A moment-by-moment analysis of a successful case of students generating and running a model of permanent magnetism

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Within PER, case studies of successful physics learning are important for many reasons, including because they provide insight into curricular development. Additionally, from a theoretical perspective, examples of successful learning as demonstrated through microgenetic analyses of moment-by-moment shifting priorities of intuitions, can also contribute to the Knowledge in Pieces (KiP) framework by providing empirical evidence for the KiP learning mechanism. Here we present a moment-by-moment analysis of a case of successful learning in which we see how intuitions about translational symmetry, scaling symmetry, and how magnets work, i.e., they have opposite poles that attract or repel, are raised and lowered as students develop and run a model of permanent magnetism that is substantively similar to the canonical model.

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I. INTRODUCTION

Within PER, analyses of successful physics learning can provide insights into how paths of learning unfold, which in turn, can inform curricular innovation (e.g., [1, 2]). Too often, the field has emphasized cases of learning difficulties and deficits (e.g., [3, 4]). Additionally, a significant body of research has documented that these difficulties and deficits persist despite high-quality instruction [5, 6]. A perspective on learning that focuses on what students know and are capable of doing, as opposed to student deficits, can be helpful to instructors as they consider how pedagogy impacts learning [7]. With this perspective in mind, here we explicitly focus on a successful pathway of learning in order to unpack a learning mechanism. Identification and analysis of learning mechanisms shed insights into what students are capable of, which could be used to support teaching, curricular innovations, and scaffolds that build on these student capabilities.

To analyze successful learning, we use the theory of Knowledge in Pieces (KiP). KiP is a theory of cognition that can be used as a way to gain greater understanding of how learners construct knowledge about physical and other phenomena [8]. One of the foundational parts of this framework is that humans have pieces of knowledge, or knowledge resources, that they use when making sense of new phenomena. These pieces of knowledge operate across various grain-sizes from small intuitions to large, complex systems of knowledge. The primacy of these knowledge pieces can be triggered by the context in which they are operating. A significant part of this framework is developing an understanding of the learning process through the raising and lowering of various pieces of knowledge as learners construct new knowledge, explanations, or understandings. Specifically, we expect different contexts to cue different pieces of knowledge, which in turn can contribute to different explanations for physical phenomena. While this mechanism for learning is a foundational part of the KiP family of theories, including resource theory [9], the learning mechanisms are often in the background of the research rather than emphasized in the analysis and results. For example, in Barth-Cohen's [10] research on learners constructing explanations of shifting sand dunes, the raising and lowering of knowledge elements when triggered by different contexts provided the background for the analysis. Less research focuses on the moment-by-moment process during which knowledge resources are raised and lowered. Such analyses can provide insights about how students develop understandings for themselves. For example, a moment-by-moment analysis of learning may shed insight into intuitions raised internally as a student wonders about the phenomena versus intuitions that are raised externally through the instructor's help. Here, we examine the process of shifting priorities in resources in a learning environment where students were generating and revising models of magnetism. Thus, our research addresses the question: How are intuitive knowledge elements used as students develop a canonical model of magnetism?

II. STUDENT REASONING ABOUT MAGNETISM

We focus on magnetism as a useful content topic for exploring how students develop understandings for themselves. This topic was chosen as students have intuitions and experiences with magnetism, going back to early childhood where magnets are a part of their preschool science experience [11], to formal schooling [12, 13], and beyond, where magnetism is an essential part of the undergraduate physics curriculum [3]. Furthermore, magnetism is interesting as students might have a sense of how they work with respect to something about sticking together, or not sticking together, and what materials attach to magnets. Formal explanations for how magnetism works are not often covered in science classrooms, yet magnetism is mentioned several times in the Framework for K-12 Science Education [14] and although it doesn't directly align with a single grade level or standard, it can be easily be covered within several performance expectations that touch upon topics related to energy or forces and interactions [15]. Thus, we expect our students to have a productive balance of both intuitions about how magnets work and some formal explanations, and yet, there is the possibility of them developing an understanding for themselves.

As a prelude, we briefly provide a background explanation for magnetism to help the reader consider students' knowledge resources related to magnetism. The magnetic field of a permanent magnet is formed when the magnetic moments of individual atoms in a ferromagnetic material are aligned. Within a ferromagnetic material such as iron, atoms will align with adjacent atoms, forming domains in which there is a small macroscopic magnetic field. However, the orientation of the domains across the object is random, such that there is no net magnetic field. Permanent magnets can be formed by forcing the majority of the domains to align, for example, by firing ceramic magnets in a strong external magnetic field. Ferromagnetic materials can become temporarily magnetized when placed in an external magnetic field, for example, when a paperclip is attracted to a magnet. Based on this background, when considering students' knowledge, it becomes important to focus on their intuitions related to individual atoms, the alignment or lack thereof of the atoms, and their intuitions related to magnets.

