Children Doing Science:
Essential Idiosyncrasy and the Challenges of Assessment

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To this volume on out-of-school STEM learning, we contribute an example of science. Our charge is to discuss what it means for children to be doing science and how educators can assess it. To that end, we've chosen an especially clear case. It happens to have taken place in school, but that shouldn't matter for our purpose here; it's the substance of the children's reasoning that we're assessing as the beginnings of science.

We open with the case. We then articulate how it is an example of science, in particular of science as a pursuit. Finally we discuss what this view means for science education, in particular with respect to assessment, whether out of school or in.

Third graders studying motion

Responsive teaching and the launching question

The snippet we present took place in Sharon Fargason's third-grade class. Sharon worked with us in an NSF funded project, "Responsive Teaching in Science" (Goldberg, Hammer, Bendall, & Coffey, 2008-2011), focused on cultivating close attention and responsiveness to the substance of student thinking. The project team developed pilot ideas for "responsive curricula" in a series of units. Each begins with a "launching question," chosen to provoke student thinking. For more on the project, the curricula, and to explore case studies, see the project website.[1]

This time, the launching question was about a toy car Sharon showed the students: What ways can they think of to get it moving? It's a question we've used many times, and it reliably has students' generating ideas, about rubber bands and springs and ramps, batteries and motors, throwing and kicking, even rocket boosters and laser beams. It also provokes new questions and things to do, from fantasizing about a roller coaster, as some students did for a time in this class, to debating what would make the car (or other object) go faster. The idea of responsive

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[1] http://cipstrends.sdsu.edu/responsiveteaching/

curriculum is that the teacher facilitates and attends to students' expressing their ideas and asking questions, listening for the beginnings of science (Hammer, Goldberg, & Fargason, 2012).

In this way, having launched students' thinking, Sharon listened for and highlighted questions about mechanism, such as a student's question about the plausibility of the car taking a particular path on the roller coaster. She pressed for clarity and consistency; she asked for evidence and arguments. There is a detailed, day-to-day account of the progress in this class, over its time in the toy car module, with many video clips and commentary, at the Responsive Teaching website.[2]

The activities that followed from the launch went on for 16 class periods, spread over six weeks starting in the middle of September. As the unit progressed, what students were saying and doing came to look more and more like science. Much of the challenge in responsive teaching is to discern subtle beginnings and draw them out. For our purpose here, we jump to a moment when it was especially clear that the children were doing science.

Day 14

The moment we've chosen took place on the 14th day of the children's work, several weeks after Sharon first posed the launching question. In the days immediately preceding, the students had been working on ramps, including to debate whether the weight of the object affects its speed. As part of that, they tried an experiment in the playground, with a student on the slide racing a toy, but the results were ambiguous.

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[2] Select Sharon, year 2, part 1 at http://cipstrends.sdsu.edu/responsiveteaching/carmodule/trajectories.html for this detailed presentation. Part 2 presents work from later in the year, when Sharon decided to resume the toy car discussions, in place of other science activities. In all, the class spent 31 class periods in activities that originated from the toy car launching question. For more on Sharon's teaching, see (Bresser & Fargason; Hammer et al., 2012; Radoff, Goldberg, Hammer, & Fargason, 2010; Radoff & Hammer, book prospectus under review)

At the opening of this day, Sharon called on Jamir, who read a conjecture from his journal that “things that are not round” do not go quickly down a hill. He tried to demonstrate how a rubber doorstop will stay put on a steep ramp, as he’d seen the day before, but this time it slid. That inspired conversation about what affects when and how an object moves down the ramp. Several students suggested and gave evidence that it’s the object’s shape (round or not), the material (rubbery things stick rather than slide), or the angle of the ramp, that determines the object’s motion. Kylie, for example, argued that the angle of the ramp matters because they had seen the same object slide quickly or not, depending on the steepness of the ramp.

Some of the students drew on their experience to contrast pushing an object on a ramp, when it only needs an initial push to get going, with pushing it on the ground, where it needs continuous pushing. Ray suggested it was about “free will,” on the ramp, and Sharon chose to ask what that means.[3] This raised ideas both about deciding, i.e. whether the toy car would have a choice in what it does, and about the need for a source of energy.

We would argue that all of this activity reflected the beginnings of science. For some contributions, that’s clear—e.g. Kylie’s citing evidence to support her claim that steepness matters. For others, it is not so clear —e.g. Ray’s invoking free will. To be sure, it is an essential part of Sharon’s expertise that she could recognize beginnings and draw them out. In the exchange that followed, however, there is no question: The children were doing science.

