correct, science ideally leads towards something that we find "in the book" (p. 3), what Michelle refers to (in this instance) as a "fact". When pressed, however, Michelle distinguishes facts from laws by noting that facts are the more obvious and immediate observations that one can make: "A fact would be like, 'this is a tape', and, 'that color is red'" (p. 3). In comparison, laws give more general predictive descriptions of the world. At this point in her explanation, Michelle is asked which of these two science is most concerned with, and she replies that "science is going after truth, the truth about everything" (p. 3). In a later interview, Michelle suggests that there are pieces of knowledge that can be "proven" (Mi4, p. 5).

For Michelle, tentativeness of scientific knowledge is ascribed to historical errors and is mostly done away with in light of modern science and its use of technology. Since nature and its explanation are discovered directly, according to Michelle, this understanding of tentativeness is reasonable within her own conceptual framework. Furthermore, there seems to be a connection between the idea that science should have some specific, utilitarian purpose, and the fact that its tentativeness is only a historical issue. By perceiving science as a technological method of changing the world, there may be less room for any change in science. That is, if science has only to serve a specific job or purpose, then the entire notion of tentativeness does not really come into play. Tentativeness is only important if science's purpose is purely for explanation, and this is not the case for Michelle.

JONI: BELIEF INFLUENCED TENTATIVENESS

Joni exhibits a contagious enthusiasm for science and learning. Upbeat and never lacking for words, Joni's personality produced enjoyable interview sessions, although her fast paced and plentiful words provided a formidable challenge for transcribing audiotapes. In class, Joni displays a similar enthusiasm and willingness to participate. Joni's enthusiasm was reflected in her performance in the course, as she earned the highest scores in the class of any student. Perhaps this fervor was especially applied towards the sciences: "I really enjoy science courses. . . . I think science is really fun and you can do a lot of neat things with it" (JoQ1).

Joni is always looking for ways to integrate different aspects of her life and different aspects of society. For example, Joni tries to bring together descriptions of different school subjects, incorporating health issues with scientific ones, and describes how religion and science can be incorporated to produce a single, personal understanding of the natural world and of our existence. Joni considers teaching at a variety of levels but generally describes the desire to teach upper elementary levels. Quite enthusiastic about what she learns in this course, she is very excited about giving her own students a similar, hands-on experience in the classroom. She wants to show how science is related to students' lives, especially as it relates to health and the human body and to students' immediate surroundings.

Although Joni's first response to "what is science?" or similar probes is typically a response that suggests how science is a way to understand something, Joni is quick to follow up on this and emphasize that science will "improve the quality of life" (JoQ1) or will "make our lives easier" (Jo1, p. 7). Joni knows (or at least claims) that science is a means of understanding, yet she understands it to have a very definite purpose. That purpose is a pragmatic one, reflecting that science should produce some kind of useful result. Joni seems to be able to incorporate this purpose of science with her more formal definition of science: "Science explains things that I do all the time" (Jo1, p. 11). The emphasis here is that science could explain for Joni how to cook certain things or to help create things that are useful in our everyday existence. In a subsequent interview, Joni continues to describe science in a similar light, more explicitly than before:

> You need to have your priorities straight in science, like what things need to be dealt with first, like where the money needs to go. Like I sometimes think, well maybe you should take the money from the space project and put it more in . . . cancer research; or, age research; or, something that can help the people here and now. . . . And science's [greatest benefit is in] helping people. (Jo3, p. 5)

In interview sessions and preliminary instruments that asked about the nature of scientific knowledge, Joni shows a strong agreement with the idea that scientific knowledge is tentative. Joni elaborates on this and makes her views more clear, describing scientific knowledge as something that is subject to change. At first (and second) glance, Joni's conceptions are what we hope them to be, yet in clarifying and exemplifying her understanding more clearly, it becomes evident that the "tentative" aspect of scientific knowledge has a very specific meaning for Joni:

> I think some of the things [scientific knowledge] are beyond doubt. . . . Like some of the laws, like gravity. . . . but there's some things like evolution theory, and . . . natural selection. . . . well, some of those things might be proven, but I think there's some doubt. (Jo2, p. 8)

Ironically, that which Joni imagines we understand "beyond doubt", such as gravity, is in fact a continually researched concept. (Though we observe consequences of gravity readily, understanding its mechanism – how gravity exerts itself – is much more mysterious.) Joni is reserving the idea of tentative knowledge for that which seems less agreeable or likely to her, rather than as a facet of all scientific knowledge.