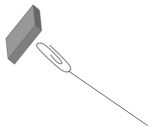
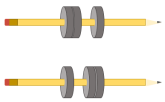
III. METHODS

To explore how students construct canonical models of magnetism, we conducted interviews of middle school-age students in small groups of 2-3. The interview protocol was developed from parts of a lesson on modeling magnetism [16]. We had previously developed this lesson to align with the NGSS disciplinary core idea of forces and interactions [15], and had piloted the lesson in several classrooms and informal learning environments. The interviews took place in a large metropolitan area in the Intermountain West. Students were recruited through social media and word

of mouth. The students were given a science-themed game as a token of appreciation. The interviews were conducted by Dr. Young, and each interview took between 1-1.5 hours.

During the interviews, the students first interacted with and made observations through a series of magnetic stations that were chosen to elicit specific knowledge pieces that we deemed necessary for constructing a model of magnetism based on our pilot data (see Table I). In the second phase of the interviews, the students drew models of the magnet. The instructions scaffolded the students to focus on the microscopic and macroscopic levels, and the phenomena happening inside and outside of the magnet. During the interviews, the students were also asked probing questions with the intent of nudging them towards a model that would predict the previously observed phenomena from the magnet stations (e.g. the magnet has a north and south pole). Finally, the interviewer asked the students to explain and "run" their model by testing if the model correctly predicted the observed phenomena. Cameras recorded the heads and torsos of the students and were angled to be able to capture their written artifacts as the students worked on their models. Afterwards, we collected the models and recorded field notes.

TABLE I: Magnetic Stations [17]

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.

To analyze the data, we used an iterative process of transcribing and coding the data. We used AI software [18] to generate rough transcriptions, and then we manually added additional non-linguistic details over multiple iterations. Between iterations, we collaboratively watched the videos and wrote narrative summaries, noting moments of interest for further in-depth analysis. The transcripts were broken into 1-5 minute sections of conversation representing a single topic or idea. Through multiple conversations, detailed transcriptions, and repeated viewings, we selected sections of conversation in which we noted moments of change as related to knowledge resources being raised and lowered. Finally, we identified intuitive knowledge resources using relevant heuristics based on the properties of intuitive knowledge elements [19]. For example, one property of intuitive resources is that they are abstracted from everyday experiences, which leads to the heuristic of "unproblematic genesis." Another example is that intuitive resources often arise from embodied experiences. Therefore, another heuristic we used is the principle of the body, in which learners will express intuitive resources through non-verbal means. Through these discussions, we achieved an interrater reliability of Cohen's kappa, $\kappa = 0.717$, which indicates substantial agreement.

Here we present a moment-by-moment analysis of one of the pairs of students as they construct a model of magnetism that is substantively similar to the canonical model. We focus on this group of students for several reasons. Important to the analysis, this pair of students had collaborative conversations as they worked together to construct their model. Therefore, they were able to respectfully disagree and offer various perspectives on the phenomenon. These collaborative conversations enabled us to follow their thinking in ways that were helpful in an analysis of knowledge resources. Their gestures and para-linguistic elements of speech were also important. The strong collaboration between these two students was unique across the interviews as they worked together on one drawing with both individuals contributing ideas, as compared to other pairs where students authored their own drawings with minimal collaboration. Thus, there are unique attributes of this pair of students that contributed to the results, and these results illuminate what learning is possible.

IV. ANALYSIS

In this analysis, we present two vignettes about the students generating and revising their models of magnetism while various knowledge resources are activated and raised or lowered. Sometimes the change in primacy of the resources is the result of questions by the interviewer, while other times it appears that the student has triggered the resource themselves. We focus on observing the shifts and the contexts in which the shifts occur. This provides a significant contribution to the KiP theory as an empirical analysis that supports the hypothesized learning mechanism [9].

A. Drawing the Model

In the first vignette, the students began generating their model of magnetism by trying to put together dipole particles. Initially, they used intuitions about translational symmetry to stack them in a way that would create a permanent magnet. However, drawing the particles raised intuitions about how magnets actually stick together, causing them to abandon their initial idea, and draw the particles in a way that would

not produce a permanent magnet. In this segment, they raised intuitions about how magnetic particles have two poles, how those poles stick together, and about translational symmetry (see Table II).

