A reconsideration of science misconceptions using ontological categories

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Introduction: A lesson from history

Tycho Brahe was a great astronomer, and, as the story goes, a key player in a scientific revolution – a large scale shift in Western culture's perspective of the universe from one that is Earth centered to one that places the Earth in the role of one of many bodies moving about the Sun. Tycho's observations of the late sixteenth century were those used by the famous assistant, Johannes Kepler. In turn, Kepler used these observations to characterize the motions of heavenly bodies into simple yet elegant rules, and these rules were used by Newton a few years later to show the universality of gravitation and the laws of mechanics. Thus, Tycho's original observations were an integral part of Newton's conceptual revolution.

Yet, despite Tycho's contribution to and obvious mastery of astronomy, one could argue that he spent his entire career misconceived about the true nature of the solar system. Ironically enough, while Tycho's data were eventually used to describe a Sun-centered solar system, this same observer still conceived of an Earth-centered universe. In fact, Tycho used all of his observations to describe a system in which the Earth sat quietly as the Sun circled the earth while planetary objects circled the Sun. So it is that one of the most influential and knowledgeable astronomers of Western culture was fundamentally mistaken about that which he spent his entire life trying to understand. How could this be?

Tycho, along with many thoughtful scholars of his day, described planets and stars much differently than modern science would. While the Earth was understood to be a spherical and physically large object, "planets" were understood to be no such kind of thing. Using the conceptual framework of his day, these heavenly bodies were not seen as "bodies" at all. Instead, they were points of light, perfect and unperturbed by the fallibility and physicalness of Earth. Like the planets, stars were seen as eternal points of light. Planets' only distinguishing characteristic from stars was that they tended to wander about the sky, never attaching themselves to the eternal background of constellations. Tycho entered the business of astronomy using the pre-conceived notion of his day of how the universe worked along with an implicit assumption of the basic nature of the objects of this universe. That is, Tycho's ontological assumptions about the character of celestial objects were misconceived, even though the fine detail of his observations of such bodies were unmatched. (The reader is referred to Kolb (1996) for a delightful discussion of Tycho; also see Kuhn (1957).)

What can we learn from this? Arguably, it would be easy to read too much into this singular example in the history of science. However, we are not historians or philosophers of science; rather, we are researchers investigating the nature of science learning. What we do see in this example is how one person can be misconceived, despite a tremendous amount of thoughtful reasoning and careful observation. We want to use the case of Tycho to point out that many of our misconceptions derive not from flawed patterns of learning or reasoning, but from the arena that the new learning is placed within. That is, Tycho understood the universe in a certain way before he made his observations, and these conceptions served to shape his interpretation of his observations. So while his observations had the potential to allow for a shift in the understanding of the universe, these observations were drawn into the framework of what he already knew. Thus, his observations fit into his knowledge structure without challenging it. If this can happen to Tycho Brahe, we would argue that it also happens to science learners today.

While science education research did not yet exist in Tycho's day[1], if he were included as an interview participant in one of our studies, we could imagine him drawing concept maps or describing his conceptions of the world in response to particular interview probes. Perhaps Tycho would have separated concepts such as "planet" and "star" into groups that belong to the celestial domain, understanding that such entities belong to the unreachable and revolving heavens, while he would place "Earth" and its components into a set of earthly objects that are stable and do not move. Encompassing all of these concepts might be the idea that circles are the most perfect of entities, and that both the earthly and heavenly domains abide by circular patterns.

We use Tycho Brahe as an example of someone who could "know" all there is to know about something, but still misses something fundamental to a concept. Looking retrospectively at this case, we see that Tycho's misinterpretation is a result of how he categorized objects in the universe: stars and planets as unreachable, heavenly entities, and the Earth and earthly objects as solid, unwieldy objects.

While current scientific frameworks are supposedly a better informed than those of Tycho's era, we suggest that today's scientists and science learners can still have the same conceptual

[1]It is entertaining to think about science education research before the dawn of "modern science". We wonder if such researchers were finding students had "Newtonian" ideas, despite the "Aristotelean" curriculum of the day?

difficulties as Tycho, and in the same fundamental manner. Understanding these conceptual difficulties is the topic of this paper.

Lessons from conceptual change theory

Teachers and researchers in science education are quite familiar with a host of student misconceptions, many similar to Tycho Brahe's (Driver, Squires, Rushworth, & Wood-Robinson, 1994). While students can learn a great number of details as the result of careful instruction, it is often the case that their most fundamental understanding of a core concept can still be flawed in some way (e.g., Chi & Slotta, 1993; Demastes-Southerland, Good, & Peebles, 1996; Ferrari & Chi, 1998; Hynd, 1998; Moss & Abrams, 1999; Slotta, Chi, & Joram, 1995; Southerland & Gess-Newsome, 1999; Vosniadou, 1991). This is especially familiar to those of us who interpret such misconceptions or alternative conceptions through the lenses of conceptual change theory. Using this theoretical lens, it is easy to see how possible, and probable, it is for a learner to hold on to her previous conceptions regarding the world in which she lives (Chi & Slotta, 1993; Strike & Posner, 1985, 1992; Vosniadou, 1991).

