Supporting Scientific Practices in Elementary and Middle School Classrooms: The Role of Quantitative Reasoning

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Current conceptions of science learning argue for an integrated strand model of science literacy (National Research Council, 2007) in which practices are a vehicle to develop and use scientific knowledge, and a context in which to understand how the discipline of science builds knowledge. The new conceptual framework for science education standards (National Research Council, 2011) argues for learning goals in science as defined as the intersection of core scientific ideas, general scientific cross cutting ideas, and scientific practices. Researchers have explored a range of approaches for defining the nature of scientific practice to guide designs of instructional supports and empirical analyses of students' successes and challenges. These approaches overlap, in that they all center on the community construction and negotiation of explanatory scientific ideas, but they take different slices through the aspects of this complex practice.

Three foci that have emerged are explanation building, argumentation, and scientific modeling or model-based reasoning. Explanation refers to the practice of developing claims and a chain of reasoning to provide an account for how or why something has occurred (Berland & Reiser, 2009; McNeill, Lizotte, Krajcik, & Marx, 2006; Southerland, Abrams, Cummins, & Anzelmo, 2001). Argumentation refers the practice of attempting to persuade peers and reach consensus about scientific claims, including explanatory accounts (Driver, Newton, & Osborne, 2000; Sampson & Clark, 2008). Modeling typically refers to the practice associated with constructing, testing and revising a model (abstracted representations that embody key features of the phenomenon or represent empirical generalizations) that can explain or predict multiple phenomena (Giere, 1988; Harrison & Treagust, 2000; Lehrer & Schauble, 2004).

Although these are often considered as individual practices, they are very interrelated. For example, developing models requires an understanding of what it means to explain phenomena, and involves attempting to persuade peers and reach consensus (Passmore & Svoboda, 2011). Scientific argumentation foregrounds the need to persuade peers of claims through fit with accepted ideas and evidence, but this is also a key component of developing explanations and models. We have been exploring how these aspects of practice interrelate and designing efforts to support these practices in elementary and middle school classrooms. We argue that while each of these analytical and instructional approaches may foreground a different aspect, there are underlying core elements of practice that pervade knowledge-building practices in science: constructing explanatory ideas (such as explanations and models), representation of these ideas, and critique, negotiation, and consensus (argumentation). We have been constructing and revising a scientific practices learning progression (Wilson, 2009) that is based on these ideas. The process of constructing and revising a learning progression is complex and involves challenges and design decisions (Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012).

Our Scientific Practices Learning Progression

In our prior work developing a learning progression for scientific modeling, we uncovered four critical dimensions that guide the work of constructing, using, evaluating, and revising scientific models (Schwarz, Reiser, Davis et al., 2009; Schwarz, Reiser, Acher, Kenyon,& Fortus, 2012). We draw on these dimensions from our modeling work as the epistemic criteria to guide construction of explanatory ideas in general, across the various explanation and model products. Thus, these four dimensions provide the epistemic guidance that helps learners guide all the work as students construct explanatory ideas, evaluate candidate ideas, critique their own ideas and others, and negotiate consensus. The four criteria are:

> 1. *Generality*: The first dimension refers to students' attention to the generality of their model or explanation. For example, students may shift from preferring models that contain specific features that match observed phenomena (more detail) to attempting to make the representation more general so that the model can apply to a broader range of phenomena
>
> 2. *Communication/Audience*: This criterion considers how well the model or explanation will help others understand and be persuaded of the idea. This may require evaluating how well the candidate idea responds to critiques and alternatives that have been or could be presented.
>
> 3. *Evidence*: This criterion refers to the students' use of evidence or authority as justification. Students can move from viewing ideas as simply correct, supported by authority (teachers, textbook), to understanding the role of evidence that must be interpreted to support candidate ideas.
>
> 4. *Mechanism*: This criterion refers to students' sophistication in understanding what it means to "explain," moving from a sense of valuing detail in a description toward focusing on defining causal relationships, and eventually toward more articulated mechanisms.

Our current learning progression includes four levels along these dimensions (see Appendix A for our construct map with these levels). Level 1 is the initial phase of the reflective practice. Level 4 plays an important role in outlining the target practice and providing the upper anchor. In our classroom-based work, we primarily see evidence of upper elementary and middle school students at levels 1-3 within these dimensions. Our learning progression is not meant to represent students' linear progression as students' gain familiarity and competence in scientific practice. Rather, it is meant to describe particularly important phases or aspects of students' reflective practice in classroom settings that have been designed to engage students in scientific practices. Much of the work around this learning progression is still being empirically tested and refined. For example, some of our recent research analyzing classroom discourse indicates that students' progressions from Level 1 to Level 2 within a modeling-centered environment is complex, nuanced and non-linear. We are also currently building assessment measures to trace longitudinal competence in practices over time and across practices to determine whether this learning progression works similarly for explanation building and modeling and whether the reflective practice develops across science content areas. We are also working to triangulate data sources and measures (e.g., written assessments, student classroom artifacts, interview transcripts, classroom discourse) in multiple sites across the country.