Isaac’s wheels[4]

Isaac raised his hand to offer another account for why a car moves freely while a doorstop doesn’t. He suggested that, “it just matters that, if it has wheels.” Sharon encouraged Isaac to say

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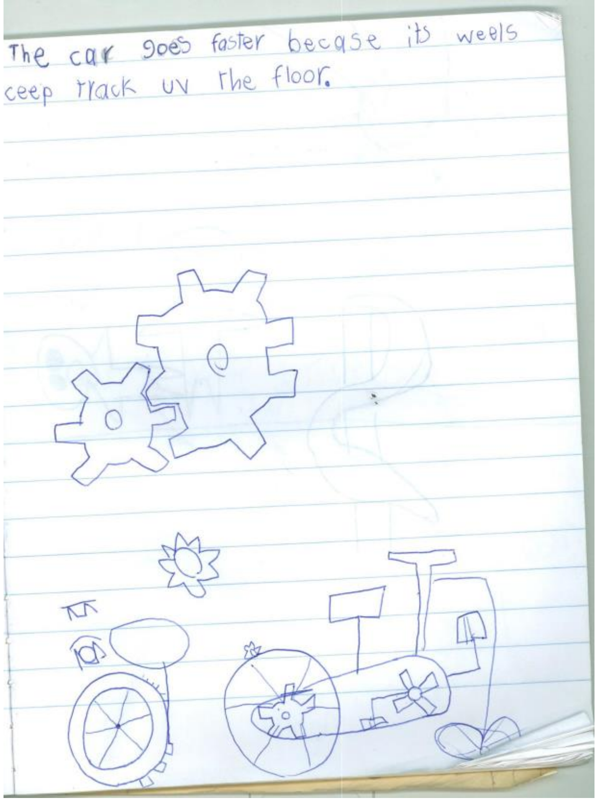
[3] For a discussion about this choice, see Radoff & Hammer (under review).

[4] See video clip #5 on Day 14, from Sharon year 2, part 1, at the link in footnote 1. Note that Isaac, like many students in the class, spoke English as a second language.

more, remembering he had written about wheels in his notebook: “This actually brings up an interesting point that’s a little different than what everyone else has said today.”

Isaac opened his notebook (Fig. 1) and read from the top of the page: “The car goes faster because its wheels keep track of the floor.”



The car goes faster becase its weels ceep track uv the floor.

Figure 1. Isaac’s Notebook

Sharon asked Isaac to clarify “keep track of the floor.” He showed her and the class his drawings of gears and bicycle. Pointing to the gears in the middle of the page, he explained, “The first one goes and then it pushes the other one like, this one goes forward and that one on the other one, then this one would be turning around and pushing the other one around.”

Isaac asked for the toy car to explain further, drawing an analogy between the gear teeth interlocking to push the gear forward and points on the rim lining up with points on the floor turning the wheel: “When you push the car, then like this part [of the wheel] will land right there and then the wheel will push it next, into the next part to land.” He also pointed out that “the car is different than these (indicating the gears) because the car it takes, it keeps track of the flat floor with a circle."

In this way, Isaac was unpacking the mechanism of rolling: "If [the car] didn't have wheels it would just have to [d]rag that makes it go slower." That is, without the wheels, the body of the car would just drag across the surface and eventually stop. What he meant by "keep track of the floor" was that the wheel touches the floor point by point, each point moving to the next as the wheel turns, without dragging.

Once Isaac explained his idea, other students began asking him questions. Ray wanted to know, "How would the carpet push the wheels?" Ray may have thought Isaac meant that the floor spontaneously acts to move the wheels, or perhaps in line with the previous discussion on "free will," he questioned whether the floor willfully acts to push the wheels. Isaac responded, "Nooo. Like you push it first, and then the wheels go like that and they hit the floor, and then it pushes it, so the car could go, and then the next part hits it and pushes it." In this way, he clarified that the floor pushing the wheels was part of his mechanistic account of rolling, not an account of how the car starts moving in the first place.

Alexis continued, perhaps because Isaac's answer to Ray still spoke of the floor pushing. "When the car goes like right here (touches his hand to the carpet), um does the, does like the carpet stay there or like it does something to the wheels?" Isaac, once again clarifying what he meant by push, responded, "It just stays there, but the wheels like, on the fl- on the carpet, they like, this part (indicating a spot on the wheel) will land right there (indicating a spot on his hand) and then it pushes it (rolling the car forward on his hand)."

