What scientists say: Scientists' views of models

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This paper focuses on scientists' views of scientific models and their use in authentic practice. Participants were 24 scientists, averaging 25 years research experience, representing four discipline areas. Views of scientific models were assessed through an open-ended questionnaire (*VNOS-Sci*) and interviews. The scientists described models relative to their research in a variety of ways, from model development to model use through testing of predictions. Model development and model use were described as distinct practices. Those who emphasized model use had a greater tendency to emphasize prediction in scientific research. The analysis revealed multiple descriptions of the purpose of models in authentic practice. The majority of the scientists reported that models explain or organize observations/predict/test. Other descriptions included: models provide understanding of system/complexity made simple/abstract made visual, models are mathematical representations, models are representations of physical systems, and models provide a directing framework for research. Variations in frequency of these descriptions amongst the scientists are discussed. Several responses demonstrated a connection between views of models and views of certainty and hierarchy of scientific knowledge. Results also suggest scientists' descriptions of model purpose and use may differ based on scientific discipline and investigative approach utilized in scientific research.

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Introduction

To promote epistemological views of science (nature of science and nature of scientific inquiry) reform advocates recommend scientific inquiry experiences as a context for learning (AAAS, 1993; NRC 1996; 2000). "Inquiry is a critical component of a science program at all grade levels and in every domain of science, and designers of curricula and programs must be sure that the approach to content, as well as the teaching and assessment strategies, reflect the acquisition of scientific understanding through inquiry. Students then will learn science in a way that reflects how science actually works" (NRC, 1996, p. 214). Scientific models are an integral part of the development and exploration of science (Gilbert, 1991). As such, learners should be knowledgeable about what scientific models are, how they are developed, and how they are used within the science community. Yet, students and teachers typically hold narrow or naïve conceptions of models (e.g. Grosslight, Unger, Jay & Smith, 1991; Justi & Gilbert, 2001; van Driel & Verloop, 2001, among others). Interestingly, teachers' use of models in the classroom has been suggested to differ by discipline (Harrison, 2001). Are views associated with particular science disciplines? Understanding scientific models is a component of understanding how science really works. If children are to learn science in a way that reflects how science really works, it is important to have an understanding of these real workings of science *and* of scientists from a variety of science areas.

The current study reports a portion of a larger study on scientists' epistemological views of science (Schwartz, 2004). The comprehensive study (1) explores contemporary scientists' view of NOS and NOSI and (2) explores potential contextual connections between views of NOS/scientific inquiry and science discipline. This paper reports on scientists' views of scientific models and their use in authentic science practice. Participants are experienced scientists from four science disciplines (life science (LS), earth science (ES), physics (Ph), and chemistry (Ch)) and who employ various approaches to research (e.g. experimental; descriptive; theoretical). The research question focused on here is "What are practicing scientists' views of scientific models?" and "Do views vary based on science discipline and/or investigative approach?"

Method

The sample was one of convenience, consisting of 24 practicing scientists (6 female, 18 male) from across the United States and representing four primary science disciplines and a variety of subdisciplines and investigative approaches (Tables 1 & 2). All of the participants were currently engaged in research and publishing. With an average of 25 years research experience since earning their doctorate, the participants were clearly experienced within their respective communities. With the exception of one participant (an aquatic ecologist with 22 years post PhD research experience, currently in a non-academic institution), all held tenured academic positions at universities. All were educated and currently employed within the United States. Most had extended international experiences through post-docs, sabbaticals, or collaborative programs.

Data Collection and Analysis

As participants in the larger study, the scientists were given two open-ended surveys, the VNOS-Sci and the VOSI-Sci, to elicit views of NOS and NOSI. They were adapted from the instruments of Lederman et al. (2002) and Schwartz, Lederman, and Thompson (2001), respectively. Modifications aimed to include advocated aspects of NOS and NOSI as well as elicit views and supporting examples from within the perspective of the scientists authentic context of practice

Table 1. Description of participants

Participant	Discipline
	Life Science (LS)
OEL1	molecular bio
UEL1	molecular bio
SEL1	cell bio
BEFL1	forest ecology
NEFL1	marine ecology
KEDF1	plant systematics/evolutionary development
MEDF1	community ecology
PEDF1	Aquatic ecology
SEDF1	entemology
mDF1	wildlife ecology
	Earth and Space Science (ESS)
GDF2	fluvial geomorphology
eDF2	atmosopheric science
cDFC2	atmospheric science
hEDFC2	astronomy
pEDFC2	astronomy
	Chemistry
gEL3	organic chemistry
fEF3	environmental analytical chemistry
wEL3	analytical chemistry
bEL3	mass spectrometry
	Physics (P)
kEL4	nuclear physics
lTC4	computational physics
jTC4	High Energy Theoretical physics
sTC4	Theoretical planetary physics; astrophysics
pTC4	relative astrophysics