For more information about our recent outcomes and learning progression, see our most recent research related to students' progress along these dimensions as well as related research about the evolution of classroom discourse and the role of the teacher in guiding these practices (Reiser, Lo, Kenyon et al., 2012). Also see current work about learning progressions from multiple researchers (Alonzo & Gotwals, 2012).

The Role of Quantitative Reasoning

While quantitative reasoning is not explicitly part of our scientific practices learning progression, it plays an important role in scientific practice and a role in the dimensions of our learning progression. Thought we have not extensively analyzed students' quantitative reasoning within scientific practices, we see evidence of such reasoning in several instances. In particular, students' quantitative reasoning often takes place in (a) *understanding regularities or patterns in phenomena (evidence dimension)* and (b) *coordinating that information with the underlying mechanistic models and explanations for the phenomena (mechanism dimension).* Quantitative reasoning is also an important aspect in (c) *students' efforts to persuade one another about the validity of their models and explanations (communication/audience dimension)*. The following section provides empirical illustrations of these kinds of quantitative reasoning.

Quantitative Reasoning Involved in Practices

A fairly common occurrence in many of our science classrooms is that students take measurements of phenomena and must reason with the numbers they obtain from the measures to determine patterns and regularities in phenomena. For the sake of describing this more explicitly, this paper will draw on data and information from a 5th grade modeling-centered unit we designed within the topic of evaporation and condensation. We briefly describe this unit below in order to contextualize classroom data. Then we return to illustrating quantitative reasoning within the practices.

Description of the Evaporation/Condensation Unit

We developed our unit on evaporation and condensation for 5th grade students as part of our earlier MoDeLS work. For a more complete description of the instructional sequence and unit, see Baek, Schwarz, Chen, Hokayem & Zhan (2011) and Kenyon, Schwarz & Hug (2008). The unit begins with the anchoring phenomenon of a solar still. A solar still is a device that purifies some forms of polluted water through evaporation and condensation. Students are asked two central questions: "Would you drink the liquid in the bottle cap that came from this dirty water? Do you know what that liquid is and how it got there?" Next, the unit is broken into two sequential sections, one on evaporation and the other on condensation within which students conduct in-depth investigations of the two major phenomena.

The evaporation section starts with its own anchoring phenomenon that guides central questions for the investigations. "What happens to the puddle or water on the plate? Where does it go? How? Why?" Students draw their first model of evaporation to answer these questions on their workbook. Next, students conduct a set of empirical investigations about evaporation to test their model. For instance, students measure humidity over time in a container in which a cup of water is placed to determine where the water evaporates. To support this activity and other investigations, the authors provided teachers and students with equipment such as humidity detectors and a weight scale. After conducting the empirical investigations, students discuss how the patterns in the empirical evidence they have collected inform their model. They write down their ideas for revising their model on their workbook. Next, the teacher gives a mini-lecture about basic scientific ideas related to the phenomenon, and shows students computer simulations about the phenomenon. Using the empirical evidence and the ideas from the computer simulations, students evaluate and revise their initial model and construct a second model of evaporation. Next, students present their model to others in each group for feedback and discuss criteria for models. They then use these criteria as they construct a consensus model, which is their third model of evaporation. Finally, they use the consensus model to try to explain or predict other phenomena related to evaporation that they can observe in their daily life.

Students then begin exploring condensation, going through the same process as in evaporation. After viewing a picture showing a bottle with condensation on the outside, they construct their first model of condensation. Using ideas they collect as they conduct empirical investigations and see related computer simulations, they make a second model of condensation. This is followed by peer evaluation and construction of a third, consensus model of condensation. Finally they apply their model of condensation for new and related phenomena.

After completing these two sections, students return to the anchoring phenomenon of solar still and the central questions. Combining information, knowledge, and resources they have acquired through the entire unit, students construct a model of the solar still to answer the central questions.

Empirical Illustrations of Quantitative Reasoning

Quantitative reasoning occurs throughout the evaporation/condensation unit in several ways. For example, students observe evaporation and condensation using measurement tools (humidity detectors or probes) that provide numerical values (relative humidity as a percentage). Those values change over time and between empirical conditions. Again, students must (a) use quantitative reasoning to understand the patterns in those data. Furthermore, the patterns in data are linked to underlying processes and mechanisms in the phenomena. Therefore, students must (b) reason with the patterns in the data in order to be able to link those to the underlying processes and mechanisms. Finally, students (c) leverage these data and patterns in the data in order to support their models and explanations of the processes in an effort to persuade peers and the teacher about the quality and validity of their models. Again, such an effort involves quantitative reasoning. In order to illustrate these occurrences in the classroom, we use excerpts of class and group discussions from two teacher’s 5th grade classes throughout the unit.