One of the most fruitful approaches to understanding the ways and reasons students tend to retain old ideas in favor of more scientifically correct ones is conceptual change theory. Stemming largely from the works of philosophers of science such as Kuhn (1970), science educators consider how individual concepts, like scientific ones, have an inertial tendency to stay fixed. With conceptions which are particularly deeply rooted in one's cognitive structure, researchers using this theoretical model understand that a kind of conceptual revolution must take place in order for a new idea to replace the old one. This revolution, it is suggested, can only take place once the learner realizes the weakness of his existing conception, understands the new idea, finds the new idea to be believable, and realizes that the new idea could be even more useful and applicable than the previous one (Posner, Strike, Hewson, & Gertzog, 1982). It is suggested that many of our most unchanging conceptions remain intact due to the fact that these pre-requisites for replacement are seldom fully realized.

While Strike and Posner have continued to clarify and refine their original theory (Strike & Posner, 1985, 1992), others have also contributed further clarifications and variations on the conceptual change theme. Specifically, many attempt to describe how knowledge is strucutred within the mind, and how such structuring promotes or inhibits conceptual change. Vosniadou (1994) describes the learner as having a framework of explicit, well developed, and interconnected theories. Such theories exist on one of two different planes: one higher plane of fundamental theories that describe the learner's epistemological and ontological assumptions about the world, and a lower plane of specific theories that must exist as a subset of the first. That is, specific theories, those which explain the details of one's interaction with the world, must obey the fundamental tenets of the higher plane theories. Conceptual change could be difficult to achieve in many learners due to their most fundamental theories, for any new specific theory would need to fit into the pre-existing theoretical structure.

A contrasting view to Vosniadou's would be diSessa's (1993) phenomenological primitives (p-prims), or "theories in pieces." Instead of possessing an overlying structure of theories which would be used as a filter and determiner for all new conceptions, diSessa suggests that there are atomistic, fundamental pieces of knowledge that are developed as the result of the learner's experience in the world. Thus, instead of the theories described by Vosniadou, diSessa argues that learners use these basic pieces of knowledge to construct more elaborate explanations on the spot, in response to a particular situation. Because these p-prims are not explicit and complete theories, one's explanation of the same situation may not be the same in every instance of that situation; though, diSessa (1993) and Hammer (1996) argue that it should be possible for p-prims to eventually be used to develop some cognitive structure that could produce more consistent explanations.

Another view on alternative conceptions and conceptual change uses the idea of ontological categories (Chi, 1992; Chi & Slotta, 1993; Ferrari & Chi, 1998; Slotta et al., 1995). Using this theoretical lens, instead of describing how one set of conceptions affect the development of new concepts, one considers how such concepts are generally organized and how this categorization in turn affects the subsequent understanding of the conceptions. Chi and colleagues describe the individual's conceptual structure as being separated according to ontological categories. An ontological category defines what kind of thing each concept represents, the most fundamental of these being matter (such as a frog), processes (such as jumping), and mental states (such as happiness). In addition, many other subsets of these ontological categories can also exist – matter can be separated into natural and artificial kinds, and subsequently, natural matter can be separated into living and non-living, etc. The premise is that a learner will categorize any new concept into the ontological category that seems most appropriate to the learner; for, it is only through the categorization that the concept can be related to other concepts and take on meaning. Thus the meaning a learner holds for a concept is largely derived from the ontological characteristics the concept is understood to hold. Unfortunately, due to a learner's bias towards and comfort for certain, more familiar, ontological categories, many misconceptions are the result of the learner trying to organize a concept in an inappropriate category.

Ontological categorization and its current applicability

As mentioned, Chi and her colleagues contend that concepts can be categorized into a variety of ontological varieties. The first, and most familiar, ontological category (OC) is that of *matter*. Matter is composed of that which we can at least theoretically hold, see, touch, and otherwise physically interact with. Because learners can interact with such entities, matter is the category most easy to conceptualize. A dog or a cat are both of the matter OC. We can draw a picture of them and feed them. We can also describe them with adverbials that can only apply to objects of the matter category. For example, a cat can be fluffy. "Fluffiness" is a property that can only be applied to things of the matter category, even though not all matter is accurately described as such. For instance, we can say for certain that a car is not fluffy. To say that a car is fluffy would not be accurate, but at least on a logical level, it is not incorrect to describe the fluffiness of a car. Similarly, a car can be green; and while a cat is typically not green, a cat is still the kind of entity which can have color. Thus, describing a cat's color is not nonsensical. These comparisons are possible because cars and cats are both of the matter OC, and thus be compared on some level.

