Students' use of symmetry as a tool for sensemaking

Tamara G. Young
Department of Physics and Astronomy, University of Utah, 115 S. 1400 E. 201 JFB, SLC, UT 84112

Lauren Barth-Cohen
Department of Educational Psychology, University of Utah,
1721 Campus Center Dr. SAEC 3220, SLC, UT 84112
Department of Physics and Astronomy, University of Utah, 115 S. 1400 E. 201 JFB, SLC, UT 84112

Sarah K. Braden
School of Teacher Education and Leadership, Utah State University, 2805 Old Main Hill, Logan, UT 84322

Symmetry is a particularly important sensemaking tool in physics; physicists use symmetry for everything from classifying crystalline solids to deriving the foundational laws of physics. In addition, symmetry is embedded in the Next Generation Science Standards (NGSS) crosscutting concepts (CCCs). In this research, we explore how students use symmetry in ways that are consistent with how physicists use symmetry. We present 5 cases of students engaged in an NGSS-aligned lesson on creating models of magnetism. In each case, we highlight one of the ways that we have found students using symmetry as a sensemaking tool: to describe, classify, predict, explain, and solve problems. These results contribute to conversations on how students learn to "think like a physicist" and how students engage in the NGSS crosscutting concepts and science and engineering practices (SEPs).

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I. INTRODUCTION AND BACKGROUND

Exploring how students learn to think like physicists is important in Physics Education Research (PER). One tool that physicists use to make sense of the universe is symmetry. Symmetry has been described as the foundational issue in deriving the laws of nature [1, 2]. Symmetry played an important role in such laws as energy conservation, Maxwell's equations, and General Relativity [2, 3]. Symmetry is used as a method of classifying phenomena and in predicting the properties of new phenomena [3], for example, in crystallography [4], solid state and molecular physics [5], and in high energy and particle physics [6]. Physicists use symmetry to explain phenomena. For example, Wigner used the rotational symmetry of allowed electron orbitals to explain atomic spectra [1]. Physicists use symmetry in simplifying and solving problems; many integrals in undergraduate electrodynamics textbooks are solved "by symmetry" [e.g., 7]. The use of symmetry in physics is profoundly important.

Given the importance of symmetry for physicists along with the PER goal of exploring how students learn to think like a physicist, it becomes relevant to consider how students reason with symmetry. Furthermore symmetry is a topic that is understudied in PER. Notably, there is some work on undergraduate students in electromagnetism courses that either focus on their use of symmetry [e.g., 8–10] or include students' uses of symmetry in the analysis [e.g., 11, 12]. However, this work primarily focused on students' difficulty with using symmetry in solving problems in electromagnetism. Demonstrations of students' productive uses of symmetry are limited in this work.

Examining students' reasoning with symmetry in PER is also important because the notion of symmetry is embedded in the Next Generation Science Standards ([NGSS], a nationwide set of standards that many states in the U.S. have adopted) crosscutting concepts (CCCs) of *patterns*; and *scale, proportion, and quantity* [13]. The *Framework for K-12 Science Education* describes the CCC of *patterns* in this way.

> *Patterns.* Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them([14], p. 84).

In the NGSS, the discussion of *patterns* mentions symmetry as one type of pattern that can "guide organization and classification" and "prompt questions" about phenomena. It also points teachers to resources on how symmetry is used in physics and other sciences [15]. In scaling symmetry, the phenomena are the same at different scales. This type of symmetry is embedded in the CCC of *scale, proportion, and quantity* [13]. Within this CCC, there is recognition that phenomena vary across scales, which can be interpreted as a version of scaling symmetry. Additionally, many ways that physicists use symmetry align with the NGSS science and engineering practices (SEPs) [13]. For example, in *constructing explanations and designing solutions* or *analyzing and interpreting data*. Given symmetry's role in NGSS, and the growing recognition of the importance of CCCs in science learning and teaching [16, 17], we suggest there is a need for greater emphasis on symmetry moving forward.

This leads to our research question: how do secondary students use symmetry in ways that are similar to how physicists use symmetry when engaging in NGSS-aligned lessons?

II. THEORETICAL FRAMEWORK

This research is situated in resources theory, particularly Knowledge in Pieces (KiP). In this framework, students construct knowledge using intuitive knowledge resources that they gain from interacting with their environment [18, 19]. Specifically relevant to this study, symmetry resources may be one type of intuitive resource [18], but little work has been done to determine the nature of these resources. While backgrounded in this study, the KiP framework guided the design of the interview and instruction, which aimed to pull out student resources regarding symmetry.