Type A Quantitative Reasoning with Empirical Data (Evidence Dimension)

There are several cases when Mr. H asks the students to report back the patterns they find from the experimental investigations. The first two cases involve data collection using a probe that measures relative humidity from evaporation phenomena. The third involves an empirical investigation using a probe that measures relative humidity from a condensation phenomenon.

Case 1. Mr. H’s class #7 – Quantitative reasoning with data from the humidity detector over a cup of evaporating water. In this excerpt, Mr. H is asking the students about the data from the humidity detector (the probe) placed over a cup of tepid water. Students are thinking about how the humidity detector numbers are changing and what those numbers indicate about the humidity.

> Mr. H: … Someone tell me, what was the measuring point at the beginning [of the experiment] and the end? So we can kind of see if everybody got the same thing. … What was your beginning, middle and end percentage [of water vapor]?
>
> Student: 26, 38 and 54.
>
> Mr. H: 26, 38, and 54. Okay. So what happened to the humidity in that hood when you put your detector in? From your results what did you get, what [does] that mean?
> Student: [The humidity percentage] went up.
>
> Mr. H: It went up, right? There is an increase. Other groups did you see this trend? Raise your hands. Yeah, you should have seen this trend. Okay. What [does] this tells us about evaporation, … There is what?

> Tyler: Evaporation (?)
>
> Mr. H: Evaporation everywhere. Okay. Was evaporation everywhere? Or was this testing a specific place? It was testing where? The area around what?
>
> Tyler: (? inaudible)
>
> Mr. H: A little cup of water. So what is that tell us about that cup of water in evaporations?
>
> Tyler: It becomes the water evaporates.

In this excerpt, we can see that the teacher is guiding students to reason around a simple set of numbers increasing due to the humidity rising. The result is that students are beginning to understand that the water in the cup is evaporating, causing the humidity levels above the cup to rise.

Case #2. Mr. H's #7 class – Quantitative reasoning with empirical data from evaporation experiment – comparing humidity changes from hot and cold water. In this second case, Mr. H reviews results from the experiment in which students held the humidity detector over both cold and hot water. Their goal was to determine how the humidity changed, whether there was humidity change over both containers and how those changes compared. In this sense, the quantitative reasoning involves reasoning about changes over time and for different conditions.

> Mr. H: … Alright; you had two beakers of water … [cold and warm]. Someone give me the results from your group and we'll see if [it] matches up. Isabelle?
>
> Isabelle: It was 47-- Mr. H: Hot water?
>
> Isabelle: Yeah. Mr. H: Okay.
>
> Isabelle: and then it was 65 and then it was 100. Mr. H: Okay. So is this a huge increase?
>
> Student: Yeah.
>
> Mr. H: Yeah. … [that is a] huge increase in what?
>
> Student: Temperature.
>
> Mr. H: Humidity not temperature, humidity. Okay? Temperature plays the part but humidity. What are the results of cold water? … Isabelle: It was 27, and then it was 42 and it was 54.
>
> Mr. H: Okay. So [there is an] increase here – not as much, but still an increase. … raise your hand if your group got the same kind of results where hot water has the major increase. Okay. Put your hands down. How does this help us kind of think about evaporation? Kalina?
>
> Kalina: It helps us (?inaudible) but evaporates faster than the other one.
>
> Mr. H: Yeah, hot water does it? Did it evaporate a lot or had more humidity? Yeah, so if we have hot water, what should be the result of that for looking in the evaporation? Julia? Julia: [it'll] evaporate faster.
>
> Mr. H: It's going to evaporate faster. … This one here is going to be a lot faster …
>
> … from this experiment, do we see how that happened? Hot waters speed up, okay? But when we're comparing it to cold water, does the cold water still evaporate? Yeah, what do we see? Did we see humidity? Yeah, but what's the difference between hot water and cold water? … What's the difference between cold water and hot water? …

> Colin: That cold water doesn't evaporate as fast as hot water. Mr. H: Right, does it evaporate still?
>
> Colin: Yeah.
>
> Mr. H: Yeah, it does, but it doesn't do at the rate at which hot water does it. Hot water is quite dramatic, I mean you guys, show the stuff right away, don't you? Yeah, okay? So, think about this for your own model, okay? If I decide to have hot water in my model, it better look a lot differently having cold water in my model. But either way can both of them evaporate?

This classroom conversation excerpt shows how the students are trying to understand the rates of change between the hot water evaporating (fast increase in humidity levels over the cup) and cold water evaporation (slow increase in humidity levels over the cup) and the implications for their models of evaporation. This shows how students are being engaged in several aspects of quantitative reasoning – rate change from individual contexts (hot water, cold water) and comparison between those two contexts (hot vs. cold).