Table 2. Investigative approach of participants, divided by discipline

Discipline	Total	Life Sciences	Earth & Space Sciences	Chemistry	Physics
Research Approach					
Experimental	10	5	0	4	1
Descriptive	5	1	4	0	0
Combination E/D	5	4	1	0	0
Theoretical	4	0	0	0	4

(surveys available upon request to first author). Included on the VNOS-Sci survey are questions directly addressing views of models. These are:

(a) What is a scientific model?

(b) What is the purpose of a scientific model?

(c) Describe a scientific model from your own area of research, if appropriate. If you do not use scientific models, describe a scientific model from another area of research. Describe why your example is a scientific model.

Semi-structured interviews served to elicit additional information as well as validate scientists' responses to questionnaire items (Lederman et al., 2002). Views of models and model use were targeted during the interviews. All interviews were audiotaped and transcribed.

Participants' questionnaires and interviews were analyzed separately to generate individual profiles of scientists' views. Analysis specifically sought reference to models and model use. All instances of the words "models" or "use models" or similar phrases were coded. Subcodes emerged as descriptors of what models are, how they are constructed, and how they are used. Cross-discipline and cross-approach analyses were conducted to compare descriptions among groups of scientists. Given the small sample size, no statistical measures were appropriate. Results are reported based on emergent descriptions, trends and patterns.

Results

Presented are results for the total sample and comparisons of views of models when participants are grouped according to science discipline. Also included are results when participants are grouped according to research approach. The inclusion of the cross-approach comparison provides additional information to aid the overall exploration as well as offer insights into discipline-based trends. This was especially useful given the fact that 4 of the 5 physicists were theoretical researchers. As such, their views, and indeed the views of all in the sample, may be reflective of their research approach as opposed to, or in association with, their discipline area. These results are discussed in terms of suggested patterns within this sample of scientists and should not be generalized beyond this sample.

The scientists described the involvement of models in their research in a variety of ways (Tables 3 and 4), from model development to model use through testing of predictions. The following results represent how the scientists describe models within their field. The subcodes are not mutually exclusive. Many of the representative quotes included here were coded in multiple subcodes. There was not an overall pattern that describes the multiple coding. For example, representatives of the largest subcodes were dispersed across the other subcodes.

Table 3. Scientists' Views of Models: Grouped by *Discipline*

		Total		Grouped by Discipline							
				Number of scientists				Frequency of group			
		24		10	5	5	4				
Aspect	Subcode	Total #	total %	LS	ESS	Ph	Ch	LS %	ESS %	Ph %	Ch %
Models	explain or organize obs/predict/test	**17**	**70.8**	7	5	2	3	.7	1.0	.4	.75
	understanding of system/complexity made simple/abstract made visual	**9**	**37.5**	3	1	4	1	.3	.2	.8	.25
	mathematics	**9**	**37.5**	2	2	4	1	.2	.4	.8	.25
	physical system	**3**	**12.5**	0	2	1	0	0	.4	.2	0
	analogy	**1**	**4.2**	1	0	0	0	.1	0	0	0
	mental construct	**1**	**4.2**	0	1	0	0	0	.2	0	0
	representation of reality	**1**	**4.2**	0	0	0	1	0	0	0	.25
	more specific than theory	**2**	**8.3**	1	0	1	0	.1	0	.2	0
	Directing framework	**3**	**12.5**	2	0	1	0	.2	0	.2	0
	N/A	**2**	**8.3**	2	0	0	0	.2	0	0	0