As with other case study participants, Joni's conceptions of "fact", "law", and "theory" reveal more about what she thinks of science than do they give us clear definitions of these particular terms. Joni, upon being asked how to define these, immediately wants to go back to her class notes to get the correct definitions, but she tries it on her own anyway. "Off the top of my head, [a fact] would be something that's been proven so much over and over and so much a part of our everyday life that no one would challenge to say it was incorrect" (Jo3, p. 8). When asked for an example, Joni suggests "gravity". Scientific laws and theories are more intimidating for Joni, and she starts by noting that in class they were described in similar veins. (Joni recalled the statement from class correctly, but did not remember that the context of this statement was in regards to a "law" and a "theory" as both being equally tentative.) Joni compares these to facts, noting that "laws are something that no one has been able to prove wrong [even though] they're continuing to try; . . . [whereas] facts, maybe people stop testing them" (p. 9). Joni contrasts her present concepts of these terms to how she otherwise would have thought of them, laws as being "more absolute" and theories being more speculative. But, she has an awareness at least that theories are "in the same world [as] laws" (p. 9).

For Joni, it is easy to describe the interaction between science and religion. These interactions can play out in different ways. One example:

> A lot of stuff that I've learned [in science] really coincides well with what I believe; just how [everything] was created with different masses and everything. So, it could be created 6 million years ago, even though our Earth is only 6000 years. . . . So that's just how it all works out. (Jo4, p. 2)

Although it is not exactly clear as to how scientific knowledge really coincides with Joni's religious beliefs (since scientific knowledge would not date the beginning of everything as occurring only "6 million years ago"), she feels confident that it does. She also sees this integration with others around her, describing doctors and professors who are in leadership positions in her church (Jo4, p. 5). Joni imagines that scientists integrate their scientific knowledge into their religious beliefs as well: ". . . after [scientists] see science, they can see ways that it works with their religion" (p. 7). Thus, not only for herself, but in all cases, Joni views the knowns of science and religion as working together towards one way of understanding.

In other instances, Joni tries to compromise science when there is specific conflict between its knowledge and the beliefs of her religion. Whereas in previous interviews Joni was quite clear that "theories" are valid scientific constructions, she changes her tone when she is asked to consider how to treat a circumstance in which a student protests the explanation posed by big bang theory:

> I'd just tell them that there's, that just because it's a theory, it's not a fact yet, but it's been tested for a long time, but in a way that it could fit together with their church. [They can] believe how they believed, and they could take the knowledge that was in the book as they wanted to take it. There's no one forcing them to believe in the theory of the big bang. (Jo5, p. 5)

Joni's personal tactic of integrating her knowledge of science with her religious beliefs is something she advocates for others as well. This is not so surprising in light of other probes. What is surprising is that Joni describes big bang as "a theory, [but] it's not a fact yet", suggesting that theories are these speculative and not-well-understood nor important facets of science. Although this may be a relatively typical view, it is not the view that Joni suggests in other probes, such as the card sort. When faced with a direct conflict between her beliefs and the knowledge produced by science, her elicited view of scientific knowledge changes radically.

Overall for Joni, science is tentative. However, on this point Joni can contradict herself with other, overriding conceptions. Some scientific knowledge (Joni's example is gravity) seems well accepted and beyond doubt, and thus nontentative. Other things can be directly observed and unquestionable. In these cases Joni confuses the purpose of science to be for solving problems rather than for giving deeper explanations of the natural world. Additionally, it could be that Joni's want for science to be useful would require her conception of science to have some definite, nontentative truth that could be relied upon. We also see in Joni's case that aspects of science become especially tentative when they are, on a personal level, controversial. Joni can suggest many examples of how science and religion can fit together to produce one cohesive body of knowledge. Therefore, when a piece of scientific knowledge does not correspond to a religious belief, she actually uses the latter belief as a falsification for the scientific knowledge.

CASE STUDIES SUMMARY

Each of the case study participants, at one time or another, gives an indication that she views scientific knowledge as being tentative in one way or another. However, *tentative* has many meanings. The rich definition of tentativeness that we may be striving to relate to students is not necessarily the definition that a learner understands, even when she states that "scientific knowledge can change". This result was similar to the work of Lederman and O'Malley (1990), who found that high school students could reflect an understanding of the tentative nature of science when asked about it in a questionnaire, but would represent this tentativeness in limited ways when they were subsequently interviewed.

In this research, each learner has a specific understanding of the tentativeness of scientific knowledge, whether or not she is conscious of her specific understanding. Laura viewed knowledge and the natural world as having nothing to hide from one another, so knowledge could just be incrementally built upon, rather than modified or restructured. Jamie, equating science with learning, viewed tentativeness of scientific knowledge as an acceptable consequence of the possibility of making mistakes in any human endeavor; yet eventually mistakes can be completely corrected and science, like learners, will get the right answers. Michelle viewed tentativeness from a historical perspective, considering that there are many examples where scientific knowledge has been proven wrong in the past; yet Michelle was less accepting that the scientific knowledge currently produced is equally susceptible to falsification. Joni viewed scientific theories as being most tentative when the theories were in direct conflict with religious beliefs, while other scientific knowledge (e.g., gravity) was viewed as well understood and not likely to be susceptible to change.