Case #3. Mr. H's #12 class – Quantitative reasoning with empirical data from condensation experiment – analyzing humidity levels for an ice pack over time and linking this to the mechanisms and conditions of the phenomenon. In this third case, Mr. H is guiding students to understand the data from a condensation experiment. In this experiment, students are asked to measure humidity levels next to an ice pack that is condensing under a plastic hood.

> Mr. H: Okay, I want you to put your detectors down, put your hoods down, whatever you have on your percentage reading, go ahead and record that. Now, just because your results are different from other groups, as far as the trend, don't be worried about that.
>
> Hopefully, since we did this as a group, we should get kind of a majority of you getting the same trend. For others over there, we've recorded it. We had to do it twice because the detector was stopping but it started at 31% and went down to 25%, which means what happened to the humidity?
>
> Student: It went down.
>
> Mr. H: It went down. Group 1, what is your humidity level?
>
> Student: It started at 36 and it went down to 27. Mr. H: So you had a decrease as well.
>
> Student: Yes.
>
> Mr. H: Okay, actually yours is huge. Group 2, what was yours?
>
> Student: It started at 30 and went to 21.
>
> Mr. H: Okay, so it's a decrease as well. Alright, group 4.
>
> Student: It started at 31, down to 27.
>
> Mr. H: So, a decrease. Decrease in humidity. So, majority of everybody right now has a decrease. Table 4?
>
> Student: It went from 33% to 27%.
>
> Mr. H: So it was a decrease, right. And then unfortunately, table 5 is going to be different in everyone else, what did you guys have?

> Student: It went up and then down.
>
> Mr. H: So, in the end, what would you say, was it an increase or decrease?
>
> Student: Neither.
>
> Mr. H: Neither? So nothing. So theirs fluctuated a lot and they can't tell whether it was up or down. But even with table 5 results, what can we say overall from our room? Student: It goes down.
>
> Mr. H: The humidity level in the hood is going to be…it's going down. Check it out. Five out of six groups got a decrease in humidity level. … Okay, so this next part is kind of a crucial part for you, … What's happening to the humidity level? You have some time to try over and think about it. Hopefully, try to explain it. It's going down. Why is it going down and where is all of that humidity going? …
>
> Student: When it's colder, like the ice pack, it collects like the water vapor and it's a lot dry in the bottle.
>
> Mr. H: … It happens to be lower, alright. So, our humidity level in our detector was low, anyway. So, why did it drop even more when we put the ice pack in there? Erin thinks it has to do with the ice pack doing what?
>
> Student: It's cold, so it collects the water vapor in the air.
>
> Mr. H: The ice pack is cold so it's collecting the water vapor. What other experiments did you see that possibly this makes sense? You saw the experiments of… Student: The hot and cold, like what we did in the [inaudible].
>
> Mr. H: We saw the ice pack on the scale, we saw the ice pack and just set it out. Student: The one with the Coke in the ice pack.
>
> Mr. H: Okay, what about it? Peter.
>
> Student: I don't…because the ice pack got condensed…
>
> Mr. H: What happened to the ice pack that we had set out? Student: It got water vapor.
>
> Mr. H: It got water vapor on it, right? Where did that water vapor come from? Some of us think it came from the air. Okay, what about the ice pack on the scale? What happened to that one, Nathalie? Listen up. Ice pack on the scale, what happened to the weight? Student: It went up.
>
> Mr. H: It went up, why? Julia.
>
> Student: Because of the water droplets on it.
>
> Mr. H: … Okay. Because of the water droplets where? Where did the water droplets come from? Where they on there already?
>
> Student: No.
>
> Mr. H: No, where did they come from?
>
> Student: From the air.

This transcript of class discussion shows a critical piece of reasoning in which the teacher engages the students. He helps them understand that they all got data showing that the humidity levels in the air decreased when they were next to the ice pack. In other words, that the humidity levels went down as the ice pack was decreasing. Mr. H asks why and the students that it was because, "it collects water vapor in the air." Mr H. also tries to connect this reasoning with another experiment in which the students saw that an ice pack gaining weight as it was condensing. Both of these pieces of information are critical in helping students understand that water vapor is coming from the air – not from the inside of the objects that are condensing.

Type B: Quantitative Reasoning when Linking Empirical Patterns in Phenomena with Mechanisms of Phenomena (Mechanism Dimension)

In addition to students' quantitative reasoning about empirical evidence, students also need to link that evidence with the phenomena's processes and mechanisms. The following excerpt illustrates that process.