Table 4. Scientists' Views of Models: Grouped by *Approach*

		Total		Grouped by Approach							
				Number of scientists				Frequency of group			
		24		10	5	5	4				
Aspect	**Subcode**	**Total #**	**Total %**	**E**	**E/D**	**D**	**T**	**E %**	**E/D %**	**D %**	**T %**
Models	explain or organize obs/predict/test	**17**	**70.8**	6	5	4	2	.6	1.0	.8	.5
	understanding of system/complexity made simple/abstract made visual	**9**	**37.5**	3	2	1	3	.3	.4	.2	.75
	mathematics	**9**	**37.5**	3	1	2	3	.3	.2	.4	.75
	physical system	**3**	**12.5**	1	0	2	0	.1	0	.4	0
	analogy	**1**	**4.2**	1	1	0	0	.1	.2	0	0
	mental construct	**1**	**4.2**	0	0	1	0	0	0	.2	0
	representation of reality	**1**	**4.2**	1	0	0	0	.1	0	0	0
	more specific than theory	**2**	**8.3**	0	1	0	1	0	.2	0	.25
	Directing framework	**3**	**12.5**	0	2	0	1	0	.4	0	.25
	N/A	**2**	**8.3**	2	0	0	0	.2	0	0	0

E: Experimental research approach

E/D: combination of experimental and descriptive research approaches

D: Descriptive research approach

T: Theoretical research approach

Scientists' Views

Explain or organize observations/used for prediction/testing. Seventeen of the 24 (70.7%) scientists indicated models were explanations or ways to organize observations that also involved testing predictions. Most responses were specifically related to the participant's research.

> As models become more complex, such as general circulation models of the atmosphere and ocean, the models are used as predictive tools. They're used to predict how climate will change as we change the composition of the atmosphere. [cDFC2, vnos]

> All scientists use models and if they say they do not then they are failing to understand what they are doing. In my research I use the model of a trophic cascade that indicates how predator-prey interactions from the top of the food web propagate down the food web to affect lower trophic levels. This model explains some of the variability observed in food web dynamics and the relative abundance of predator and prey groups in ecosystems. [PEDF1, vnos]

> A scientific model is a description of a physical system that provides an understanding of what the system is and how it works. A scientific model allows us to organize our information about a system and to predict how the system might evolve or react… We use mathematical models of stellar atmospheres to compute what the spectrum of a star ought to look like. We compare the predicted stellar spectrum with the observed stellar spectrum to determine the composition of the star. [pEDFC2, vnos]

> A model is a quantitative mathematical/physical/biological model that explains observations in a verifiable manner…The purpose of a scientific model is to understand and predict observable phenomena in the universe, ie, verifiable truths…[Example from work] the numerical weather prediction (NWP) model. With the use of a computer, an NWP model combines a mathematical and physical model of data and observations to obtain an initial state of the atmosphere...The model is scientific because its predictions can be verified quantitatively by peers. [eDF2, vnos]

This atmospheric scientist continued during the interview by discussing modeling of a system:

> You have to model the statistical ensemble. You have to model what is happening on the average over the whole cloud. ....You are probably aware that the treatment of clouds in climate models is one of the weakest links in the chain of things that we need to put together to say something sensible about global warming. And we don't do it very well. The models are all over the map, depending on how they parameterize the cloud process. [eDF2, int]

Several responses within this subcode demonstrated a connection between the scientists' views of models and their views of certainty and hierarchy of scientific knowledge.

> It [a model] is a mental or physical construct. ...The model is a way to test whether we got our ideas right....It is the assembling of those ideas into a model and watching them and comparing to what we really see that tells us if we have all our ideas right about the real system, or if something is missing or goofed up…If they are similar, then that tells me there is a good chance the ideas that went into making the model are actually pretty good at representing what is going on in reality. Then you can test it and try a different set of conditions. If they do, then it means the model is working, at least for these conditions, and it has some predictive function.

> One is to test the input to see if I have my ideas straight and the other is to make predictions. [fEF3, int]
>
> *So the model is useful where it can be predictive.* We have a prediction on the structure of the atom and how it should function under new circumstances. And then we can test that. so that would be through experiment, to test the predictions made by the previous model.....It is useful because it can help predict what new compounds might be, what kinds of molecules might be constructed under what conditions. There can be practical uses as well...[Models are] useful to guide experimentation and serve as a provisional understanding of a phenomenon.
>
> A useful model in my work is that ribosomal pauses lead to errors, like frameshifting. It is a model because it is based on fundamental laws about chemical reactions....This is only a model because we cannot directly measure the reaction rates... It is something to be refined, but it is getting better all the time. [UEL1, vnos and int]
>
> The theory of natural selection is also a model that explains much about the origin and behavior of biological systems. It provides a basis for making predictions about species responses to environmental changes…A lot of these conclusions are drawn from tests with models that show that if you create this kind of structure it accounts for the behavior that you measure. Again, just because you can come up with a model that explains it doesn't necessarily mean that is the only model. Just maybe we haven't thought of the model that works better…Models work at all these levels [hypothesis, theory, law] A hypothesis is a model. The model becomes more robust as it becomes elevated to theory and then law. But a model initially is a hypothesis. [SEDF1, vnos and int]

