High School Students' Modeling Knowledge

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Abstract

Modeling is a core scientific practice. Over the past three years, the MoDeLS project (Modeling Designs for Learning Science) has developed a learning progression for this practice, focusing on the late elementary and early middle school years. This study probed the modeling knowledge of high school students who had not any explicit exposure to modeling. The goal was to see if the upper levels of the learning progression are attainable during K-12 and to evaluate the degree to which modeling knowledge is dependent on content knowledge. Nine high school students majoring in physics, chemistry, biology, or learning general science, were interviewed about models twice, once in a context related to their science major and once in a non-related context. The interviews were coded using construct maps developed by the MoDeLS project. All the students displayed modeling knowledge superior to that of elementary and middle school students, despite the lack of a formal introduction to the practice. Their modeling knowledge was independent of content, but their ability to engage in the practice was content-dependent. This indicates, that while the upper levels of the modeling learning progression can be reasonable goals for K-12 education, students appear to attain these levels of understanding without explicit instruction on modeling. The value of explicitly focusing on modeling knowledge in science education is re-considered.

Introduction

Modeling is a core practice in science (Morgan & Morrison, 1999). Science can be viewed as an ongoing process of developing, testing, refining, and improving models to explain the material world (Windschitl, Thompson, & Braaten, 2008). Indeed, models are seen as the prime mediator between theory and reality (Develaki, 2007). Following Schwarz et al. (2009) we define scientific modeling as including the elements of the practice (constructing, using, evaluating, and revising scientific models) and the meta-modeling knowledge that guides and motivates the practice (e.g., understanding the nature and purpose of models).

The MoDeLS project (Modeling Designs for Learning Science) has developed a learning progression to represent consecutively more sophisticated levels of engagement in, and knowledge of scientific modeling practices (Schwarz, et al., 2009). Studies conducted by this project to construct and test this learning progression (Fortus, Weizman, Shwartz, Merritt, & Schwarz, 2008; Kenyon, Schwarz, Hug, & Baek, 2008; Schwarz et al., 2008) have investigated upper elementary and middle school students' ability to engage in various aspects of the practice and their MMK. The conclusions from these studies can be summarized as follows:

- Upper elementary and middle school students are able to construct and revise increasingly accurate models that included powerful explanatory mechanisms.
- These students are able to use these models to predict closely related phenomena.
- With appropriate supports, students can progress along the levels of a suggested learning progression, moving from the construction of illustrative to

explanatory models, from viewing models as correct or incorrect to being able to represent multiple aspects of target phenomena.

While these are encouraging results, few students reach the higher levels of the learning progression. For example, we have seen only very few cases of middle school students realizing that a model can aid their own sense-making, and seeing model construction and testing as a way to generate new knowledge rather than just to represent what they have already learned.

To probe possible higher levels of the learning progression, we decided to investigate the modeling knowledge that high school students have and whether they can use this modeling knowledge in familiar and unfamiliar contexts.

Methods

Participants.

We interviewed nine Israeli 11th grade students (5 girls and 4 boys) from 4 different high schools. Two of the students were physics majors, two were chemistry majors, three were biology majors, and two were studying general science. The students were selected by their teachers as articulate and of average knowledge of science in the fields they were studying. Modeling is not an explicit part of the Israeli curriculum in any of these subjects. Therefore, these students had no explicit experience engaging in or thinking about modeling.

Instruments.

Each student was interviewed twice – once on the use of models in the subject in which they were majoring, and once on the use of models in a different scientific subject. We developed three different interview protocols – one for modeling in physics, one for chemistry, and one for biology. The two students who were studying general science had just participated in a unit on air quality, so much of the content underlying the chemistry-oriented interview was familiar to them. The scientific field the students were studying, their gender, and the fields of the interviews in which they participated are shown in Table 1.

Table 1: Participants’ Educational Background and Interview Protocols

Participant	**Gender**	**Major**	**Interview 1**	**Interview 2**
1	F	Chemistry	Chemistry	Biology
2	F	Chemistry	Chemistry	Biology
3	F	Physics	Physics	Chemistry
4	F	Physics	Physics	Biology
5	F	Biology	Biology	Chemistry
6	M	Biology	Biology	Physics
7	M	Biology	Biology	Physics
8	M	Science for All	Chemistry	Physics
9	M	Science for All	Chemistry	Biology

None of the students could recall any prior experience learning about or using models in their education.