Another category is known as the *process* OC. (Chi originally called this the *event* OC (1992), but later realized that a time-constrained event was one sub-category under the more general category of process (Chi & Slotta, 1993).) Processes are concepts which "do," rather than those which "are." That is, while we can interact with a process, we cannot describe its physical existence. Working, questioning, answering, writing, thinking, etc. are all processes, as are driving and eating. While one can say that a car is green, one cannot say either positively or negatively that one's driving is blue. Our point here is that such a statement is beyond inaccurate – it does not make sense. This insensibility is due to the fact that driving, as a process, cannot be described by the same descriptors which explain the likeness of matter. Similarly, one can describe a person's driving as being slow, using "slow" as a description of the process. However, to say that "my car is slow," an extra connection is being made between two different ontological entities. This "slow car" has a small engine, which means that the process of driving will be slow. When we make statements such as, "my car is slow," we are actually describing first the process of a car, and from this making an inference about the car as matter. As we will argue later, such extrapolation can lead to conceptual difficulty if one is unfamiliar with the entities (and their OC's) being described.

The last of the three major OC's (at least as they are described by Chi – there could well be others) is the *mental states* OC (Chi & Slotta, 1993), originally referred to as the *abstraction* OC (Chi, 1992). These are those types of entities which can exist within the mind, but have no physical manifestation. Thus, dreams, thoughts, emotions, desires and the like are all mental states[2]. Arguably, while this category is the furthest removed from physical reality, it is also the one closest to our mentality. This makes the description of this OC rather strange, though it is fortunate that we have many examples as to what such elements of the mental states OC are.

Underneath each of the three main OC's are further subcategories. So, matter could be further divided into natural and artificial categories, and the natural category could be divided into living and non-living things, and living things could be further divided into animals and plants, etc. Processes could be divided into procedures, events, and acausal interactions (such as forces, energy, etc.); and, mental states could be separated into emotions and intentional states (such as desires, vengefulness, etc.) and probably other categories, though these categorizations are less clear and have not been described in previous work. What is important to note is that ontological categorization of entities can differ on any of a number of levels. While rocks and turtles both fit into the matter OC, they are sub-categorized into different OC's. Thus, ontological categories allow for a kind of hierarchical organization to be made by the learner.

What does any of this do for us, researchers and teachers? As researchers we are looking for a more useful description of the conceptual change process itself, and specifically what inhibits or enables such changes. We will argue that ontological categorizations (or miscategorizations) can

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[2]We suppose that if one really wants to think hard, they can consider that a dog exists as matter, but our conception of the same dog exists as a mental state. So, where *is* the dog, really? This is a point of contention for philosophers interested in the realist/anti-realist debate.

be used as a basis to understand the process and patterns of conceptual change. If the learner does in fact categorize concepts ontologically, then misconceptions could arise from miscategorization.

In physics, one of the more difficult concepts to convey to novice students is that of heat. Often we (teachers, physicists, etc.) discuss how heat "flows" from one place to another. From the physicist's perspective, this is meant as an exchange of energy – a process whereby energy, while conserved, is redistributed. However, most novices to the physics classroom associate the description of flowing with things such as water or some other fluid-like substance. In this way, the description is being used to modify a member of the matter OC. To take literally the expression "heat is flowing" is to possibly succumb to the error of miscategorizing heat as matter, rather than conceptualizing it as a process.

It has been demonstrated (Chi & Slotta, 1993; Slotta et al., 1995) how novices and experts in physics classify their concepts of heat into ontologically different categories. Both Slotta and Chi describe that while the experts had a strong association of heat as a process, novices pictured and discussed heat as being a material thing, leading to further misconceptions. For example, a novice would suggest that heat could be lost through a styrofoam cup more easily than through a ceramic cup, due to the fact that the styrofoam cup has air chambers within it, which are essentially holes that would not inhibit the flow of heat, if heat is considered to be a kind of material. On the other hand, the expert discussed the process of exciting nearby molecules and the fact that the ceramic cup had more molecules proximate to the warm liquid inside, thus making this transferring process more efficient. Note that both the categorization and the predictions of the novice and experts differ. Slotta and Chi argue that the miscategorization of the novice leads to further misconceptions and thus the novice's flawed predictions. If the novice is to truly understand the correct answer to the ceramic versus styrofoam cup problem, he must first understand the true essence of heat so that the correct prediction could logically follow.

In biology, one of the more elusive and challenging concepts is that of natural selection. It has been shown by Demastes-Southerland how difficult it is to construct a scientific understanding of this concept and how this process of conceptual structuring and restructuring can take place in a variety of ways (Demastes-Southerland, Good, & Peebles, 1995; Demastes-Southerland et al., 1996)[3]. Ferrari and Chi analyze the concept of natural selection and its learning from the perspective of ontological categories (Ferrari & Chi, 1998). In so doing, they describe how students tend to categorize natural selection, like so many other processes with which they are already familiar, as an event. The event OC is a subcategory of the process OC. It is distinguished by the fact that it has some finite period of time in which it exists – an event has a beginning and an end (Chi & Slotta, 1993). In contrast, another kind of process identified is that of *equilibration* (Chi, 1997). Unlike an event, equilibration is an ongoing process, with no particular aim nor endpoint. An event is understood to have a particular sequence of occurrences, lined up in some causal order, and is understood to reach a point of completion. In contrast, the equilibration process not only has no endpoint, but also has no beginning event or order of events that can be predicted.