This last statement was also coded under the NOS category of "theory and law" (Schwartz, 2004). The scientist held a hierarchical view of hypothesis, theory, and law; yet also saw a connection with scientific models at each "level" of scientific knowledge. According to this scientist, the more robust the model, the higher its status within the perceived hierarchy. In contrast to other scientists who described models as having predictive capabilities based on assigned parameters (and these parameters could change according to what the intent is), the position described above may suggest a view that models can approach certainty. Even though different scientists held differing views of certainty of models, they held the common view of models having predictive ability.

One participant began to question her views as she thought about the model of the atom. In her VNOS response, she described a model as, "a representation of a phenomenon." She explored her ideas further during the interview.

> It makes me pause and think really about it. Because to a certain extent, I guess you could say what these are is models. And, I mean, if you haven't really seen it, it is a model. Drawing a relationship to religion, What is God? ...What does God look like? Different people draw different images. They haven't ever seen him, that I know. Or her. I guess...so what they base it on and why there are images of what an atom is or drawn the way they are...I can't tell you. .....And I think, I teach this stuff! [NEFL1, int]

In response to a prompt to discuss the development of the atomic model, one participant explained the explanatory and predictive power of this model across disciplines.

> The prediction was that if the plum model existed, the scattering would be very weak, that is very small angles of scattering. But what they observed were huge, very huge angles. They only way you could explain these huge angles was with the planetary model. From the origin of that experiment became our idea of what the atom had to look like…the planetary structure. That held up. From that structure as well, they were ultimately able, on the basis of that model, refinements to that model, explain and predict the phenomenon of how the atoms interact with light...... Once the planetary model became acceptable, things that could be predicted from this model were consistent with what physicists were observing then it was quickly discovered that it was also consistent with the chemists, this whole body of knowledge that chemists were building. All of a sudden the world was falling in place. Chemists could see very neatly how their atoms stuck together and begin to explain things. Linus Pauling came along and used the model, extended the model, to explain the chemical bond and all of modern chemistry …Of course over the years the model continues to be used and refined in ways we hadn't even imagined. We are comfortable with that until some day we bump up against something we can't explain with the model. At that time we go back and try to adjust the model or come up with other explanations. It's progressive. [bEL3, int]

Complex made simple/ abstract made visual. Nine participants (37.5%) describe models more specifically as a means to simplify a complex process or system or a means to visualize an abstract concept. Most representatives from within this subcode were distinct from the previous in that rather than considering models as explanations of observations that serve a predictive function; models here are considered limited, but useful, explanations because they serve to simplify natural phenomena that would otherwise be too complicated to investigate further.

> I use models all the time. In nature, systems are invariably far more complex than the idealized simplifications we rely upon to establish our theories and laws. [cDFC2, vnos]

Three of the scientists who demonstrated this view of models included a description of model use within the context of ecology. Typical descriptions included,

> A scientific model helps to explain a natural situation. Often it is a small scale general version of a more complex phenomenon. Scientific models help us to grasp a complex situation as a more watered-down version. In the field of landscape ecology, scientists often cut fields into different patch sizes and patterns and study animal movements in them to model (simulate) how larger animals move about in larger more complex landscapes. Models can be increased in scope and complexity to further explain the variability we often encounter in nature. [mDF1, vnos]

> Community ecology has often been compared to nuclear physics and astrophysics. ...[more complexity, the less predictive ability.] You have to use approximation methods. The same thing happens in looking at the structure in an atom where they don't know actually where every electron is…probability theory…Community ecologists often end up doing the same thing. For example, we might end up lumping all the bacteria together because its just impossible to figure out the details of what is going on with individual species. Or we may not even sometimes care about individual species...there is actually a big division in community ecology against people in ecosystem ecology. They are really just interested in energy flow through trophic levels and nutrients flow through trophic levels and don't care at all about the individual species. They don't think they are important for the level of predictions they want to