As mentioned earlier, there were three different interview protocols: a biology protocol focusing on photosynthesis models, following Van Helmont, Priestley, and other key experiments; a chemistry protocol focusing on models for the gaseous state including the ideal gases equation and the van der Waals equation; and a physics protocol focusing on models of the solar system, following Ptolemy, Copernicus, Kepler, Newton, and Einstein. All the interviews were designed to assess the same meta-modeling knowledge:

- Conception of what a scientific model is

- Ability to use various models to explain phenomena
- Evaluation of scientific models, advantages and limitations
- Revision of scientific models

In addition, the interviews also probed for prior knowledge of the scientific content and the students' ability to use a model to explain specific phenomena. The physics interview protocol is presented in the Appendix.

Analysis.

The interviews were transcribed and divided into segments, with a segment ending and another beginning when the focus of the interview shifted to a different aspect of modeling. Student utterances in each segment were mapped onto a construct map with two dimensions developed the MoDeLS project and presented in Table 2. The two dimensions are titled Generative and Change, focusing on the use of models and the critique and revision of models, respectively. The construct map contains four aspects. The first is divided into two sub-aspects, literalness vs. salience, and specificity vs. generality. The second aspect focuses on who is the intended audience of the models, the third on how the components and the relationships between the components of the model are justified, and the fourth on type of relationship between the model and reality for which the model is used.

Table 2: Modeling Construct Maps

Category	**Level**
A-I. Literalness vs. salience	1. Models are literal illustrations of phenomena 2. Models consider things that are inaccessible to the senses 3. Multiple different representations of the same phenomena are possible 4. Models can represent unknown phenomena
A-II. Specificity vs. generality	1. Models are representations of a single

	phenomenon 2. Models can represent similar phenomena 3. Models can represent multiple related phenomena 4. Models are representations of ideas
B. Who is the audience?	1. Models are made for the teacher 2. A) Models are made to show what I think B) Models are made to help others understand 3. Models are made to communicate with others 4. Models are made to help me think
C. How is a model justified?	1. No justification needed 2. A) Content knowledge B) Authority C) Evidence in a specific case 3. Evidence in general
D. What is a model used for?	1. None 2. To explain in general 3. To describe, explain, and predict 4. To predict possible new phenomena

After each interview was coded, the total number utterances each student made that were mapped to each dimension, aspect, and level of the construct map were counted. A single combination of dimension, aspect, and level was counted only once per interview segment. These numbers were registered in four different tables, one for each aspect in the construct map. The distribution of the utterances across the various levels was treated as indicative of the actual level at which the student was in relation to each aspect.

Results

Table 3 shows the distribution of the students' utterances in relation to aspect A-I – literalness vs. salience and specificity vs. generality. G in the table stands for *Generative* and C stands for *Change*. Numbers on the left of a column and in black are the number of utterances from the first interview (the one whose content matched the student's major); the numbers in red and on the right of a column are from the second interview, the one done in an unfamiliar content area.

Table 3: <u>Aspect A: Literalness vs. Salience and Specificity vs. Generality – Distribution of Students' Utterances</u>

Participant	GA1		CA1		GA2		CA2		GA3		CA3		GA4		CA4	
1					1		1		2	2	1					
2					2				1	1	1		1			
3					1				4							
4			1						3	1	7		1			
5									2	5	3			1		
6								1		1						
7										3				1		
8	1						1		1		2					
9						1			1	3	2					
Physics			1		1				7	1	7		1			
Chemistry					3		1		3	3	2		1			
Biology								1	2	9	3			2		
SFA	1					1	1		2	3	4					
Total	1		1		4	1	2	1	14	16	16		2	2	0	

It is apparent that all the students are at level 3. There are still some remnants of level 2, a sporadic level 1 utterance, and the beginnings of level 4, but the vast majority of the responses are at level 3, for both the generative and the change dimensions, and regardless of the whether the content of the interview was familiar or not. An example of a level 3 utterance is:

> I - Let's look at some common astronomical phenomena and see how the two models can be used to predict them. Take a solar eclipse, for example. This is caused when the moon blocks the sun. Could you explain it using Ptolemy's model?
>
> S - Yes, you could.
>
> I - Could you explain it using Copernicus' model?
>
> S - Yes, you could.
>
> I - Let's take another phenomenon, a lunar eclipse.
>
> S - **You could explain it, using either model.**
>
> I - How about the phenomenon that Mars, when viewed from Earth, seems to move in one direction, and then in the reverse direction. Could you explain this phenomenon by using these two different models of the solar system?
>
> S - **Yes, you can explain this by each of the models.**

> I - So we’ve got a problem. How can we decide and justify which model is correct?
>
> S - **You could calculate when you’d expect there’d be a solar eclipse or a lunar eclipse, using each of the two models, and then to confirm which model was right, in other words, to measure the actual time and see if it’s closest to what was predicted by one of the models.**

This utterance shows understanding that: A) multiple models can be used to explain the same phenomenon and B) the same model can be used to explain multiple phenomena.

Table 4 shows the distribution of the students' utterances in relation to aspect B – intended audience.

Table 4: Aspect B: Intended Audience – Distribution of Students' Utterances

Participant	GB1	CB1	GB2	CB2	GB3	CB3	GB4	CB4
1								
2			1					
3			1		1			
4								
5								
6								
7					2			
8								
9								
Physics			1		1			
Chemistry			1					
Biology					2			
SFA								
Total	0	0	2	0	3	0	0	0

The interview protocols did not adequately probe this aspect of modeling, and any utterances related to the aspect of audience were made spontaneously, without any probing. Therefore there aren't enough utterances to identify any pattern in the responses. It appears that the students are transitioning between level 2 to level 3. Interestingly, all the level 3 utterances were made in the context of the second interview that was based on unfamiliar content, while the level 2 utterances were made in the context of familiar content. An example of a level 3 utterance is:

> I - So we've seen that we can have multiple models representing the same phenomenon. How would you, or how do you think scientists determine which model is the best?
>
> S - Well, one of the considerations would be with which model it's easiest for them to show what they think.

This utterance shows an understanding that: A) models are to show what you think and that B) they need to be easy to understand.

Table 5 shows the distribution of the students' utterances in relation to aspect C – justification of models' components and relationships.

Table 5: Aspect C: Justification – Distribution of Students' Utterances

Participant	GC1		CC1		GC2		CC2		GC3		CC3		GC4		CC4	
1										2						
2										1		1				
3									1	1						
4									1		3	1				
5									1		1	1				
6									1	3	1					
7									2			1				
8					1											
9						1				2	1	1				
Physics									2	1	3	1				
Chemistry									1	3	1	1				
Biology									4	3	2	2				
SFA					1	1				2	1	1				
Total	0		0		1	1	0		7	9	7	5	0		0	

Here too, as in aspect A, the students are firmly situated at level 3, regardless of the dimension or the familiarity of the content, although there is no sign yet of level 4 appearing. An example of a level 3 utterance is:

> I - Now let's consider how scientists got to your model of photosynthesis from van Helmont's model. Any ideas?
>
> S - Through a lot of experiments on plants on the relationship between plant growth and other factors, such as water and sunlight. Plants don't grow without sunlight and C0$_2$. I don't know how they would measure C0$_2$. Perhaps they'd measure the effect of C0$_2$ on plant growth by its absence.

Table 6 shows the distribution of the students' utterances in relation to aspect D – the uses of models.