One of the primary misconceptions about natural selection is that it is teleological in nature. Often students understand that natural selection proceeds for a specific reason – to "right a wrong" and allow a species to continue its existence (Demastes-Southerland et al., 1995, 1996; Settlage, 1994). In this light, a student may think of a giraffe as having grown a long neck in order to reach upper branches of a tree, because this allows it to survive. Students have a tendency of perceiving an initiation of this process (giraffe is hungry), a cause within this process (giraffe will die if he does not eat; food is out of reach), an effect (giraffe grows a longer neck), and some conclusion to the process (satiated giraffe can cease neck growing). This, of course, is not the scientific view of natural selection, nor is it the storyline that is being taught in most curricula. Instead, at least within a scientific framework, natural selection is understood to be an equilibration process that is ongoing. Each change in a species is random, and if it allows the species to survive long enough to reproduce, then the species will live for another generation. Thus, the process of natural selection is not only ongoing, but also not goal-directed, as an event is.

Ferrari suggests that if students were first shown the differences between the equilibration and event ontological types, they may be able to better understand the scientific characteristics of the process of natural selection. Without knowledge of this distinction, students are so familiar with event-like processes that they are preconditioned to seek out such processes. They use the OC

[3] The many pathways of conceptual change may suggest that the framework of the mind is less procedural in how it functions than it is categorical, since the procedures by which change occurs in varies between individuals. This presents an interesting possibility for a research pursuit.

which they have already applied in other situations to a new situation – in this case, a mis-application of the event OC. When the learner grapples with understanding natural selection, use of the event OC leads to the development of misconceptions.

How could this help us?

While a wide array of research into alternative conceptions exist, many researchers argue that we must find a way to characterize such conceptions in a more general way, rather than to simply identify every misconception which exists ad infinitum (Wandersee, Mintzees, & Novak, 1994). In answer to this call to move beyond simple descriptions, through research we want to understand the underlying cause of common and deeply rooted alternative conceptions, so that we can not only understand how to address such conceptions on a case by case basis, but also so we can have a more useful portrait of the processes through which we understand and learn. Thus, we look towards some theoretical description of why some alternative conceptions are so prevalent, how they can be so cognitively entrenched, and ultimately how curricula could be enhanced to better address them.

While many of the theories of conceptual change employed by science educators are concerned with what is required for learners to restructure their conceptions (either on the part of the learner or on the part of instruction), few pay more than scant attention to the actual nature of knowledge structures. The theory of ontological categories proposed by Chi and her colleagues can be used to address this oversight in the literature. While ontological categories have been used as a means to understand alternative conceptions of heat (Slotta et al., 1995), electric circuits (Chi & Slotta, 1993), and evolution (Ferrari & Chi, 1998), the use of ontological categories as a theoretical basis to understand science learning has been largely limited. In our research, we use Chi's theory of ontological categories (Chi, 1992) to consider the nature of scientific conceptions and to allow us to understand how science conceptions are classified and reclassified by the learner. Through an analysis of conceptions previously described in the science education literature (including the nature of science, scientific models, and astronomical entities), we explore the extent to which ontological categories can be used to explain a variety of alternative conceptions, how Chi's theory intersects with other conceptual change theories, and how such research could ultimately be used to inform theories of science learning.

An analysis of previous research in science misconceptions

As suggested above, this piece is intended to provide a thoughtful discussion of how research in science misconceptions could (and we suggest *should*) proceed. The remainder of this paper proceeds by taking a fresh look at other research in alternative science conceptions held by learners, and then shows how the use of ontological categories can be used to explain where these conceptions originate and why they tend to be so resistant to change. Our data come from an analysis of selected pieces of research. These come from publications in journals as well as in conference proceedings. While we are not collecting new data nor producing new theoretical constructs, we intend to show that future research could benefit by more clearly looking at knowledge structures when investigating learners' alternative conceptions, and then evaluating the legitimacy of such knowledge structures. Ultimately, this gives us a more clear understanding of what conceptual change should (or should not) look like. Specifically, we ask of the data collected by other researchers, 'How are ontological categories used (or not used) by learners as reflected by this research?'

Admittedly, analyzing the work of someone else and inferring new meaning from it is a dangerous path to tread. We offer this as a beginning. We will restate at the end of this piece that more research is called for; but, at the same time, it is only through this re-analysis that we can begin to suggest and justify the need for such further research. Additionally, other published papers have used the re-analysis of others' work quite successfully, as demonstrated by Aikenhead and Jegede (1999). While not a methodology we should make too great a habit of, we feel that the potential of ontological categories as a theoretical construct justify our reconsiderations of others' work.

We chose the following three groups of alternative conceptions for our analysis: astronomical structures/relations, unifying concepts of science, and the nature of science. Specifically, we consider the work of:

- Vosniadou (1989; 1991) in children's conceptions of astronomy (in conjunction with our own experience in astronomy classrooms);
- Moss and Abrams (1999) in unifying science concepts such as systems, models, and change; and,

- students' understandings of "science" as a concept itself as characterized by Lederman (Lederman, 1998), Abell & Smith (Abell & Smith, 1994), and Southerland & Gess-Newsome (Southerland & Gess-Newsome, 1999).

We choose these because we have some familiarity with them, they represent a broad range of conceptions in science education, and because they are particularly important conceptions when one considers reform movements and their standards (American Association for the Advancement of Science (AAAS), 1990,).