Next Jourdan asked, "you just push it on the carpet like that (pushing an imaginary toy car on the carpet), and it goes like that and it doesn't stop until the wheels try to stop?" Here

Sharon added, “I was actually wondering that too. What makes it, does it go forever?” Jourdan seemed to be drawing an implication from Isaac’s explanation, that it is the wheels’ ‘trying to stop’ that makes the car stop moving. That is, if rolling prevents dragging, and dragging causes slowing, then is it the wheels’ ‘trying to stop’ that makes the car slow down?

Isaac, who until this point had been articulating his idea about rolling he’d developed in his journal, now needed to invent a mechanism to account for the car’s slowing: “No, not really, because the wheels get tired and it stops. On a real car, it just presses a button so the car can get ene- keep on getting energy. And it keeps on going.”

Scarlett was quick to challenge him, “How could the wheels get tired?” Sharon pointed at her saying, “I had the exact same question! Thank you for asking that.” Isaac responded, “Because they, cause they didn't push that hard to get enough energy and it doesn't have electricity like a remote car.” Rather than accounting for why the car slows, Isaac explained that the car needs some outside energy source to keep going.

Not satisfied with Isaac’s response, Jamir further articulated Scarlett’s question, “I still don't get it, if the wheels get tired, cause if you get tired it’s like you can't run no more and you stop for a little bit and then you keep on running.” Thus, Jamir questioned the validity of wheels’ “getting tired” as an explanation. Isaac answered, “I know but on the- on the- on the remote control cars, like you- you push the button, and while you push the button, it keeps on getting energy from the batteries.” Jamir tried to revoice that reasoning, “So you mean that the wheels get like get slower, the wheels get slower more time it goes, like each time it keeps on going-”

As Jamir spoke, Isaac was looking closely at the car, and he came back with a new answer: “Because you see those strings that hold the wheels together? Those strings that go to the little holes made of rubber, and it can stand, it can kind of stand the rubber that's scratching the metal like that. So then that's why it gets slower and slower."

Sharon, recognizing a sensible mechanism, jumped in: "Say that again." Isaac repeated his idea that the axle ("strings that hold the wheels together") scratches against the hole that attaches it to the car, and the scratching is what slows the car down. He emphasized that "it scratches, but it could stand it kind of," meaning that the car keeps moving despite the scratching, which gradually slows and eventually stops the car. At the end of the episode, Isaac explained that the remote control car also experiences scratching, but the constant energy source overpowers the slowing due to scratching, "Because like in the remote control cars, it has the same thing that, rubber that scratches it, but why it keeps on going is because the car it has remote control and you control it and it can stand the scratch."

The beginnings of science

Our assessment of the students' activity centers on our view of science as an intellectual pursuit. In particular, it is a pursuit of understanding the natural world in ways that are coherent (i.e. holding together) and mechanistic (i.e. building from and connecting with familiar and reliable causes and effects) (Hammer, Russ, Scherr & Mikeska, 2008). The children were engaged in that pursuit in several threads of reasoning.

One thread was Isaac's idea about rolling as "keeping track of the floor." The other threads came from other students' questions about the motion of the toy car, in reaction to Isaac's account: What makes the car start moving? What makes it slow down? Throughout the snippet Isaac and the others who contributed were doing science: They were working to understand rolling and the car's motion in ways that drew on and were consistent with other things they know, in particular about causes and effects with material objects.

Isaac’s diagrams from his notebook showed him thinking about gears, including on a bicycle, and how they “keep track” of each other, teeth fitting into teeth. This gave him the idea that, in rolling, a point on the wheel lines up with a point on the floor, like interlocking gear teeth. Thus he worked to make sense of the phenomenon of rolling by connecting it to the mechanism, more tangible for him, of interlocking gear teeth. The point-by-point “keeping track of the floor” is what lets the wheel roll, rather than drag.

Other students in the class checked Isaac’s reasoning for consistency with their sense of the toy car’s motion, and their questions focused on mechanisms. Ray asked “how would the carpet push the wheels?” Isaac showed in his response that he was not thinking of the carpet as causing the motion — “you push it first”— but this led Jourdan to ask another question: Is it the wheels’ ‘trying to stop’ that makes the car stop? Jourdan’s question suggests he understood Isaac’s argument: Since rolling prevents dragging, and dragging is what causes objects to slow down, what makes the car slow down when it’s on wheels? In this moment, the car’s slowing needed mechanistic explanation.