> make...On the other hand, community ecologists, from my approach, tend to look at individual species and in doing so we often tend to neglect understanding how multi [unclear] are restricted by energy flow or nutrient flow....A model is a simplified view of something complex used to analyze and solve problems or to make predictions. Simplification allows the user to focus on particular factors of interest while, of course, ignoring or holding other factors constant. [MEDF1, vnos]

Four of the physicists also appeared in this subcode. Their comments included:

> So we have models, theoretical models, mathematical equations you need to solve. In the past they have had to be solved approximately with very simplified models. We use the term models as distinct from theory because theory you think is correct. Model is simplified. [lTC4, int]

> I think it is impossible to make an accurate representation [of the atom]. I think you have to start somewhere to explain things at a certain level of complexity…A cloud isn't really the right idea. Repeated measurements of the position of the atom over and over again you would see something like a cloud. But that is misleading because when you measure the electron around the atom you will find it at a particular point. The cloud represents the probability that you will find it at a particular point. If you look for it you will see it. You can't see it without changing what is there. There is an interaction between the observer and the thing that you observe. It is very very complicated. If you are studying quantum mechanics and haven't been thoroughly confused by the theory, then you haven't really understood it…The models are okay as long as you understand the limitations of them. That isn't really how it is but it's the way we think about it....We are showing pictures here that relate to certain aspects of an atom. That is what you do when you see an elephant. It depends where you are looking on the elephant and what scale. [jTC4, int]

This physicist provided an additional example from his field:

> It [a model] permits us to try to isolate and explain a few aspects of a mysterious system, without having to 'get it all right' in a consistent fashion. [For example] Quark model of Strongly Interacting Particles.....This model doesn't even pretend to tell us everything we know about protons, but it allows to study situations in which the strong force is the most important interaction. This model may be an adequate description of protons in a nucleus, but it will not explain how we can extract energy from the sun or a thermo-nuclear reaction. [jTC4, vnos]

Mathematics. Nine participants referred to models as mathematical representations. Within this subcode were statements to demonstrate the role of mathematics in dealing with complexity. As the complexity of the phenomenon increases, capabilities of mathematics becomes more important.

> …the practice in environmental science has been it is far too complicated, we know it [the phenomenon in nature] is 1000 or 2000 [factors involved], but why don't we represent it as 1 or 2. So that has been the practice in the field for 20 years. Just not to deal with the complexity. What we are working on are mathematical methods to say, ok folks lets stop kidding ourselves. This problem is far more complicated than that. So let's just accept the high degree of complexity and deal with the best way we can. [wEL3, int]

> So for particle physics there is a theory now known as quantum chromo dynamics, QCD. It is a field theory….To solve that problem requires exchange of 16 different particles simultaneously. So it requires hundreds of equations to be solved simultaneously, and they are integral equations. That has taken years of computer time for most elementary, even models there, how to solve that. But in theory one has a complete mathematical description. In practice you say lets model it by limiting the number of particles. That makes it a model. [lTC4, int]

Directing framework. A few scientists explicitly made reference to models as a theoretical framework. This view is a specific example of connecting a type of scientific knowledge to the theory-laden nature of science (subjectivity).

> Without models, observation would amount to cataloging data … There is a lot of data and its doesn't mean anything until you have a model. If you have all these data and lots of satellites taking all these data...it doesn't tell you what to look for. It just tells you whether a model you have is plausible or not. It is all indirect. [pTC4, vnos]

> A gene network is a scientific model, postulating patterns of interacting among gene products following an analogy with a computer wiring diagram. It illustrates a mechanism, and helps develop hypotheses about other genes that must be involved to produce the observed phenotype. [KEDF1, vnos]

Discipline-based Comparisons

The highest category for the total group, the "explain or organize/predict/test", was also the highest for the discipline groups except the physicists. The physicists had a greater tendency (4 of the 5 Ph; 4 of the 9 total) to fall within the category of "complexity made simple/abstract made simple." Interestingly, 100% of the ESS discipline group fell within the former category (explain or organize/predict/test). The physicists clustered in the "complex made simple/ abstract made visual" and "mathematics" subcodes (4 of the 5 Ph). Overall, there were scientists who clearly emphasized the use of models in their research, either through model development or model testing. The two atmospheric scientists and the aquatic ecologist especially stood out from the group as ones who strongly emphasized models throughout their questionnaire and interview responses. All three of these scientists reported using models for testing predictions in their work.