Table 6: Aspect D: Uses of Models – Distribution of Students' Utterances

Participant	GD1	CD1	GD2	CD2	GD3	CD3	GD4	CD4
1					1	1 1		
2					2			
3			1		3 2			
4					5	1		
5								
6			1		1			
7					1 2	2		
8			1					
9			2 1		2 1			
Physics			1		8 2	1		
Chemistry					3	1 1		
Biology			1		1 3	2		
SFA			3 1		2 1			
Total	0	0	4 2	0	14 6	2 3	0	0

Here too, most of the students are at level 3, with a few indications that level 2 hasn't been completely left yet. The students displayed an understanding of the generative dimension of this aspect more than they did of the change dimension. Apparently this is an artifact of the interviews' structure. An example level 3 utterance is:

> I - So let's say you were a scientist and you wanted to contribute to science. Which strategy would be best? How would you spend your time?
>
> S - That depends on your budget.
>
> I - Let's say you have a good budget.
>
> **S - I'd check out where the accepted models don't work, and try to figure out why this is so.**
>
> I - Why does this approach work better than working on what we know?
>
> **S - Because we already know what we know. But what we don't know, you can develop it to another level, to something new which wasn't known before.** Just as Einstein further developed the model of Newton, another stage forward.

An important finding is that, while the students displayed meta-modeling knowledge at level 3 across the various aspects, whether or not they were familiar with the content, they were unable to use a model to explain a phenomenon based on unfamiliar content. In most cases, a quick introduction to the central concepts, using the models as instructional tools, changed this situation and allowed them to use the models as explanatory aids.

Finally, all the students liked the idea of using modeling as an instructional approach. They thought modeling made the content interesting, challenging, and authentic. For example: “I think using models is a good way to learn. It’s not just throwing things on the blackboard. Also in math, if you know how a formula was developed, it helps you understand what’s happening and what influences things. You can actually understand, and when you understand you remember better.”

Discussion

All the high school students, whether they were science majors or learning general science, once they had a rudimentary understanding of the relevant content, were able to use models to explain or predict related phenomena. They all demonstrated level 3 meta-modeling knowledge, irrespective of whether the content was familiar or not. Signs of level 4 understandings were beginning to appear. This level of modeling knowledge is higher than was demonstrated by middle school students in familiar content after participating two 8-week modeling-rich units (Schwarz et al., 2008; Fortus et al., 2008). This raises three points:

A. It provides evidence that level 3 meta-modeling knowledge, as defined by the learning progression (Schwarz et al., 2009) is an attainable and reasonable goal for K-12 education. Level 4 understanding may too be attainable, given appropriate instruction and experience. This picture matches pretty well the situation with 11 grade science AP students described by Grosslight, Unger, Jay, and Smith (1991). They described a triple level hierarchy of meta-modeling knowledge and found that most 11th grade students were at level 2. Their level 2 matches the combination of levels 2 and 3 in our study. The main difference was that some of our students were beginning to show signs of level 4 understanding (their level 3). This may be a result of cultural differences or past educational experiences.

B. Meta-modeling knowledge appears to be independent of content knowledge. On the other hand, the ability to use a model to explain phenomena seems to be content-dependent.

C. Is it advisable to expend much time and effort in helping middle school students develop modeling knowledge, as the high school students in this study appear to have constructed a level 3 understanding without explicit instruction? Focusing on meta-modeling knowledge in elementary and middle school is beneficial if it helps students develop a deeper understanding of content, a more positive motivation to learn science, or if it is an important learning goal in its own right. However, it has yet to be demonstrated that an explicit focus on meta-modeling knowledge as a learning goal improves middle school students' knowledge of science content or improves their motivation to learn science. Actually, anecdotal evidence indicates that a focus on meta-modeling knowledge may actually be detrimental to content learning because of additional cognitive load it places on students and because of teachers' unfamiliarity with the topic and how to teach it (Fortus, et al., 2008). Also, every additional learning goal must come at the expense of another, because of the limited time available to classroom instruction. Finally, is it important that students graduate from high school with a level 4 understanding? Is level 3 understanding not sufficient for students who will not continue to scientific careers? These are all issues that need be considered and studied further before the importance of focusing on meta-modeling knowledge can be decided.

References

Develaki, M. (2007). The model-based view of scientific theories and the structuring of school science programmes. *Science and Education, 16*, 725-749.

Fortus, D., Weizman, A., Shwartz, Y., Merritt, J. D., & Schwarz, C. V. (2008). *Incorporating modeling practices into middle school project-based science*. Paper presented at the Annual Meeting of the National Association of Science Teaching, Baltimore, MD.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799-822.