When Isaac said, “the wheel’s get tired,” Scarlett was quick to challenge him: “How could the wheels get tired?” Jamir elaborated on the problem with that explanation, saying if a person gets tired, “you stop for a little bit and then you keep on running.” In these ways, the students were holding Isaac accountable to explanations with mechanistic plausibility.

Isaac, who had been focused on his keeping-track mechanism of rolling, shifted his attention to the mechanism of slowing. He noted the lack of an energy source — the toy car doesn’t have electricity — but that is not a mechanism for slowing. Thinking further, he described the metal “strings” (the axles) as scratching the rubber on the wheels—an explanation for why the wheels slow.

So the students were asking questions, and they were having, assessing, and revising ideas, seeking coherent, mechanistic understanding. They worked to understand Isaac's idea in a way that was consistent with how they know objects to behave: "pushing" is suspect for a carpet, and "tired" is suspect for wheels. In these ways, what we see and hear from students in this episode exemplifies science.[5]

Disciplinary assessment

Part of what's compelling about this example for physicists is that so much of the students' reasoning here is correct. Isaac's account of rolling, by analogy to gears; the children's challenges to the floor pushing or the wheels getting tired as explanations for why the car slows down; Isaac's subsequent identification of the "scratching" at the axle are all correct in the sense of alignment with Newtonian thinking. Moreover, they are matters that have a history as difficult instructional targets for much older students — for experienced physics teachers, it is impressive to hear these ideas and arguments coming from third-graders.

For this volume, as at the conference on which it is based, we chose an instance that includes children generating canonically correct ideas and arguments. We made that choice to have a clear example: That so much of what they have to say is correct, when there was no specific guidance in that direction, is evidence they were doing science.

It is also a *de facto* challenge to the stance we often hear that educators need to 'give some information' as a prerequisite to learners' engaging in inquiry. As this example illustrates so powerfully, even third-graders already have a great deal of relevant and productive "information" about the natural world. These children all knew many ways to get a toy car to move; they knew that without a supply of something they eventually called "energy"—a battery,

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[5] Of course, there are many students who do not speak in this episode; we do not have evidence within this snippet about what they were doing.

gasoline, a push, an incline— the car would slow down and stop; Isaac knew about bicycles and gears.

The risk to our choice of this episode for some readers, however, is that it could reinforce another problematic stance, namely toward canonical correctness as the objective and “bottom line” of pedagogical assessment. In other writing, more focused on challenging that stance, we and our colleagues have presented examples of children’s doing science when their reasoning was inconsistent with the canon (e.g. May, Hammer, & Roy, 2006; Russ, Scherr, Hammer, & Mikeska, 2008).

To emphasize, we are assessing students’ activity within the snippet more in comparison to what scientists *do* than to what scientists *know*. Scientists are professional learners about the world; the essential state of scientists is not-knowing-and-trying-to-find-out. They ask questions and wonder; they look for gaps and inconsistencies in their current knowledge; they have ideas and consider whether they might be true. That the students in this snippet were generating ideas and arguments in line with scientists’, in the absence of any specific guidance toward those ideas and arguments, is compelling evidence they were engaged in the pursuit. But it is vital to recognize that doing science (or learning to do science) does not generally mean being correct.

Right now, for example, there is a debate in cosmology being covered in the press: A project has found a pattern in the polarization of the microwave background radiation that, they claim, is “smoking gun” evidence of gravitational waves from the first moments of the universe’s existence (Overbye, 2014). Other scientists have challenged that interpretation, arguing that the pattern might well have arisen from galactic dust (Byrne, 2014). The original team is under pressure now to refute the alternative interpretation, which will mean collecting further evidence. Clearly they are all doing science, regardless of what survives the test of time.

Doing science fundamentally involves working to decide what is “correct,” the assessment of ideas: Is the idea consistent with other knowledge? Does it make sense? What does it imply, and do those implications check out? The field has evolved to include practices of checking for gaps and inconsistencies. Scientists assess ideas for explanatory power (can they readily account for what is known?) and for predictive power (do they predict phenomena that are not yet known?). Call it *disciplinary assessment,* what scientists do of ideas, as well as of approaches to developing ideas (“is this a good method for our experiment?”). For this reason, that assessment is fundamental to science, teaching science means involving students in assessment (Coffey, 2003).