Approach-based Comparisons

100% of the E/D group and 80% of the Descriptive group described models fitting with the "explain or organize/predict/test" subcode. Three of the four theorists (75%) responded favoring the "complex made simple/abstract made visual" description. The theorists also had a higher tendency to explain models as mathematical entities (75% versus 37.5% for the whole group).

Model Development versus Model Use

The scientists in this sample discussed models in terms of development AND use. They saw these processes as separate; even though several indicated they did both in their work. Model development is described as the process of collecting information (empirical and/or theoretical), identifying relationships, and composing an explanation of the relationships. All but the theoretical physicists suggested the proposed relationships should lead to predictions that are testable. Model use, then, involves testing of the predictions and identifying problems or cases where the existing models do not work. This distinction is articulated by one of the atmospheric scientist who works with cloud climate models:

> Most of my work is testing models. Model development is a whole other field. That might be the theoretical side. So I put myself in the observational side as opposed to the theoretical side. The models themselves are so complex. How do you build them in the first place? So what do they do to build these models? They look at radar data of clouds where they do precipitate. The radar data tells them something about how big the droplets get before precipitation starts. And so they simply look at this data. Now data are collected from clouds that rain. …..so they say, when droplets get to a certain size, it rains. Real clouds don't behave this way. …it is easy to suspect these models.

This scientist went on to describe how he tests the models and gives an example of a current situation where his work has raised questions about the validity of currently accepted cloud models:

> R: You talked about testing models. What do you use to test them?
> S: Satellite observations. So we just talked about a good point. If the models are right we get more water. They don't, we get less water. That is one way to test. The other one we are working on right now is the partly cloudy pixel problem…in most of our cloud climate models we take clouds as plain vanilla. They are uniform layers of constant droplet sizes and constant number densities…completely homogeneous. That is the way we do the calculations of how much sunlight goes through or whatever. Doing the realistic calculations is very difficult. It takes a lot of number crunching and time. But we can test these ideas. …if we know what we are doing there should be no difference between the model and our observation of the clouds…. They don't [work]. Even the bumps on the tops of clouds are enough to throw it off…. When we build these models and test them, we play games like this. We try to develop a test where we know what we should expect. We predict the results and see whether we get them or not. We see the failure of the prediction and start probing and say ,"how come?"

<u>Models and Anomalies</u>
A category within the larger study is "Anomaly." Scientists described how anomalies are identified and dealt with in their work specifically, and in science in general. They often connected use of models with identification of anomalies. The question of "how come?" offered by the atmospheric scientist above marks the curiosity and exploration into why a model doesn't hold. For many of these scientists, it is in the testing of the models that anomalies are identified. Through exploration of anomalies, models are refined and/or new models are constructed. The connection between anomalies and models is evident in this study and critical to understanding how science progresses.
One scientist stated the sentiments of most of the group with respect to the excitement and importance of finding an anomaly:

> That is when you come up with the new stuff, is when you absolutely can't rule out the possibility, that there is something new...some bit of biology there. That is the fun stuff. That is why you get up in the morning, for the things that don't fit. If all the data fit every existing theory, we'd be out of work. [KEDF1, int]

In response to an anomaly, 46% of the scientists said they would maintain, but revise, their original model. They indicated they would examine and attempt to explain the new observation from the perspective of their existing framework. The cloud climate modeler quoted above fell within this category. In discussing competing models for the same anomaly, he described the need for better analysis and refinement of his model to explain the data. His statements also indicate a critical role of creativity.

> We are going to get better at our analysis of our data and when we do that it gets harder for people to say, "Ah.." or how do you say, it motivates people to start looking at the model and ask what is really going on here. How do we understand this? Obviously there is something strange going on here. By pursuing this and keeping the pressure up, I am hoping that people like John [colleague] will come along and start thinking again, "Well maybe if I did something else in *my* model…maybe we could pull this off." [cDFC2, int]

In contrast, 29% suggested they may develop a new model. Ideas here related to notions of falsifiability and, moreover, methods of paradigm shift within the scientific community. This is not to suggest change is easily accepted. Change may come about through accumulation of discrepancies between predictions and observations:

> Now, where you see paradigm shifts is when anomalies tend to add up and add up, often times in contradictory ways. So one of the ways to deal with this is to make the ad hoc correction to the hypothesis. That should lead to further predictions of where you should find what would be anomalies for the original hypothesis. And so you go and test that and either the original hypothesis is correct or you will really generate more anomalies. In an extreme case you generate so many contradictory anomalies that you need something completely new to accommodate everything you've got.