The ontological status of planets and stars:

Vosniadou (1989; 1991) originally used children's alternative conceptions in astronomy to show how these conceptions could be understood to be fundamental and well-articulated theoretical assumptions about the world. Most notably, the children in Vosniadou's study tended to state that the Earth is "round" in many circumstances, echoing school instruction. Yet, when asked more questions which required application of this idea, such as questions about what would happen if they kept walking in one direction on the Earth or a request to draw a picture of the Earth, it was demonstrated that the children still held some form of a flat Earth conception. Certainly, as Vosniadou claims, this has something to do with their most fundamental assumptions about how the world should be; or, perhaps a supporter of p-prims would suggest that all experience with regards to the Earth has been that it is basically flat, and thus so is one's most fundamental conception of the Earth. Yet, in this work of Vosniadou as well as in others' (Driver et al., 1994), we see that learners do change their conception of the Earth, even if they do not change from a flat Earth perspective to that of a spherical Earth. We should ask of the data, then, what it is that makes a flat Earth perspective so appealing to a learner, even as she is willing to change other aspects of her conception.

We suggest that the reason that children see the Earth as a flat object is because they categorize it in a way that does not allow it to be a planetary, spherical object. That is, when viewed from a perspective utilizing ontological categories, our most fundamental conception of the Earth is certainly a matter based object, but one that acts as a container of entities, rather than as an entity contained within some other greater system. If such a miscategorization exists, it would lead to further difficulties in understanding the motion of the Earth and its relation with other celestial objects. Looking to learners who may have more formal experience with a spherical Earth but little experience with the ontology of the Earth versus other objects would help see if the miscategorization we suggest does exist.

Looking for a group of students who may at least have a more developed conception of a spherical Earth, we examine our own experiences with students in college level astronomy courses. While these learners probably have a better understanding of a "round Earth" than do 6-year-olds, they still seem to exhibit extensions of ontological problems when relating the sizes and positions of objects such as planets, stars, galaxies, and the universe. Generally, these students understand that the Earth is a round object (probably due to the use of globes or more formal instruction on the Earth and the solar system) (Driver et al., 1994; Vosniadou, 1989, 1991), but they continue to have a difficult time understanding its relation to its greater surroundings. In two astronomy classes (both taught by the first author, n=121 students), students were asked on a test question about the size-relation between four kinds of objects: planets, stars, galaxies, and universe. As listed here, these objects are in order from smallest to largest. Yet, as shown in Figure 1, many college students, even after having had five weeks of instruction and an introduction to the nature of astronomical objects, get this seemingly obvious ordering confused.

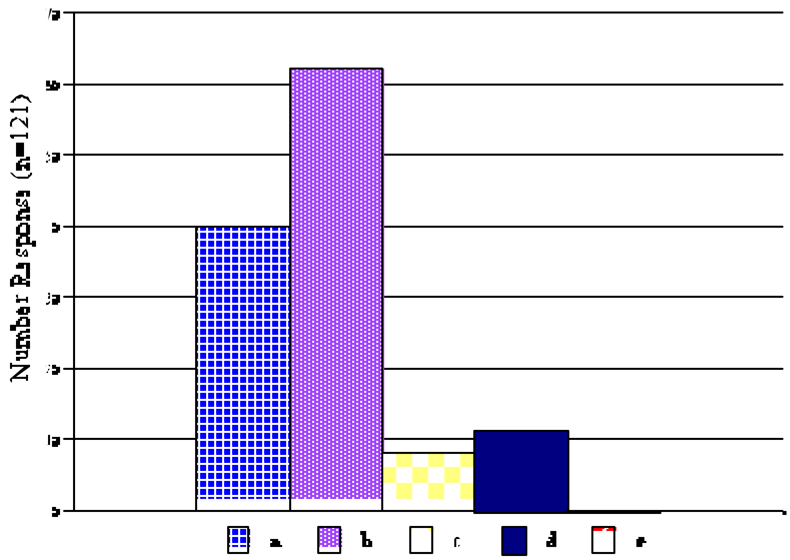

Figure 1: Student responses to astronomy structure question:
Select the list below that is ordered from smallest to largest:
a. Stars, planets, galaxies, universe.
b. Planets, stars, galaxies, universe. **CORRECT**
c. Stars, planets, universe, galaxies.
d. Planets, stars universe, galaxies.
e. Stars, galaxies, planets, universe.

What is especially notable about this is the students' specific misconception regarding planets and stars. While all understand that galaxies are larger than planets, many fewer understand the relation between stars and planets. Thus, these students do not have a zero understanding of these relationships, but instead have very specific misconceptions: while galaxies are understood to be large objects, stars are not.

These astronomy students view the universe in a very similar manner to the view of Tycho and the view of other ancients in Western culture, such as Aristotle. While these students have been enculturated enough to understand planets as objects like our Earth – objects which can contain other objects such as people, puppies, and probes – stars do not earn the same ontological status. While these learners can "see" planets in the popular media and so recognize them as places to set foot upon or orbit about, students generally do not realize that these same objects are viewable in their own sky, albeit as small points of light. On the other hand, for students, "stars" are those bright specks of twinkling that emanate above our heads, seemingly very small and all an equal distance away from us.