Additionally, we are interested in the ways that students use symmetry in sensemaking. Sensemaking is a process in which students will create or revise explanations in order to "figure something out" [20]. Here we are interested in the ways students use symmetry in figuring things out. For example, in describing things, classifying things, explaining things, predicting things, or solving problems.

III. METHODS

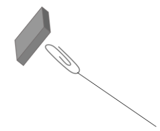
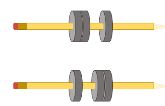
A. Data acquisition

To explore how secondary students use symmetry in ways that are similar to physicists, we used a lesson on the NGSS disciplinary core idea of *forces and interactions* [13], in particular, the forces and interactions of magnetism. We selected magnetism to explore student use of symmetry due to the types of symmetry present in a standard dipole magnet. A dipole magnet has reflective and rotational symmetry in the magnetic field and the orientation of the poles. In addition, a permanent magnet has scaling symmetry in the magnetic domains and translational symmetry in the arrangement of these domains. Students participating in this research engaged in an NGSS-aligned lesson in which they constructed models of magnetism by interacting with magnetic phenomena and drawing models of what was happening inside and around the magnets [21].

This research was conducted in a large metropolitan area in the Intermountain West. Participants were recruited in two ways. The participants for Group A were involved in an afterschool program for refugee students that focused on Science, Technology, Engineering, Art, and Math, (STEAM). These students engaged in a lesson on magnetism as part of their afterschool program; later, they participated in small-group interviews with the researchers and colleagues. The data was taken from the interviews. In total, 13 students in grades 7-12 were interviewed in 5 groups. Each interview lasted between 1-1.5 hours. The participants for Group B were recruited through social media and snowballing techniques, in which volunteers were asked to identify friends who might also be interested. These participants were interviewed by the lead author in small-group interviews in their self-identified small friend groups. For Group B, 11 students in grades 7-9 were interviewed in 5 groups. There are differences in the experiences the students had with formal magnetism instruction both between and within the groups.

In all the interviews, the students explored magnetic phenomena and then constructed models of magnetism based on their observations. There were four parts to the interviews. First, the students were introduced to the motivating phenomenon, a floating paperclip. Next, they interacted with magnet stations that we developed to allow the students to make important observations about magnets (see Table I). Next, the students were asked to draw what was happening inside and around the magnets. During this step, the interviewer asked the students questions intended to push them to construct a model that explained the observed phenomena. Finally, the interviewers asked students questions about the model and about running the model. The interview protocol included questions designed to elicit the use of symmetry in constructing and describing the models. For example, to elicit the use of rotational symmetry, the interviewers asked the students about how the shape of the magnetic field would change if they rotated the magnet in different ways. Cameras were set up to record the heads and torsos of the students as well as capture the written artifacts as the students worked on their models. After the interviews, the models were collected, and the interviewers provided written or verbal field notes. We also collected backup audio during the interviews.

TABLE I. Magnetic Stations.

Magnet Station	Description/Image	Intended Observation
1. Floating paperclip		This is the anchoring phenomenon. The students are asked what is happening in and around the magnet and paperclip to cause it to float.
2. Bouncing magnets		Magnets have different poles.
3. Broken magnets	A broken bar magnet is compared to a broken disk magnet.	When a magnet is broken, it forms two poles. The way the magnet is broken affects the behavior of the broken magnet.
4. Magnetic viewer	A thin clear plastic device filled with iron sediment suspended in kerosine.	The shape of the magnetic field. The magnetic field looks different for a disk magnet than for a bar magnet.

B. Data analysis

We used an iterative process to transcribe and code the data [22, 23]. First, we ran the audio through AI software (*transcribe* by Wreally [24]) to obtain a rough transcription. Next, we watched the video and wrote narrative summaries of the interview, making notes of sections of interest. After this, we created more complete transcriptions of the previously marked sections. These sections were short conversation segments, 1-5 minutes long, representing a single topic or idea. We then coded these segments based on the types of symmetry the students appeared to be using: rotational symmetry, reflective symmetry, scaling symmetry, translational symmetry, and pseudovector symmetry. We also noted the context in which the students were using symmetry. For example, were the students discussing a single magnet or several magnets? Were the students discussing the particles that make up the magnet? etc. After this initial round of coding, we selected exemplar cases and added non-verbal elements (e.g., gestures, positions) to the transcripts to aid interpretation. We then completed a second round of coding informed by our theoretical framework of sensemaking, which was based on how students used symmetry. The codes for symmetry that emerged from the data include: describing phenomena, classifying phenomena, explaining phenomena, making predictions, and solving problems. From this round of coding, we selected cases (from the original exemplars) that highlight how students used symmetry similarly to physicists [25].