Kenyon, L., Schwarz, C. V., Hug, B., & Baek, H. (2008). *Incorporating modeling practices into elementary students' scientific investigations*. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Baltimore, MD.

Morgan, M. S., & Morrison, M. (1999). *Models as mediators: Perspectives on natural and social science*. Cambridge, UK: Cambridge University Press.

Schwarz, C. V., Reiser, B. J., Fortus, D., Davis, E. A., Kenyon, L., & Shwartz, Y. (2009). Developing a learning progression of scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-655.

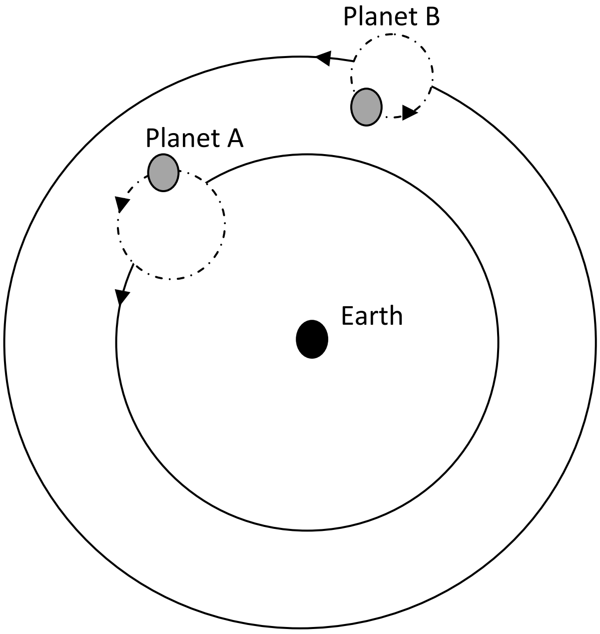
Schwarz, C. V., Reiser, B. J., Fortus, D., Krajcik, J. S., Roseman, J. E., Willard, T., et al. (2008). *Designing and testing the MoDeLS progression*. Paper presented at the Annual Meeting of the Association for Research in Science Teaching, Baltimore, MD.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967.

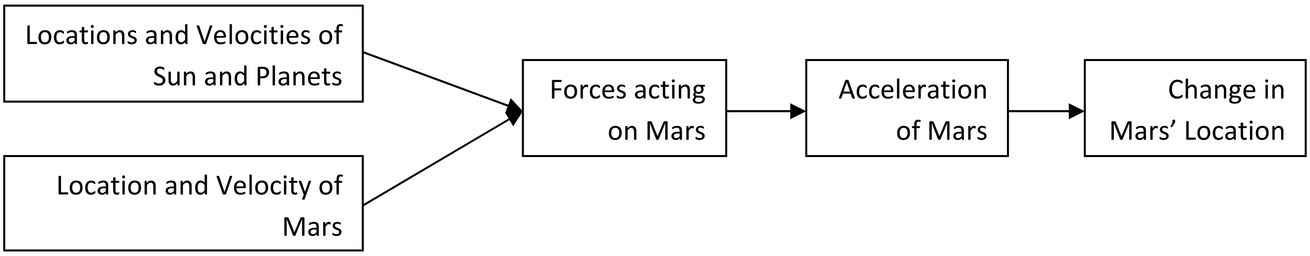
Appendix – Protocol for Physics-based Interview

1. Please describe, in words and using a model, the structure of the solar system. (This will assess the student's prior knowledge of the solar system and see if s/he will use a drawing as a model or whether s/he will view a drawing as something other than a model.)

2. Show the student the Ptolemaic model of the heaven and ask him/her whether this is a model of the solar system. Ask when they might use it, how they might evaluate it, and what they would do if their assessment turned out negative. Do the same with an equation of the motion of a planet, a flowchart showing cause-and-effect in the solar system, and a simulation of the planet using "Dance of the Planets." (This will help see what they consider a model. Questions 1 & 2 help assess the student's "position" relative to level 1).