Case #4. Mr. H constructing a consensus model of condensation. In the following excerpt from the 15th class at the end of the unit, Mr. H and the students are constructing their class consensus model of condensation. In this part of the class discussion, Mr. H is asking students what he should include in the model, trying to prompt students to recall the outcomes of their experiments and use the reasoning from the results to inform their model. He has drawn a bottle on the left side to represent "before condensation" and one of the right side to represent "after condensation." See figure 1 below for the final drawing of the condensation model. Mrs. H asks:

> Mr. H: … What is missing from this [=the after condensation picture]? Like [it] doesn't really explain what happened in the before [condensation] picture? Kelly?
>
> Kelly: We need molecules still in the air. Mr. H: Okay, we need molecules in the air.
>
> Kelly: Less than in the before.
>
> Mr. H: Less than in the before. What do you think? Why should there be less in the air here [= the after picture] than over here [= the before picture]? … Okay, Kelly, why do you think there should be less water molecules in the air? What evidence do we have that says that's probably a good thing?
>
> Kelly: (Because molecules, water molecules have) (inaudible)
>
> Mr. H: Can you think of an investigation where we saw that? Kelly: Humidifier (inaudible)
>
> Mr. H: Okay, in the hood, what about … [our] detectors in the hood? What happened with that one? Remember? We put an ice pack in there, put the hood over it, what happened to humidity level in that hood? Kelly: It went down.
>
> Mr. H: It went down, telling us what? … The water molecules, there's less in the air because where they're going?
>
> Kelly: (inaudible)
>
> Mr. H: (Onto the cold surface.) You're right, you're right, … If I have a level of 28% humidity like on a humidity detector. If I continually take some of that out, is it going to stay at 28 or continue to stay there at that level or is it going to go down, no matter how they big the room is?

Isaac: It's going to go down.

Mr. H: It's going to go down and then where is the humidity coming-where is the rest of humidity coming from?

Isaac: ([its] already in the air)

Mr. H: … think about this for a second. If I have so much humidity in a room, okay? Alright? And there is no other sources putting humidity in? If I take some of that out, will that level stay the same or will it go down?

Some students: [It] will go down.

Mr. H: Okay, think about it. Just think about. Okay? [Changing his tone] So, what do you think about me representing humidity, moisture in the air a little bit less in this [after condensation part of the] model? Thumbs up? Okay, [drawing five little circles] so I'll just put it four or five [circles]. Okay? Good. What else do I need? Anything?

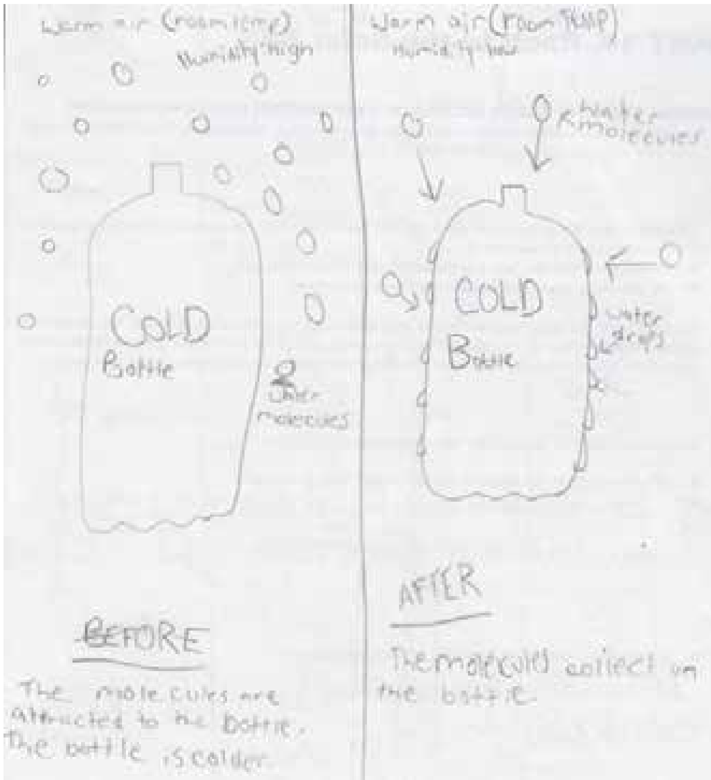

Figure 1: Mr. H's class condensation consensus model

As Mr. H's discussion with the class indicates, he is trying to help them understand that if the humidity levels went down after the cold pack showed condensation, that the water vapor in the air must have changed from vapor to a liquid water that had condensed on the ice pack. This type of scaffolding helps students link the quantitative results and semi-quantitative reasoning (water vapor levels going down after condensation) to the mechanisms in their models (when water vapor cools, it slows down and clumps together on the side of the container where there is a temperature decrease.)

Type C: The Importance of Measurements and Quantitative Reasoning for Persuading the Audience (Communication & Audience Dimension)

The following set of transcripts comes from a different 5th grade classroom (that of Mrs. M.) and indicates how quantitative reasoning plays a role when models of evaporation and condensation become artifacts for evaluation and revision both individually and as a class. In particular, students learn to leverage the numbers and patterns from their empirical work and the resulting quantitative reasoning in their models and to show others how the system in their models works and that their models are correct.

Case #5 Mrs. M's class. To illustrate how this occurs, we begin with Mrs. M's seventh class from the evaporation and condensation modeling unit. Mrs. M and the students discuss how they need to revise their initial models of evaporation based on the empirical investigations they have just conducted. In this brief excerpt, we see how Mrs. M emphasizes the importance of showing 'data' of the humidity levels in their models.