Put in these terms, our *pedagogical* assessment of the snippet above, that the children doing science, and doing it well, reflected our seeing evidence of the children’s involvement in *disciplinary* assessment. It is a challenge for science education in schools, unfortunately, that the pervasive criterion for assessing students’ thinking is alignment with an authoritative body of knowledge (“did you get it right?”). That’s at odds with the disciplinary practices of science, in which authority plays a limited role. Happily out-of-school settings are not so constrained to assess by that criterion.

Truth be told, authority is not entirely absent from science. A theorist, for example, might calculate a quantity and then check the result against a highly regarded, reproducible empirical measurement. But there is no absolute authority determining what is true. In science, the “truth” is what survives extended disciplinary assessment, “the test of time”: many checks, opportunities for counter-arguments and conflicting evidence.

Pedagogical assessment and idiosyncrasy

We picked and described a clear example of children doing science, their seeking coherent, mechanistic understanding of the natural world. It is, of course, just one example, with various idiosyncrasies, but there are plenty of others, including from the same project (Lineback, 2014; Maskiewicz & Winters, 2012; Sikorski, 2012) and many many more in the literature (e.g. Duckworth, 1987; Engle & Conant, 2002; Gallas, 1995; Leander & Brown, 1999; Roth, 1995; Shapiro, 1994).

Here's the thing: They're all idiosyncratic! Much as Emilyn Green described children's work in "Community Science Workshops" (during her presentation at the NRC's National Summit on Successful Out-of-School Learning), their productive work in science is idiosyncratic.[6] On Day 13 of this class, Priscilla had the idea of dropping two paper towels, one soaked in water, to give evidence that weight matters for how quickly something falls. One of Sharon's students the previous year had an idea for why a ball on a less steep ramp ends up moving faster: it has more time to gather up energy, which it does like a snowball gathers snow. In another third-grade class, a student gave an explanation of earthquakes resulting from lava pressing up against the ground from underneath, giving an analogy to adding ice cubes to water at the dinner table. In another example, third and fourth-graders had a fire-drill on a cold day, hurried outside without coats, and came back in with ideas about what coats do, including that "a coat traps all your body heat" (Rosebery, Ogonowski, DiSchino, & Warren, 2010). And so on. If children are genuinely free to have and pursue their own ideas, then what happens in any activity is going to depend on the particular children involved, how they're getting along, the physical materials and setting, what the facilitator notices and how she responds—it is a highly complex system.

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[6] http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_088711#EmilynGreenPresentation

In a forthcoming paper, Levrini, *et al* (in press) discuss and operationalize analysis of idiosyncrasy in learners' ideas and discourse as essential evidence of their genuine engagement. It is the students' "populating scientific discourse with personal intentions, purposes and tastes" that shows their "authentic and personal" seeking. When, in contrast, students arrive at and express ideas in terms straight from a curriculum, it is difficult to see evidence of their taking up the pursuit of science themselves, to distinguish that from the pursuit of, say, completing an assigned task. In other words, idiosyncrasy is an essential aspect of pedagogical assessment.

Challenges in-school and out

There is broad commitment in science education to students learning the "practices" of science, notably represented in the Framework (NRC, 2012) that guided the Next Generation Science Standards (NGSS) (2013) as one of three dimensions, alongside "core ideas" and "cross-cutting concepts." The commitment derives largely from a shared sense of the view we have taken here, of science as a pursuit and scientists as professional learners. The practices describe what scientists do, as learners, seeking, assessing, and refining their understandings of the natural world. It derives as well from another shared sense, that students' understanding the established concepts of science requires their "active engagement," active in ways that overlap with the practices of science — posing questions, looking for gaps in their understandings, and so on.

But following through on that commitment has been difficult, for a variety of reasons, all of which, we suggest, trace back to the essential idiosyncrasy of authentic disciplinary engagement.

There are, first, challenges of planning "material" across courses and in preparation for standardized assessments. The class in our example had exceptional freedom for in-school science, which is why it could do what it did. The original idea of the toy car launching question was to elicit student ideas and thinking as productive resources for thinking in ways that would lead to the scientists' idea of "energy." There was no plan to address rolling! More often, teachers are held accountable to a number of specified conceptual targets, and the challenges of responding to novel, emergent lines of reasoning are obvious.