While these college students are more capable than younger students of describing the Earth and planets accurately, they are unable to see such objects for what they really are within an astronomical context. This is not because they do not understand what planets truly are – in fact, they understand the concept of a planet better than Tycho Brahe ever did. However, their own experience with stars as tiny points of light is ontologically incorrect. As points of light, stars are seen as objects that are small components and are a subset of the Earth or of space, rather than categorizing stars as large objects which can interact with and contain other objects, such as planets. Because of this miscategorization, not only do they not understand the true nature of stars and their size, but they also misunderstand the true nature of planets and how they relate to stars. That is, as points of light, stars will not be able to be objects which planets orbit about, nor will the Sun be classified as a star. Having experienced stars as being objects contained within our immediate sky, yet experienced planets (through pictures and interactions with our own Earth) as objects which are large and potentially very far away, the tendency of many of us is to segregate stars from planets into quite different classifications that are improperly related.

The ontological status of unifying science concepts:

Recently, Moss and Abrams (1999) researched student conceptions of models, systems, and change. These broad paradigms are organizing principles upon which many other concepts are based. Because they show science and its principles as having coherence and connection, AAAS includes them as concepts that are important for scientific literacy (1990; 1993). However, we seldom, if ever, teach such concepts explicitly. Thus, the aim of Moss and Abrams was to see how well students came to understand such unifying themes through a curriculum that, while focusing on such issues, did not address them explicitly.

Moss and Abrams (1999) describe that students' (in this case, 11^{th} and 12^{th} grade biology students) conceptions of the unifying concepts (models, systems, and change) fall short of the benchmarks set for science literacy. It was suggested that this is unfortunate, since understanding such unifying principles could help to bring other concepts together in a logical and understandable way. It was also suggested that students' conceptions of models, systems, and change were not altogether misconceived, just in forms that were too simplistic to be used as a unifying theme. While Moss and Abrams describe that these concepts were not well understood, the source of students' difficulties with these topics was not immediately apparent. The authors argued that more explicit instruction regarding such concepts was in order, and that when such instruction occurred, student understanding seemed to evolve; but their findings on this point were not definitive.

In analyzing the work of Moss and Abrams, we suggest some intriguing tendencies in student conceptions of the unifying themes, beyond those which Moss and Abrams state. One example begins with the researchers' distinction between various kinds of *models*. In speaking of models, physical models were contrasted with conceptual models. A physical model is used to represent the physical reality of another object, but usually on a smaller scale. However, a conceptual model is designed to approximate some process in order to make predictions and explain how such a process works. In everyday life, we explicitly interact with mostly physical models: we have globes, model cars, and miniature figurines, such as the "Kermit the Frog" character that occupies the top of a filing cabinet. In contrast, conceptual models, while they are used, are not nearly as evident in our everyday existence. So, conceptual models are not only different from physical models in their use, but also in their everyday prominence.

When Moss and Abrams asked students to describe what a model was, students tended to refer to ideas of physical models rather than models that reflect a process or interaction. As we consider how students are most likely to categorize concepts ontologically, we think that the findings of Moss and Abrams are most likely the result of students being most familiar with models which are simply meant to represent objects of the matter OC. That is, when one initially pictures a "model," such an entity represents something which physically exists. Thus, a student would be most used to and prone to conceiving of such a model as a physical one, rather than as a conceptual model, especially if the model itself is built in a physical sense. For example, one might build a model that represents the erosion of a riverbank or the orbiting of planets, but a student is likely more focused on the physical representation of the river or individual planets than he would be with the concepts that are trying to be represented withing the construction of such a model.

Examples of students' naivete with models are suggestive that student concepts were ontologically different from the desired concepts. In using a modeling program on the computer, students characterized the use of the program as something to make graphs, rather than to model. That is, students used the program for a physical representation rather than a representation of a process, as was intended in this conceptual model. Students also created a model of a river in which the processes of the river and its surroundings were to be modeled. Instead of using this focus, students tried to create pictures of the physical reality of the river setting. Students would focus on the details of the picture, placing trees and people in the scene, rather than using the model as an approximation of how the river flows. Students are unfamiliar with both the use of models and especially with something that, at first glance, seems to portray some aspect of the matter OC, but is actually supposed to represent something of the process OC. Because the students already have an idea as to what the model is supposed to be, but this idea is ontologically incorrect, so too is their resulting conception of the model. Thus, we argue that before students could be expected to understand these models, they need to understand the ontological properties of such entities.

As also described by Moss and Abrams (1999) in considering the unifying concept of *systems*, students exhibited rudimentary and unchanging views. While students could describe the interconnectedness between members within a system, they did not show conceptions of balance within a system or energy flow within a system. Again, it could be argued that this lack of attention is due to the fact that these concepts are ontologically distinct from the matter category. Since "energy" and "balance" are concepts that cannot be concretely seen or analyzed firsthand, they are not obvious to the novice student.