Discussion and Implications

Creating and using scientific models is central to scientific inquiry (Gilbert, 1991). In the current study, there was overwhelming sentiment that models are used to explain or organize observations, then predict and test through further observations. The emphasis here is on empirical observation in the development and in the testing of models. In comparison, half as many scientists saw models as a means to visualize something abstract or simplify a complex process. This latter view seems to place less emphasis on direct observation and incorporates theoretical entities, although these are not necessarily mutually exclusive. These results show that these scientists' perceptions and use of models fit broadly with published descriptions of functional roles of models in science, including descriptive, explanatory, and predictive characterizations (Justi & Gilbert, 2003; Van Driel & Verloop, 1999). The multiple descriptors that the scientists used for models, such as mathematical, physical, and analogical, are also consistent with prior characterizations. In comparison to the range and multiple categories of meaning for the seven aspects of models identified in the Justi and Gilbert (2003) study of teachers' views of models, the present study suggests these scientists may hold more consistent views of scientific models, with predictive ability being a priority for most.

Definitions of "model" used by scientists have been suggested (Justi & Gilbert, 2003). However, these descriptions are not necessarily based on direct empirical data. The present study provides a definition, with supporting data. According to practicing scientists from a variety of specialty areas, a scientific model may be a mathematical, physical, analogical, or mental construct that (1) explains or organizes observations, that then enable prediction and testing through further observations, (2) simplifies a complex phenomenon or renders an abstract concept visible, and (3) provides a framework for guiding further investigation.

Differences based on context?

The Earth and space scientists and the physicists were clearly disparate in their descriptions of models. The approach groups were also distinct, with 100% of the E/D group describing models as "explain or organize observations/predict/test." The results for the "prediction" category (data presented elsewhere: Schwartz, 2004) also show the Earth and space scientists and physicists are disparate with respect to the requirement of predictive ability in justifying scientific knowledge and the role models play in achieving prediction. The E/D approach group falls into a similar pattern as the Earth and space science group. These results suggest the Earth and space scientists and/or those who engage in combination of experimental and descriptive research hold more similar views of scientific models than they do to theoretical physicists or even to the whole sample of scientists. That is, these former groups tended to emphasize models and their explanatory and predictive functions more frequently than the other scientists in this sample. The ESS group and the E/D and D approach groups also held a greater tendency to discuss the use of models with respect to their own research.

The physicists did not relate model use to anomalies to the extent that the rest of the scientists did. Considering their view of models as "complex made simple/abstract made visible" rather than explanations that lead to prediction and testing, it seems reasonable that they would not associate identification of anomalies with fitness of observations to predictions. The theoretical physicists do not necessarily work with empirical observations. As such it is not surprising that they hold different conceptions of models and use of models as catalysts to scientific progress.

The results suggest conceptions of scientific models and their use in science *may* differ with context of scientific practice. Overall, differences are likely slight and related to individual scientists' explicit reliance on models in their work. The fact that differences were evident between the theoreticians and the rest may be an artifact of the small sample size. In any event, the sample demographics do not allow distinction among discipline or approach. Results suggest there may be contextual –based differences, and these should be explored further with other samples.

Relevance to classroom science

What can we learn from scientists about models and model use? We can learn how scientists develop and use models in authentic scientific inquiry. First, the different descriptions noted here suggest models are not a "one size fits all" concept. Not all models explain empirical observations and not all models take an abstract concept and make it more concrete. Furthermore, model development may be a practice distinct from model use. In order to help students "learn science in a way that reflects how science actually works" (NRC, 1996, pg. 214), teachers should incorporate a variety of experiences that demonstrate models and model use in an authentic light. That is, both model development and model use may need to be addressed in multiple contexts, with clear objectives that align students to distinctions and similarities among models with respect to the contexts. Physics activities may represent models differently from Earth science activities; Experimental activities may represent models differently from descriptive activities.

Second, the connection of model use and anomalies has intriguing implications for classroom science. There is potential to *model* the practice of model testing, anomaly identification, and scientific progress. How are anomalies typically identified and dealt with in the classroom? Are models used to make predictions and test them? Are students given opportunity to experience the excitement of finding a contradiction between prediction and observation? Are students given opportunity to refine models or develop a new model in light of contradictions? These are questions that should be considered in instructional design so that classroom science might more closely reflect "how science actually works."

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