> Mrs. M: […] Who would like to share what they would change after using the humidity detectors? …
>
> Mackenzie: …I would show humidity. …
>
> Mrs. M. And what did the humidity detectors give you? … Debbie: It gave us the percentage of humidity.
>
> Mrs. M: It gave you the percent of the humidity that was in the air. So was that data?
> Student: Yes. …

The way in which Mrs. M emphasizing the humidity percentage as data sets the stage for the importance of measurement and quantitative reasoning in evaluating and justifying students' models to the teacher and one another.

In Mrs. M's 11th class, small groups are working together to create consensus models of evaporation. In this small group, students argue about how they should include the level of humidity in their model.

> Andrew: We should put the humidity to show that hot water is more humid. …To show that hot water evaporates fast and stuff
>
> Melanie: Wow, maybe we could just say like faster and slower, y'know, instead of humidity or….
>
> Andrew: Yeah, but I want to put the humidity. It's just more detail, y'know?
>
> Melanie: Yeah. Okay. Humidity.
>
> Melanie: Okay. …. Wait. … Do you want percentage? Because we don't really know the exact percentage. …
>
> Andrew: We could just make up a percentage.
>
> Melanie: No, that's….
>
> Andrew: How about we do both? I'd say we do both.
>
> Melanie: Maybe. Or, we could do um. Oh, I have an idea. We could do the humidity but still do slower or faster, you know?
>
> Andrew: Yeah.

In this excerpt, we see Melanie and Andrew debate whether they should include the exact humidity levels or the relative difference between humidity (faster/slower) to show they have 'more detail' in their model. This debate implies they are considering the importance of audience (in this case, other classmates and their teacher) in using exact measurements from the humidity detector – or at least estimated measurements to show the nature of the increase in humidity for cold and hot water. See figure 2 below of their consensus model.

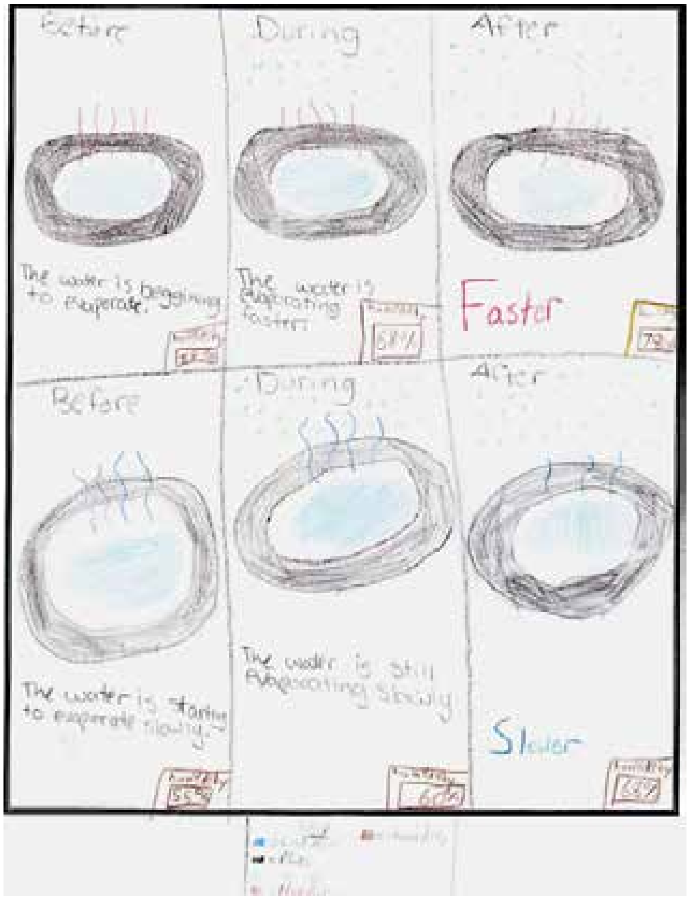

Figure 2: Small group evaporation consensus model from Mrs. M's class

After the students constructed their models, those models were evaluated by the whole class. For this group's particular model, the class gave them the following feedback:

> Barak: I like how they show the percentage of humidity.
>
> Mrs. M: Okay. Barak likes how they show the percentage of humidity, which directly comes from the humidity detector investigations. ....

Among other aspects, the class praised them for the detail and specific levels of humidity, emphasizing the importance and role of the measurements in their models.

Towards the end of the unit in Mrs. M's twenty-second class, the small group is evaluating another group's consensus model of condensation. They remark on several aspects, but in particular note the importance of using the quantitative measurements to show how the humidity works in the model.