In contrast, our own ideas of how to describe the tentative nature of science, based on philosophical ideas, had a much different emphasis. While the learners described above were focused on the pragmatic aspects of scientific change, our discussion of Popper, Kuhn, and Planck all assumed a specific epistemological basis for science. Each learner had a different view of the epistemological basis for science, which meshed with their descriptions of scientific change. To be fair, each learner also described partial truths about scientific change. It *does* sometimes change as a result of simply adding more knowledge (Laura), correcting error (Jamie), improving technology (Michelle), or changing acceptance (Joni). However, none of these change processes is the underlying mechanism for scientific change, and none of these acknowledge the creative, explanation creating aspect of scientific knowledge that truly represents science.

Implications for Teaching and Learning

What we witness in looking at the multiple views of what “changeable” or “tentative” scientific knowledge is that this particular concept is problematic not only because a student may not be aware of this aspect of science, but because she can easily misinterpret this aspect. Even if a learner were taught explicitly and given examples of how “scientific knowledge is tentative”, this could be construed in a wide variety of ways, as is documented above. All of the learners in this case study may be able to associate scientific knowledge with “changeable”, but what this means is not exactly what is strived for when we imagine someone who fully understands the nature of science.

In science conceptions in general, misinterpretation of a scientific concept is seen quite often, so it is perhaps not too surprising that we should also witness this in the case of nature of science conceptions. For example, young learners may be able to state that the “earth is round”, yet this “roundness” can be represented in a number of ways. Also well documented in the literature (summarized by Driver et al. 1994), elementary and high school students have a difficult time coming to the conception that the tilt of the earth's axis of rotation is responsible for seasonal changes; but, in addition (according to the first author’s experience in teaching astronomy to undergraduate students), even when learners state that the seasons are caused by the earth's tilt, they can still attribute the ultimate cause of seasons to one of two possibilities. One possibility is that such a tilt determines the angle at which the Sun's rays are directed towards a specific hemisphere of the earth. This is the correct, scientifically acceptable understanding. However, even students who say that “the earth's tilt creates seasons” can still be misunderstanding the concept, because they see this tilt as making some parts of the earth closer to the sun (and thus warmer) as compared to other parts of the earth. In other words, in multiple instances we find students who can recite an appropriate answer, but their understanding of this answer is not what is being strived for in science education reform (AAAS 1990; NRC 1995). This happens with the statement versus the understanding of “science is tentative” just as it happens with other, more traditional science concepts. In all such cases, it is difficult to determine if the partial misconception completely inhibits a conceptual change toward the scientifically accepted conception, or if the partial misconception is an appropriate step towards the development of the scientifically accepted conception. The latter situation has been documented in the work of Demastes-Southerland et al. (1996), though, in the case of this research, we would argue that learners tend to experience little, if any, controversy with their existing conception of tentativeness, so they have no catalyst to promote a change in their ideas.

To us, the most notable aspect of this research is the fact that these conceptions of tentative science are not islands unto themselves. Instead, they are deeply tied to other concepts regarding the nature of science. Past experience could already tell us that students have difficulty pinning down the exact meaning of “tentative” in reference to science knowledge. Our data expose an important facet and potential cause of this.

Students develop or apply differing forms of "tentative" to science in order to coincide with the epistemological standards they associate science to have. For example, the individual who views science as being historically tentative also suggests that the knowledge of science is discovered directly by observing nature. From this epistemological stance, it is sensible to assume that science knowledge will become less tentative as we continue to observe nature more and with greater technological prowess. In a similar vein, the individual who applies "tentative" only to specific aspects of science typically does so as a result of comparing her religious beliefs to specific scientific knowledge, and evaluating knowledge as being tentative as a result of its contention with her own view of reality. In this case, because she overlaps the ontologies and epistemologies of science and religion, her view of the tentative nature of scientific knowledge develops a specific character.

To be fair, our data do not demonstrate that a specific epistemological view *causes* a specific view of tentativeness. Rather, we demonstrate 4 in-depth examples of how a specific epistemology and tentativeness understanding can coincide, and seem to be incorporated with one another in a learner's conceptual framework. Our case study examples imply that in teaching the tentativeness of science knowledge we might be neglecting a more fundamental concept. We argue that students must understand more of the epistemological background of science before science's tentativeness can be understood and appreciated in the appropriate manner. Similarly, other concepts within the umbrella of the "nature of science" may be better understood if learners can consider them after developing a deeper understanding of the production of knowledge in general and, more specifically, the production of scientific knowledge. If a student does not understand these, then there is little hope for full understanding of other nature of science concepts, such as tentativeness. However, science educators continue to look at nature of science as a compilation of a great number of individual ideas (see for example, McComas [1998]), rather than an all inclusive set of interdependent ideas that have a specific relation to one another. For example, it is *because* science's knowledge is constructed by humans (while at the same time based on empirical data) that it *must* be tentative. Thus, the epistemological basis of science determines what the nature of science will be. Should students understand more about such basis? If they do not, will they ever really understand the nature of science?