Those challenges apply more to in-school than out, but many out-of-school efforts are beginning to use the NGSS as a guide for objectives, and they specify a significant number of conceptual targets. The number of targets was reduced in response to concerns (Coffey & Alberts, 2013), but it is still large enough to make it difficult to spend serious time in digressions, such as Isaac's ideas about rolling. Most out-of-school settings can better afford children's initiative and autonomy, to make room for doing science, but it make take vigilance to keep it that way.

Second, and related, there are challenges of assessing quality. We focused on a moment that was easy to assess, but in that respect it was unusual. Was Ray doing science well when he raised the idea of "free will"? Is it a good idea, that a ball rolling down a ramp has more time to gather energy? In general, it is easier to assess students as doing science well when their thinking aligns with core ideas and cross-cutting concepts, but very often it does not. In that, of course, they are like scientists, historical and current, most of whose ideas will not survive the test of time, but can seem (and be) productive for the moment.

Alignment with the canon cannot serve as a proxy for assessing students' engagement in science. This, we argue, is a serious flaw in the NGSS, as in the Framework on which they are based: Doing well on the "practices" very often means thinking in ways that conflict with the canonical targets represented in "core ideas" and "cross-cutting concepts." This was the original insight of misconceptions research (Strike & Posner, 1992), but it got lost; misconceptions became obstacles to overcome, rather than signs of productive rationality. The flaw in NGSS and the Framework is that there is no mention of this tension among the three dimensions.

Toward meaningful assessment

Acknowledging idiosyncrasy as essential to students' engagement in science leads quickly to recognizing educators' professional, subjective judgment as essential to meaningful pedagogical assessment, whether formative or summative. During the conference, a teacher argued for encouraging state policies that "include seat-of-the-pants moments" in their view of what should be happening in class. There is no other way to support learners' taking up and developing facility in science as a pursuit! Educators need a strong sense of disciplinary practices, and they need a discerning awareness of children and their ideas and questions. To say this another way, they need to become connoisseurs of learners' emergent thinking.

This is a familiar topic in school-based discussions of formative assessment, as integrated within learning activities in teachers' awareness of student thinking (Bennett, 2011; Coffey, Hammer, Levin, & Grant, 2011), and regarding teacher preparation to have that awareness, such as with video case studies (Hammer & van Zee, 2006; Sherin & van Es, 2009). The same considerations apply, we expect, to preparing the educators who guide out-of-school science.

To be sure, the same reasoning applies across STEM fields, as other presenters at the NRC's National Summit on Successful Out-of-School STEM learning discussed, as it does in the arts and humanities.[7] Recently, there has been a strong focus on "education for innovation" in the national discourse, toward a citizenry and a workforce not bound to existing ideas but able to invent and design and create. One way or another, that means educators not only contending with, but cultivating and celebrating idiosyncrasy.

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[7] http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_088709

In our projects, we have focused mainly on matters that concern assessment within learning: disciplinary assessment as part of doing science, pedagogical assessment of the students' progress, and the need for coherence between them. Discussion at the conference, however, focused more on assessment at much larger scale, assessment of *programs*, for purposes both of improving learning and for accountability to external stakeholders. We do not claim to have clear answers to the question of how to assess programs. It does seem clear that programmatic assessment needs also to cohere with pedagogical and disciplinary assessment.

What we suggest, in closing, is perhaps a shift of expectations of large-scale assessment, more continuous with assessment at smaller scales. Thus programmatic assessment could rely on intersubjective agreement among expert reviewers, whose expertise derives from experience in their own STEM inquiries and in guiding learners, that is in disciplinary and pedagogical assessment. This is the essence of the peer-review system, how academia makes decisions regarding publications, grants, and promotions, as well as how institutions evaluate programs. This would mean devising processes of sampling from programs: Rather than administering standardized outcomes testing for all children in the program, find ways to choose examples likely to be representative. Look closely at records of what took place, from video recordings to discussion board postings to reports and products.

That is, rather than look for ways to be reliably objective, the STEM education community should look for ways to support, improve, and draw upon professional judgment.

Acknowledgements

This work was supported by the National Science Foundation under grant # DRL 0732233, *Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy*, and by the Gordon and Betty Moore Foundation under Grant # GBMF 3475, *Dynamics of*

Learners' Persistence and Engagement in Science. The views expressed here are those of the authors and are not necessarily endorsed by the foundations

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