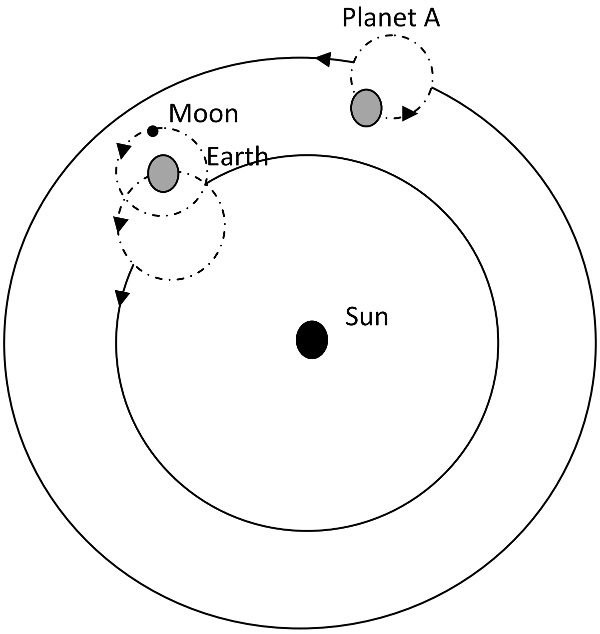


$$M_i \frac{(\vec{R}_i - \vec{r}_m)}{|\vec{R}_i - \vec{r}_m|^2}$$



3. Tell the following story:
    a. Once upon a time, people thought that the Earth was located at the center of the universe, while the sun, moon, planets, and stars all rotated around Earth. Greek astronomers had built a model of the heavens that was pretty good at predicting the locations of most of the heavenly bodies, but not all of them. A Roman astronomer called Ptolemy revised and enhanced the model of the Greeks and built a model that described very well the observed movement of all the heavenly bodies. According to Ptolemy’s model, the Earth was surrounded by 8 spheres. On each sphere one of the heavenly bodies was located, in the following order:
        i. Moon
        ii. Mercury
        iii. Venus
        iv. Sun
        v. Mars
        vi. Jupiter
        vii. Saturn
        viii. Fixed Stars
    b. Each one of these heavenly bodies moved on an epicycle which in turn moved on its sphere.

The Ptolemaic model worked excellently, but several hundreds of years after Ptolemy introduced it, it was replaced by another model, shown below:



In the new model, called the Copernican model, the sun was at the center of the universe. It was surrounded far away by stars which did not move, and the planets revolved around the sun on epicycles like in the Ptolemaic model, with the moon revolving around earth.

In many ways, the new model was more complicated than the Ptolemaic model. At that time there was no way of knowing which model was a better description of reality.

4. Ask the student why s/he thinks people chose to use the new model rather than the original one, even though it was more complicated? How are two models compared? What is the basis scientists use to determine whether a model is accurate? (This will assess whether students know that models are evidence-driven)

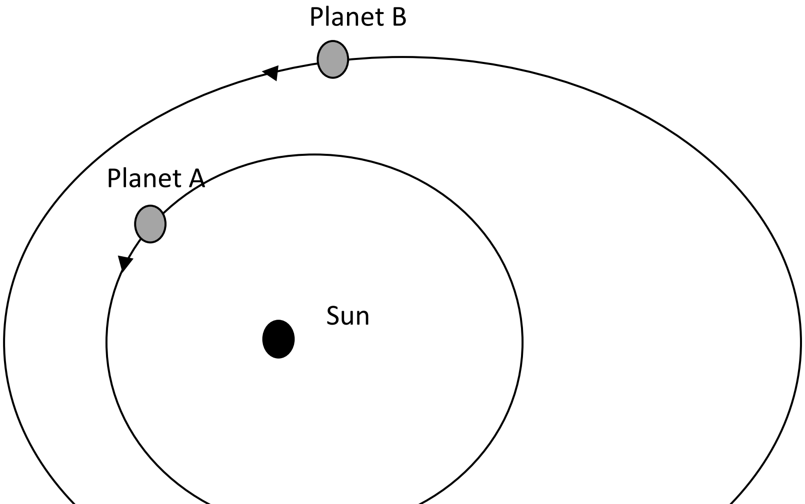
5. Ask the student to use any one of the models, or more than one, to explain:
a. How a solar eclipse occurs (tell him/her that the moon blocks the sun).
b. How a lunar eclipse occurs (tell him/her that the earth blocks the moon).
c. Why Mars, when observed from Earth, sometimes seems to be going one direction and sometimes in the other direction.
d. Why Mercury is never seen more than 11˚ away from the Sun.
(This gets at their ability to use a model to explain)