TABLE II: Relevant Intuitive Knowledge Resources

Intuitive resource	Definition
Translational symmetry	Things here are the same as things there
Scaling symmetry	Things stay the same after changing size
Magnets are dipoles	Magnets have 2 opposite poles
Opposites attract	Opposite poles of a magnet attract each other while like poles repel each other

The students were asked to generate a model of magnetism by drawing the arrangement of the magnetic particles in a zoom-in bubble (see Figure 1). During this process, they made choices about how to stack the particles together. Different choices correlated to different intuitions about magnets and translational symmetry being raised or lowered. Oscar drew the first particle as a dipole (see Figure 2 a), indicating that Oscar was using intuitions about magnetic dipoles in making this decision. Additionally, there is evidence for this knowledge resource to be in primacy, as Oscar drew the first particle immediately after observing the magnetic viewer and stating that the particles in the viewer must also be dipoles. Clarisa likely drew on knowledge resources about translational symmetry when she placed the second particle above the first particle so that it was stacked north-north and south-south (see Figure 2 b). This configuration is how the domains in a permanent magnet are aligned. Oscar then said he would place the next particle here, and drew it stacked south-north with his first particle (see Figure 2 c). Here, he may also have been drawing on intuitions about translational symmetry. However, stacking the particles south-north likely raised intuitions about how magnets stick together, in that as he draws this particle he said "So they're all stuck together in a line," which he then followed with "no wait, cuz then the souths are touching" indicating that intuitions about how magnets stick together were raised at that moment. Oscar then suggested they should be drawn differently, and added another particle to the drawing of the model, stacking them north-south and south-north (see Figure 2 d). In response, Clarisa drew 2 particles, arranged in a 4-grid checkerboard pattern, with the particles stacked south-north, north-south (see Figure 2 e), and suggested that the particles could be drawn like that. Looking at the particles that Clarisa drew likely raised knowledge resources about magnets having 2 poles, as Oscar then wondered how that configuration could make one side of the magnet north and the other side south.

To summarize, in this vignette, we see how several different intuitions about how magnets work arise when the students are thinking about how to put the particles together to create a permanent magnet. Initially, intuitions about dipole particles and translational symmetry allow the students to begin constructing a canonical model of permanent magnets.

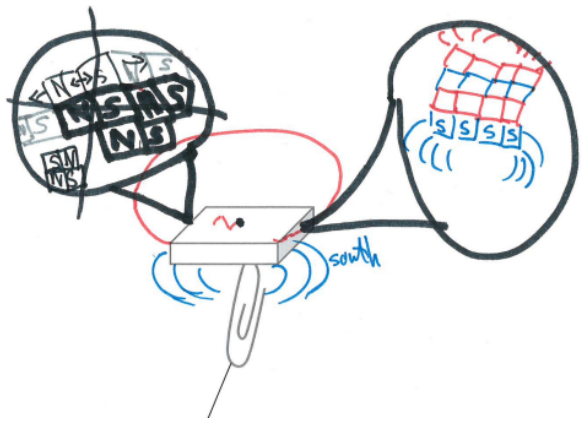


FIG. 1: Oscar and Clarisa's drawing. The magnet is labeled with N on the top and south on the bottom. The zoom-in bubble on the left (the initial drawing) is filled with black dipole N/S particles arranged in several different configurations. The zoom-in bubble on the right (the final drawing) is filled with 8 dipole particles, with red/north and blue/south particles arranged in 2 rows. The right zoom-in bubble is substantively similar to the canonical model. The magnetic field is drawn as red and blue loops above and below the magnet.

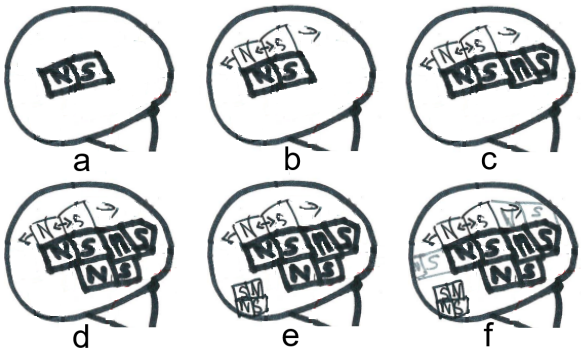


FIG. 2: The left zoom-in bubble from Oscar and Clarisa's drawing (see Figure 1), edited to show the order the particles were drawn. a) The first particle. Oscar drew this particle as a N/S dipole. b) The second particle that Clarisa drew, oriented N/S above the first. c) The third particle Oscar drew, oriented N/S to the right of the first. d) The forth particle that Oscar drew, shifted to align S/N, N/S. e) The pair of particles that Clarisa drew, oriented S/N, N/S. f) The remaining particles that Oscar drew, aligned with the first.