The unifying concept of *change* is a particularly nice example of a concept that can be ontologically categorized, since it describes a fundamental kind of process. "Change" (as well as "constancy") should describe the interactions of components of a system and how such interactions are manifested. Based on the report of Moss and Abrams, students did not seem to emphasize that change is a process. Instead, students focused on the products of change. The result of a change process, such as a new commercial development (p. 13), was more recognizable to the student than the process which manifested such a physical result. Thus, students' bias towards and familiarity with concepts in the matter OC would lead them to associate change with a physical result of the matter OC rather than the change itself, which would have been appropriately categorized as part of the process OC. As a result, even though student conceptions of change are related to the change process, these conceptions are ontologically mistaken. Just as it is fundamentally incorrect to describe "jumping" as being "blue," it is similarly incorrect to describe "change" (of the process OC) solely with the results of change (of the matter OC).

Even when students were able to describe change as a process, such descriptions tended to describe "change" as things that were event-like, happening over short time periods, even when long-term processes, such as equilibration, were more appropriate. Students in this study also seemed to have little concept of why changes took place. This is reminiscent of Ferrari's work (Ferrari & Chi, 1998) in studying ontological categorization of student conceptions of natural selection. Being most familiar with event-like processes, students try to find the characteristic beginnings and ends of a change process rather than conceptualizing change as a continual process with continual driving mechanisms.

What these examples suggest is that student conceptions of these unifying themes are not only oversimplified and naive, but miscategorized. Because students do not understand the underlying assumptions of different model types, systems, and changes, they cannot understand the use of the concepts themselves. Understanding these alternative conceptions as a result of miscategorization is important to us, because we can use this miscategorization to describe the cause of the alternative conception. While it is important to note when and where students conceptions are disparate from those which we are trying to convey in the classroom, it is perhaps even more important to give such misunderstandings a general explanation. In this way, alternative conceptions do not have to be addressed as singular learning issues to be dealt with singularly, but rather as an entire class of conceptions that could potentially be addressed in a more holistic manner.

The ontological status of "science":

Because of the complexities of science, the concept of science itself provides an intriguing way to apply ontological categories. In the following section, we will show how considering ontological categories helps the learner and teacher to more appropriately frame science and its nature to enhance understanding. At the same time, it may be that a concept as complicated and important as science will provide the impetus necessary to further develop a theory of conceptual change utilizing ontological categories.

Based on research in conceptions of the nature of science, it becomes evident that many students have a conception of science as a static set of known facts and rules that govern the world, rather than as a dynamic way of knowing. Abell and Smith (1994) found that students tend to categorize the idea of "science" into distinct categories, some of which emphasize the knowledge base of science and some of which emphasize the procedures of science. Understanding science as either a set of tangible facts and rules or as a kind of process is inadequate, since science is a complex interaction of these two groups. In this section, we will argue that students largely misconceive science due to the complexities of categorizing it.

Defining "science" brings up an interesting problem for analysis via ontological categories: Exactly what ontological category *does* science fit into? As documented in Lederman's work, (1998), the nature of science is described by multiple categorizations: products of science, processes of science, and science as a way of knowing. Each of these categories are ontologically distinct. Thus, it might be argued that one inhibitor to a student's full understanding of the nature of science is that science, as a singular concept, does not belong to any single ontological category. This multidimensional facet adds to science's (as a concept in and of itself) abstract nature and thus students' difficulty in constructing a full understanding.

At first glance, the identification of a concept that does not fit into a single ontological category might be recognized as a serious limitation and a good reason to abandon this research agenda. Instead, we argue that there exists a fundamental correlation between two facts: Fact 1, that the nature of science concept is difficult for students to understand; and Fact 2, that this complex concept crosses multiple ontological categories. If it is so that these two facts are related to one another, then "science" may be one of the most difficult concepts of them all, as it defies the very categorization that we might be so adept at. Anyone who researches student understanding of the nature of science would be little surprised to see our categorization of "science" as a difficult endeavor.

As we consider Lederman's (1998) categories of "science" (product, process, and way of knowing), there is suggestion that two of these three are more familiar to students than the other. As Abell and Smith (1994) as well as Southerland and Gess-Newsome (1999) demonstrate, even adult learners (more specifically, preservice elementary school teachers in these cases) have a difficult time understanding science as a way of knowing. Instead, while these learners can describe the knowledge produced by science (product) and the idea that science is a way of trying to gather this knowledge (process), they also see this production of knowledge as one that is ultimate and unquestionable. That is, they have a naive realist's view of the world and see science as describing nature as it truly is, rather than as humankind's attempt at creating such a description. While such a view is not especially harmful in its own right, it is when placed in a greater social context which includes other ways of knowing, such as religion; or, when confused with endeavors that have different purposes, such as technology. A naive realist has a difficult time demarcating the processes and products that belong to science and those that are more rightfully associated with some other way of knowing, such as religion. Not being able to make such a distinction, these individuals cannot fully describe science, and thus may not be able to teach it as adequately as current standards call for.