IV. ANALYSIS

Here we present cases of the five ways we observed students using symmetry in our interviews (see Table II); we provide more in-depth descriptions for three cases that align strongly with the NGSS SEPs. In these cases, we find that students use symmetry as a sensemaking tool. They use different kinds of symmetry, and they use symmetry for different purposes to meet specific goals. All of the symmetry types discussed in the following cases are embedded in the NGSS CCC of *patterns*.

A. Case 3: Using Scaling Symmetry to Generate an Explanation

In addition to the NGSS CCC of *patterns*, scaling symmetry is also embedded in the NGSS CCC of *scale, proportion, and quantity*. An exemplar use of scaling symmetry to explain a phenomenon occurred in an interview with two stu-

TABLE II. Students' use of Symmetry.

Use of Symmetry	Context	Transcript
1. Using Bilateral Symmetry to Describe	Raj uses gestures to indicate the symmetry in the magnetic field to describe its shape (magnetic station #1).	"So, it goes on the opposite side of the, kind of like this. So this is on top and bottom <drawing a line back and forth with his hands>, I couldn't really show because it's a 2-D graph, but like it'd be like, like top to bottom <drawing a bilateral magnetic field in the air>."
2. Using Rotational Symmetry to Classify	Wesley uses the symmetry of the broken magnets (magnetic station #3) to classify a broken donut magnet (magnetic station #2) as a disk magnet, not a bar magnet.	"So you can see they stick just regularly <sticks pieces of the magnet together> and if we rotate it, <turns the magnet over> it does not care <sticks pieces of the magnet together again>."
3. Using Scaling Symmetry to Generate an Explanation	Raj and Habte use the symmetry between the parts and the whole to explain why the paperclip sticks to the magnet but the pencil does not (magnetic station #1).	How to represent the particles of the pencil. Habte: "Just little dots like that <drawing little dots on the model>." Comparing this to the particles of the paperclip. Raj: "Maybe both <draws pluses and minuses on the model>".
4. Using Rotational Symmetry to Make Predictions	Ali uses the rotational symmetry of a dipole magnet to predict that the magnetic field of a disk magnet will look similar to a bar magnet if rotated 90 degrees (magnetic station #4).	Observing a disk magnet. "It's [the iron filings] all getting attracted to that side because... I bet if you turned it over this way <gesturing to rotate the magnet 90 degrees>, it would look the same as that <indicating the bar magnet>."
5. Using Bilateral Symmetry to Solve a Problem	Andrew uses the magnet's bilateral symmetry to figure out why the broken disk magnet will not go back together (magnetic station #3).	"So if this is north, and the bottom's south, so then, I break it apart, now these two are north, so they don't like each other and these two are, and the bottoms are south, so they don't like each other. So it pushes away. But if you flip it around like before. And then they'll stick. It makes sense now. <throws arms wide and pushes chair away from table>."

dents in Group A who were trying to figure out why the paperclip will stick to the magnet but is not magnetic itself (magnetic station #1). In this case, Raj and Habte, both 11th-grade students, had constructed models in which the magnet was a dipole composed of positive and negative particles, with more negative particles on one end and more positive particles on the other end. This model represents an instance of imperfect scaling symmetry in that the pieces that make up the magnets are approximately smaller versions of the magnet.

Raj wants to discuss the paperclip because he is unsure how to draw it since it "attracts to both sides" of the magnet. Tamara asks Raj and Habte to think about the difference between the particles that make up the paperclip and the particles that make up something non-magnetic like the wooden part of a pencil. The students decide that while both the paperclip and the wooden pencil are magnetically neutral, Habte states that the particles of wood should be represented by "just little dots like that <drawing the little dots on the model>," and Raj agrees by saying "no charges." This model uses scaling symmetry in that both the pencil and the particles that make up the pencil are non-magnetic. Tamara then asks the students what the particles of the paperclip would look like, and Raj responds with "maybe both" charges and then draws the particles with a mix of positive and negative particles. When they subsequently ran the model, the students decide that the charges of the paperclip will be "more clustered" when in the magnetic field, allowing them to attract to either side of the magnet, but not be a magnet themselves. Thus, their models explain the difference between magnets, magnetic materials, and non-magnetic materials. This is important in that explaining phenomena is both in the NGSS standards and one of the ways that physicists use symmetry.

B. Case 4: Using Rotational Symmetry to Make Predictions

In our data, we find that the students are able to use their models to make predictions, which is one of the goals of the NGSS SEP *developing and using models*. Additionally, even before they develop their models, they are able to use the symmetry of the system to make predictions. Here we see students using the rotational symmetry of a dipole magnet to predict that the magnetic field of a disk magnet will look similar to the magnetic field of a bar magnet if rotated 90 degrees.