However, later intuitions about how magnets stick together result in the students abandoning their initial drawing and trying a model that does not produce a magnet. In this instance, the shifting of intuitions resulted in a less effective intuition taking primacy at an important moment. This prevented the students from creating a model that provided a mechanism for magnetism.

B. Running the Model

In the second vignette, we see the students reasoning with the model that they had previously generated and considering the details about how this magnet might work. They go through a multi-step process of considering different aspects of their model. First, they consider the behavior of the magnet that would be formed by the original 2 particles, deciding that it is a magnet, and that it would produce the expected behavior of magnets if it were broken. Next, they consider the behavior of the magnet that would be formed by most recent set of particles they drew, and decide that it does not form a magnet, it does not behave like expected when broken, and it does not have a north and south pole. In this vignette, intuitions are raised and lowered externally as the interviewer specifically asks the students questions about how to arrange the magnetic particles, whether they form a magnet with 2 poles, and how they would behave when broken (see Table II).

After Oscar noticed that arranging all the particles north-south and south-north, did not form a magnet, the students discussed various ways they could rearrange the particles so that they would form a magnet. At this point, Tamara interrupted their discussion to ask them to run the models they had already drawn. Initially, Tamara asked them to consider the first 2 particles they drew, and to extend that group of particles. The students likely used translational symmetry as Clarisa described where each of the poles of the particles needed to be with respect to the particles already drawn, and Oscar drew these particles (see Figure 2 f). Next, Tamara asked them about what would happen if they broke that model of a magnet in half. Oscar replied "You would still get a south side ((*touching the middle Ss*)) and a north side ((*touching the middle Ns*))," possibly triggering knowledge resources about things staying the same when scaled. After this, Tamara asked the students to repeat this with the two particles they had drawn at the end of the first vignette. Here, without prompting, Oscar immediately explained that "Yeah then if you broke it that wouldn't work" suggesting that knowledge resources about things staying the same when scaled was still at primacy. Tamara then asked where the north pole would be. Clarisa responded that it would be at both the top and the bottom, and Oscar said that the top would need to be jagged to have a north pole. These responses indicate that the students were likely using resources related to how magnets have 2 poles. Tamara then asked the students if this would be a magnet, and Oscar replied "No. They would just all be attracted to each other." As these particles were drawn in the context of how particles interact with each other, likely, this intuition was again raised in primacy when Oscar answered Tamara's question. Finally, after this reasoning process, where they figured out why their prior model doesn't work, the group generated a final (new) canonical model (see Figure 1).

In these two vignettes, we have observed a single episode of conceptual change, which involved the raising and lowering of multiple pieces of knowledge, including intuitions about translational symmetry and scaling symmetry, and intuitions about magnets having opposite poles and that opposite poles attract. Importantly, these intuitions were triggered by different contexts. Sometimes, intuitions were raised or lowered by internal context, such as when Oscar recognized that the south poles can't touch, while other times they were triggered by external contexts, such as when Tamara asked the students to think about breaking the magnet, triggering intuitions about scaling.

V. DISCUSSION

The analysis captures a single case of how two students collaborated to successfully generate the canonical model for magnetism. Through a KiP analysis of the raising and lowering of knowledge pieces, specifically of intuitions related to translational symmetry, scaling symmetry, and intuitions related to magnets having opposite poles and how these poles attract or repel, we showed how they generated an initial model, rejected that model because the particles were stuck together in a way that was different from how magnets behave, created a second model which they rejected because it did not produce a permanent magnet, and then, upon further consideration of how magnets work, eventually generated a final model. Our analysis is important as we have identified that the mechanism of raising and lowering the relevance of knowledge pieces can be used when middle school-age students are generating models of magnetism. This work contributes to the broader resource theory and Knowledge in Pieces literature in documenting that these theories can be successfully used to capture students' learning processes, across a variety of science phenomena and academic levels. Another important aspect of this research is that we were able to document the way the way the raising and lowering of the intuitive resources was triggered–whether it was done internally by the student, or with the instructor's help. The notion of external versus internally raising intuitions adds a new theoretical dimension to KiP. Further research is needed to explore this new dimension.

Importantly, this research provides contributions to building future instruction and scaffolds for magnetism (e.g., [20, 21]). Specifically, this research suggests that future magnetism instruction might benefit from including opportunities to generate models, reason with models, and run models in ways that students will be able to question and revise the model. Across this progression, it might be helpful to provide opportunities and scaffolds that allow students to raise and lower different knowledge pieces across the instruction in ways that eventually support building the canonical model. For instance, we can imagine instruction that has students generate models of magnetism and then asks the students to reason with their model: to examine if their model has poles, has a magnetic field, and works like a magnet. Importantly, this approach to instruction is built on successful learning pathways, not an assumption of deficits.

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