The use of ontological categories in the analysis of this problem becomes insightful. As Chi and colleagues have already described, products and processes are ontological categories most familiar to us (Chi, 1992; Chi & Slotta, 1993; Ferrari & Chi, 1998; Slotta et al., 1995). However, the "science as a way of knowing" concept is enigmatic in that it does not fit neatly into either of these slots. In one sense, the "knowing" of science is procedural, yet much of what it describes is within the ontological category of matter, in contrast and addition to all of the natural processes which are described by science. To make matters worse, the knowledge itself of science (both in what it knows and its philosophical assumptions) fit into the least tangible of the three primary ontological categories: mental states[4]. In considering the concept of "science," it seems that we have found a concept which tries to outrun categorization. We suggest that this facet is what makes concepts in the nature of science so very problematic. While learners are accustomed to dealing with concepts that fit a straightforward, singular categorization, they cannot use the same cognitive

[4]It might be argued that another, yet to be identified, category is more appropriate. For now, the mental states category will suit our needs. Expanding and redefining ontological categories would require another paper.

structuring to understand the concept of science that they might use for other concepts, because it spans ontological categories.

Research up to this point has done a good job in describing what it is that learners do not understand about the nature of science and what alternative conceptions learners are most likely to have before and after instruction (Lederman, 1992). In addition, such research has been able to describe the nature of instruction that is most apt to address these conceptions (Lederman, Schwartz, Abd-El-Khalick, & Bell, 1999) and has even gone so far as to suggest that learner's of the nature of science need to be confronted with more cognitive conflict (Dickinson, Abd-El-Khalick, & Lederman, 1999). The latter of these suggestions most closely resembles that which conceptual change researchers advocate, yet we suggest that research and teaching must make still another stride: To investigate and consider the knowledge structures that are being used when a learner is coming to understand (or not understand) the nature of science. This has two purposes. First, it pushes our own understanding of the learner and thus can eventually better guide instruction. For example, in considering ontological categories, we realize that a learner who is used to understanding concepts that are ontologically singular is going to have difficulties learning about the nature of science because of its ontological complications. Second, a deeper understanding of the knowledge structures used in coming to understand the nature of science allows us to test the very knowledge structures, such as ontological categories (but also possibly including p-prims and others), that we might use to describe learning and the conceptual change process in general. Because the concept of science is so elusive, it provides a particularly good testing ground for theories of learning.

Implications for research

We should reiterate that our purpose in this research is not to claim to have discovered anything new about knowledge structures. Rather, we feel that in order for the conceptual change and alternate conception research agendas to proceed, a more concerted effort needs to be made to put potentially fruitful descriptions of learning and knowledge to the test. We argue that our re-analysis of previous findings and some presentation of new data point us in the direction of looking for the use of ontological categories and their use in organizing knowledge. This seems particularly compelling when one considers that which learners have the most difficult time learning and how such concepts are either ontologically distinct from concepts that we are most accustomed to, or concepts that may have multiple ontological categories, such as “science” as a concept.

At this point, we have only presented confirming evidence for the idea of ontological categories. However, continuing to find easily identifiable cases that further suggest the use of ontological categories may not be the way research should continue. Instead, we suggest that research begins to look for cases that may instead falsify the notion of ontological categories. (We would hope that the idea of fasifiability so advocated by Popper (1962) and taught in science education reform should also be a standard that we hold our own research to.) For ourselves, we have already begun to look more in-depth at student conceptions of “science” in order to truly test the applicability of ontological categorization to such a complex and multidimensional concept.

As presented, there are likely other explanations for the alternate conceptions witnessed in the data presented. Certainly, one could make a case for p-prims and their potential use, or a theoretical framework that is very non-organized in how it relates concepts to one another; or, other theoretical descriptions could exist as well. At this stage, our biases make us search hopefully for ontological categories because they suggest that the mind does have a method of organizing knowledge that is more systematic than p-prims but less restrictive than theoretical frameworks.

Conclusions

While much more work needs to be done, we have shown that using ontological categories as organizing knowledge structures can prove fruitful for research. Not only do many “standard” concepts (such as heat, natural selection, and astronomical relations) suggest the use and misuse of certain ontological categories by learners, but also more abstract concepts – concepts still important to a rich understanding of science – such as unifying concepts in science and concepts of the nature of science are suggested to be miscategorized by learners. As science educators, we grimace at the notion of students misunderstanding science concepts; but, we might be given hope if it can be shown that there are fundamental similarities in how many misconceptions arise. We suggest that ontological categories demonstrate such similarities.

In addition to giving research into science misconceptions some firm theoretical foundations to stand on, ontological categories show just how far removed certain alternative conceptions can be from scientifically accepted understandings. While some misconceptions might seem almost trivial, when looked at through the lens of ontological categories it is shown that they are fundamentally more severe. Even though Tycho Brahe knew most all that there was to know about the astronomy of his day, he was still fundamentally and ontologically misconceived when considering the true nature of planets and stars. This led him to apply all of his most accurate and precise astronomical data towards a model of the universe that was fundamentally flawed. Likewise, students who simply mis-order two types of astronomical objects may not seem to have made such a grave error; yet in considering how they are categorizing such objects, it seems that our students know just as much (and just as little) about the universe as their predecessor, Tycho Brahe.

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