The Copernican model, although more complicated than the Ptolemaic model, had a huge advantage – its predictions fit the evidence perfectly. There were many arguments between astronomers and the pope's representatives whether to accept the Copernican model. Couldn't the Ptolemaic model be revised to maintain its relative simplicity yet upgrade its accuracy?

6. Ask the student what kind of evidence s/he thinks astronomers used to evaluate these models. (Shows if the students understands what evidence is in this context)

This controversy remained until a German astronomer named Kepler suggested making a change to the Copernican model – assuming the planets move around the sun in ellipses and eliminating the epicycles. The Keplerian model, just like the Copernican model, fit the evidence perfectly. At this point astronomers dropped both the Ptolemaic and Copernican models and permanently adopted the Keplerian model.

7. What advantage do you think Kepler's model had over the other two that it was adopted? (This gets at the notion of simplicity).



8. Based upon what you’ve heard till now about this true story, could astronomers actually *know for sure* what the structure of the solar system was? Did any of these models have better access to the *truth*? Because astronomers adopted Kepler’s model, does this mean that that model was the correct representation of reality? (Gets at the non-permanence of models)

While Kepler’s model described the observed motion of the planets, stars, sun, and moon, it didn’t explain *what made them* move as they did. Newton, with his laws of motion and his principle of universal gravitation, succeed in developing mathematical relations that described the planets’ motion perfectly. These equations predicted the planets’ motion perfectly. No longer did astronomers have to make complicated drawings of planetary motion and tables of data to know where the planets were and would be; all the needed were some simple equations. Astronomers immediately adopted Newton’s equations as their model of choice, because it matched the observation excellently and was clearly the simplest one around.

9. Do you think that Newton’s equations are a model? Why?

10. Do you think that astronomers stopped using Kepler’s model of the solar system once Newton developed his equations? Does Kepler’s model have advantages and/or disadvantages compared to Newton’s equations?

Many years later, an astronomer called Herschel discovered a new planet which he called Uranus. There was a problem with Uranus, however. Its observed motion did not match the predictions of Newton’s equations. Astronomers were perplexed. Did this mean that Newton’s model was wrong?

11. What do you think? If an example is found that doesn’t fit a model, does the model need to be abandoned?

Two astronomers hypothesized that there might be another planet, yet undiscovered, whose gravitational force was making Uranus behave differently than what it was supposed to according to Newton’s model. These astronomers used Newton’s equations to calculate where this new planet should be for it to have the needed influence on Uranus. When they pointed their telescopes at the predicted position – lo and behold – there was Neptune! So there was no need to get rid of or revise Newton’s model. All that needed to be changed was to add an additional planet.

Many years later, another potential problem with Newton’s model was discovered. With more powerful telescopes than had been available before, astronomers were able to determine that Mercury’s actual orbit deviated slightly from what Newton’s equations predicted. Many astronomers predicted, that just as had been the case with Uranus and Neptune, a new planet would be found, even closer to the sun than

Mercury, which would be the source of Mercury's odd behavior. However, they were unable to predict where this planet should be and indeed, an additional planet was never found. In spite of all the attempts of scientists to modify Newton's equations to explain Mercury's motion, they never succeeded.

12. What do you think? If scientists repeatedly fail to explain a phenomenon with a model, does the model need to be abandoned?

This problem remained until Einstein showed that Newton's equations were actually incorrect, that they were good only for cases where the planets are far away from the sun. Mercury was too close to the sun for Newton's equations to be correct. Einstein developed a completely new theory of gravitation and motion which replaced Newton's equations. These equations explain the motion of ALL the planets, including Mercury.

13. Do you think that Einstein's theory of gravitation and motion is the *correct* theory, that they are the correct description of reality?