> Andrew: …I like how it shows humidity percentage. I like how it shows how the humidity lowers and rises. It has air.
>
> Hyun: Okay, my turn. I like the way they put the humidity increasing and I like how you put color to make clear….
>
> Melanie: I like how they showed the water droplet zoomed in so you can see it better. I also like that they put a lot of detail. It shows that they put a lot of effort into it. The last thing is I like that they had arrows and a key. … My wish would be to make it have more air, because air is all around us…it's like air should be all around.
>
> Andrew: Okay. You should have put the water drops in your key like these ones. …It should have weight [measurements.]

These students' discussion indicates, among other things, how the quantitative aspects ("the humidity percentage", "how the humidity lowers and rises," the need for "weight [measurements]") are important in a good model and how they are important for persuading one another (and the teacher) that the authors have included the best aspects in the model.

Discussion

We have seen that there are several important places where students used their quantitative reasoning as they engaged in scientific practices. To summarize, students used quantitative reasoning to understand patterns in their evaporation and condensation data (e.g., humidity levels rise over an evaporating cup of tepid water; humidity levels rise faster for hot water, but still rise for cold water; humidity levels decrease near a condensing object). Furthermore, the patterns in data are linked to underlying processes and mechanisms in the phenomena. Therefore, students must reason with the patterns in the data in order to be able to link those to the underlying processes and mechanisms. Mr H. helps students understand that the particles of water (as water vapor) are not disappearing – but changing location from liquid to the air at different rates, and back to a liquid when the water vapor is near a colder object. Finally, students leverage these data and patterns in the data in order to support their models and explanations of the processes in an effort to persuade peers and the teacher about the quality and validity of their models. Mrs. M's students receive feedback from both Mrs. M and peers that they should include specific humidity levels for their models and they request that information for other students to "show how it lowers and rises." These aspects of quantitative reasoning are related primarily to our Scientific Practices evidence dimension of our learning progression, but also important to our mechanism dimension and the communication and persuasion of audience dimension.

In reviewing these transcripts, we note several critical aspects that play an important role in students' quantitative reasoning. For example, *students must be able to collect and interpret data or have access to quantitative data as they engage in making sense of the world.* Otherwise, students have little reason to engage in quantitative reasoning. We do not suggest that numerical data should always be included in students' scientific investigations as some elementary science unit topics make it difficult to collect quantitative data. However, collecting data gives students first-hand experience with phenomena, a better sense for how the phenomena works (qualitatively and quantitatively), and a chance to link the phenomena with the scientific theory.

In addition to incorporating quantitative data, *students must have opportunities to better understand the patterns in those data and to make sense of those data in connection to mechanisms and theory about the phenomena.* We note that this must occur not as a means to either discount the data or the theory as often happens in traditional classrooms, but to try to align and understand both. We also note that *the curriculum materials and the teacher play a critical role in the nature of the quantitative reasoning* – both in providing opportunities and in guiding students towards more productive ways of engaging in the reasoning. The investigations cannot be cookbook laps or existence proofs – otherwise, the students will not meaningfully engage in the quantitative reasoning. The teacher needs to be very careful at guiding students at interpreting and resolving the coinciding of the data with the mechanisms. Finally, the *classroom norms including the effort to persuade others of the validity of the claims, as well as the value of doing so by recalling patterns in empirical evidence is important to the quantitative reasoning*. Such aspects have played an important role in other classrooms and it seem reasonable to assume that doing so will further support quantitative reasoning in others.

While we have been able to support some quantitative reasoning in our project, we also realize that our approach can be improved. For example, through the curriculum and the teaching, we could provide additional scaffolding for students/teachers so that they pay more attention to the patterns in investigations of the world and better help students understand experimental design, measurement and error – all critical parts of science and quantitative reasoning. At the same time, students should have some flexibility to decide what data to collect and how to collect it as well as opportunities to develop their own representations and ways to capture the meaning of the data. For example, while teachers like Mr. H play an important role in helping students focus on the patterns in empirical data, students should also have some opportunities to design and interpret the data more flexibly in order to obtain more sophisticated engagement in quantitative reasoning. Students and teachers can also benefit from further understanding that quantitative reasoning can be a foundation for addressing alternative ideas about mechanisms and processes. Furthermore, while our learning progression does not explicitly take on quantitative reasoning as its main focus is on the epistemic commitments of scientific practice, we are working on more explicitly determining how quantitative reasoning plays a role in the levels around our evidence dimension (as well as our communication/audience dimension). We have seen that students' current quantitative reasoning most closely addresses the quantitative interpretation of the quantitative reasoning learning progression (Mayes, Bonilla, & Peterson, 2012), but it does not address the other dimensions as they are heavily scaffolded by the curriculum materials and the teacher. Nonetheless, quantitative reasoning is an important part of how students engage in science and needs to be further addressed.