We, and perhaps the reader as well, are actually scared of our own suggestion. If we *do* need to teach about epistemology and knowledge in a more general manner before we can expect students to learn about other specifics within the nature of science, are we ever going to attain true science literacy? Indeed, an explicit emphasis on epistemology could seem impractical. It would require significant change and upheaval in our current educational norms if we were to require all students at the university to take an "Introduction to Epistemology" course. However, given the role a sophisticated understanding of the nature of science may play in the learning of controversial science content (i.e., evolution, big-bang) (Southerland & Sinatra 2002), perhaps such an approach may be worth the investment.

It may be that a learner's conceptions of the nature of science are tied to broader epistemological beliefs -- that is, their beliefs about the nature of knowledge. If so, much can be learned by referring to the educational psychology literature (Hofer & Pintrich 1997; Schommer 1993). Based on this literature, we do know that general epistemological beliefs change as a consequence of education, but it is not clear that young learners are capable of developing a relatively sophisticated set of epistemological views. It is typically not until post-secondary education that learners can develop an idea that often there are no clear answers to questions; before that period of education, most students tend to leap toward simply wrong and right answers (King & Kitchner 2002; Kuhn & Weinstock 2002; Moore 2002). Thus, if development of nature of science conceptions are tied to a learner's more general epistemological views, it may be that young learners, including all those before the postsecondary years of education, may not be developmentally ready to grapple with more sophisticated nature of science conceptions. Or, alternatively, nature of science instruction before that time may need to be much more intensive to be effective.

Perhaps the issue is less a matter of "what" we teach or "when" we teach it, and more of "how" we teach. Akerson & Abd-El-Khalick (2000) show how conceptual change teaching and learning strategies can make a learner more aware of his own existing conceptions and thus more awakened to the fact that they may be different than the conceptions being advocated in a classroom. The problem, however, may be that it is easy for one to be satisfied with her conception of tentativeness, because it may seem so obvious. *Science changes*. Each of the case study participants would agree with such a statement, even though they had widely differing views as to exactly what this means. We might wonder if conceptual change strategies can somehow become even more sophisticated and alert learners to all the details of scientific knowledge and that which makes it tentative. If this is possible, then what would these strategies look like?

Another potential solution to the problem of tentativeness would be to eliminate this conception's importance in our standards altogether. We cannot begin to take such a suggestion too seriously, yet we also recognize that it is not completely clear what it is that we really want out students to know about the tentative nature of science. Yes, we want them to have a concept that is deeper and more elaborate than simply, "science changes". On the other hand, it would be difficult to fathom even a sophisticated undergraduate or secondary teacher to tackle involved philosophical problems. Is there a specific conception in between these two extremes for which we should strive? For us, this question remains unanswered.

Conclusion

By examining learners' conceptions of the nature of science, we find that it is not only important to look for the statement that "scientific knowledge is tentative", but the meaning behind such a statement. Because "science", "knowledge", and even "change" can each have their own meaning, so too can this statement regarding the nature of science. But what does this leave us with? We contend that there are two important aspects of this research that should be more deeply considered.

First, we are left to wonder exactly *what* do we want our students and teachers to know about the nature of science, specifically the tentativeness of scientific knowledge. Do we want them to simply understand that it *does* change, that it *will* change in the future, or that it *has* changed in the past? Certainly, a learner may readily acknowledge one of these changes without recognizing the others. Similarly, what do we want our students to understand about the reason behind science's tentative nature? If we do not teach them anything in this regard, then the learner is free to construct this aspect of the nature of science in whatever way they choose, either consciously or unconsciously. If we do teach them something in this regard, to what extent do we dive into philosophical discussions regarding the very epistemological underpinnings of science? And, where would such a discussion start? Exactly how important is it?

Second, we suggest that giving students some background regarding the epistemology of science *is* important. (Exactly *how* important and *how* involved such a treatment should be is unresolved for us, however.) We argue that to understand specific aspects of science, the nature of science, and specifically the tentative nature of scientific knowledge without understanding more fundamental issues about the source of scientific knowledge is simply nonsensical. As with the knowledge of science, the knowledge of an individual learner must fit into a broader conceptual framework for the nature of science. The learner must see how all the pieces fit together. If the tentative nature of science is not given a rationale, then it is simply an isolated fact, devoid of context and meaning. In these cases, learners will produce their own explanations and justifications for the change of scientific knowledge, and these explanations may simply reinforce each learner's misconception of what science truly is.

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