In this case, during an interview with two students in Group A, Tamara is showing Ali, an 11-grader, and Raphael, a 10th grader, the magnetic field through the magnetic field viewer (magnetic station #4). Tamara first shows the students the bar magnet, and the students note how the shape sort of balloons out. Tamara asks them to predict the shape of the disk magnet. Raphael says he thinks the shape would look "the same, just stronger, probably." However, when they try it, Ali notes that “it’s all getting attracted to that side because... I bet if you turned it over this way, it would look the same as that.” Here Ali is using the rotational symmetry of the magnetic field to correctly predict that the fields of the bar and disk magnets are the same if rotated 90 degrees. After Ali makes this prediction, Tamara turns the disk magnet on its side, and they observe that while it doesn’t look identical, it has the same type of ballooning shape that the bar magnet did. This is noteworthy because making predictions is embedded in the NGSS standards and is an important way physicists use symmetry.

C. Case 5: Using Bilateral Symmetry to Solve a Problem

One problem of particular interest in this study was the problem of why the broken magnet will not fit back together. While not every group of students was able to solve this problem, many were, and they all used the symmetry of the magnet to figure this out. Here we present how Andrew, a 7th-grade student from Group B, used the magnet’s rotational symmetry to figure out why the broken disk magnet will not go back together (magnetic station #3).

In this case, Tamara is asking the students to run their models. Tamara asks Andrew what would happen with his model if they broke it across the poles. Andrew recognizes from the symmetry of the model, that “the tops, I think, would stay north and the bottoms would stay south.” Tamara agrees and asks what would happen to the pieces. Andrew reasons that the two north sides would repel and the two south sides would repel. But if you turn one of the sides over, they will stick. At this point, it is clear from Andrew’s enthusiastic “it makes sense now! <throws arms wide and pushes chair away from table>” Andrew is pleased that he has solved the problem of the broken disk magnet. This is meaningful because solving problems “by symmetry” is an experience that every physics student is familiar with; physicists use symmetry as a problem-solving tool in both teaching and research.

V. DISCUSSION

In this paper, we observed students using symmetry as a sensemaking tool in describing phenomena, classifying phenomena, generating explanations, making predictions, and solving problems. Here the students are in the process of learning to think like physicists. While this analysis may not have captured this learning, it provides insight into the process, and future work may be able to capture it.

The students’ conclusions about symmetry are not what an expert would say; they do not use the same language as a physicist. Rather, the students use language that is familiar and comfortable to them to describe the magnetic phenomena, which is frequently not the vocabulary that a scientist would use. Additionally, they do not discuss the concept of symmetry; rather, they express symmetry-related concepts through their embodied actions and tone of voice that indicates a sense of obviousness to symmetry-related questions. Nevertheless, the students have symmetry resources that are productive and can be leveraged for future learning.

Our research primarily focused on geometric symmetry, given that this type of symmetry is highlighted in the physical aspects of permanent magnets. The cases presented here are all instances of the geometric symmetry of the magnet and other items. Case 2 and Case 4 involve executable types of symmetry (i.e. rotations and translations). Case 3 uses non-executable types of symmetry (i.e. reflections and scaling). There is some ambiguity in Case 1 and Case 5, in that bilateral symmetry can occur as a result of both rotation and reflection. While students most often used symmetry when asked triggering questions, occasionally, the students would use symmetry spontaneously. These spontaneous uses of symmetry occurred most often when the students were engaged in productive struggle during their sensemaking process. That there are other types of symmetry, and other uses of symmetry, than the ones we focused on in our research, leads us to ask if students also use other types of symmetry in sensemaking, such as the translational and rotational symmetry of spacetime. Or how might we trigger the use of symmetry related to formulating mathematical laws of physics?

An additional contribution of this study is in instructional design, curriculum, and teaching. The instruction was built to forefront the NGSS science and engineering practice of *developing and using models*. However, when looking at the data, the students are using other SEPs, such as *constructing explanations* and *analyzing and interpreting data*. Additionally, in constructing their models, the students are using the CCC of *cause and effect* in addition to the CCCs of *patterns*; and *scale, proportion, and quantity*. In as much as making the SEPs and CCCs explicit in the lesson is a best practice when teaching NGSS-aligned lessons [16, 17], we suggest teachers and instructional designers working with NGSS-aligned lessons revisit the lessons to look for additional SEPs and CCCs that may be hidden in the lesson and bring these concepts to the forefront. In particular, we encourage teachers and instructional designers to be more explicit about symmetry in their NGSS curriculum and teaching.

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