There are some productive directions for future research around quantitative reasoning and learning progressions. For example, while many are working towards developing learning progressions of important content, reasoning and practices to define important aspects and trace their development over time, it is important to determine how learning progressions of content, practices, epistemic commitments, types of reasoning, and habits of mind overlap and work together (or opposite to one another) for learners pre-K to adult. It is important to determine how these learning progressions work within different subject matter or content domains (e.g., science, math, as well as language arts and social studies) if one is to design curriculum or teach at the elementary level and beyond. In the near future, it will be important for our learning progression as well as those of others to overlap to produce a coherent guideline that can inform the education community. Additionally, learning progressions work needs to coincide with standards, assessment measures, teachers, curriculum materials design, etc. It also must be flexible enough to take into account local, school, and individual cultures and ways of knowing – otherwise, it will be ineffective. We look forward to determining how our Scientific Practices learning progression can simultaneously advance the work of others and build on the work of others to improve the science and mathematics education of all children.

Acknowledgements

This research was funded by the National Science Foundation (NSF) under Grant ESI-1020316 to the Scientific Practices project at Northwestern University and Grant ESI-062819 to the MoDeLS project at Northwestern University. The opinions expressed herein are those of the authors and do not necessarily reflect those of the NSF. I am indebted to my colleagues on the project as well as the graduate students who have provided input into these ideas through their work on the MoDeLS project. In particular, I thank Brian Reiser, Lisa Kenyon, and Leema Berland as well as graduate students Hamin Baek, Li Zhan and Mete Akcaoglu.

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Appendix A – Draft Learning Progression for Scientific Practices

Change Construct Map	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Summary Description of Level	Students refer to models and explanations in absolute terms of right and wrong answers. For models, this includes a focus on whether the model replicates the phenomenon.	Students revise models and explanations based on information from authority (teacher, textbook, peer) or plausibility rather than evidence gathered from the phenomenon or new explanatory mechanisms. Students make modifications to improve detail, clarity or add new information, without considering how the explanatory power of the model or the explanation's fit with empirical evidence is improved.	Students revise models and explanations in order to better fit evidence that has been obtained and to improve the articulation of a mechanism. Students compare models and explanations to see how different components or relationships fit evidence more completely and provide a more mechanistic explanation of the phenomena.	Students evaluate competing models and explanations, and attend to counter- evidence to consider revising their current model or explanation. Model changes are considered to develop questions that can then be tested against evidence from the phenomena
Underlying Subdimensions	*Model and explanation changes, comparisons, and evaluations…*	*Model and explanation changes, comparisons, and evaluations…*	*Model and explanation changes, comparisons, and evaluations…*	*Model and explanation changes, comparisons, and evaluations…*
A. Attention to generality Explanations rely on general principles to construct causal accounts. Generalized explanations are the goal of models and are seen when attempt to extend the model to make it address more cases.	…are made by considering model or explanation as either right or wrong. …are made without considering whether model or explanation contains general knowledge	…modify or add to the explanation or expressed model to make it fit a new case, without attention to trying to explicitly communicate the generalization that makes it fit the multiple cases. (This is like making an analogy rather than a generalization)	...modify the explanation or expressed model to replace more specific with more general components (in diagrams) or add additional language (in explanations) that makes explicit how the model or explanation can handle new cases. It maps the specific explanation of the target case to the underlying more general explanation (which may be principles in explanation or more general components in expressed models).	

Change Construct Map	**Level 1**	**Level 2**	**Level 3**	**Level 4**
B. Attention to communication and persuasion of audience	… are made to make an incorrect model or explanation correct, and so do not consider audience. The audience is viewed simply as the teacher.	…consider how clearly the model or explanation shows the ideas behind it. Communicating models and explanations is to show others what we learned. No consideration of rebuttal or what others would do with the product.	...consider how well the model or explanation will help others understand and be persuaded of the idea. Also consider how well the model or explanation responds to critiques and alternatives that have been presented. The model intent now goes beyond communicating what we figured out to persuading others.	…consider whether potential alternatives and critiques (that have not yet been raised) could be rebutted by the model or explanation.
C. Attention to evidence or authority	…are made based on personal preferences unrelated to the phenomena; …are made by appeal to make model or explanation “more scientific”; … are made to make model or explanation “correct,” but without citing justification.	…are based on content knowledge, or logical reasoning but with no justification from the evidence; … are based on appeal to an authoritative source; …are based on observational or experimental evidence.	…are based on observational or experimental evidence with a justification using that evidence to make the change.	…focus on accounting for counter- evidence

Change Construct Map	**Level 1**	**Level 2**	**Level 3**	**Level 4**
D. Attention to mechanism	… do not consider whether the model or explanation provides a mechanism; instead focus on including more detail, or to make the model a more veridical description of the phenomenon.	… are based on a simple association between a model component or scientific principle and a phenomenon, without describing a process or mechanism. …take account of a simple sense of cause or correlation without addressing mechanism.	…are based on a more precise sense of explanation, such as describing a mechanism or showing a process. …focus on salient features of the phenomena, and on removing unneeded detail.	