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Epistemic Systems: A Knowledge-Level Characterization of Epistemic Games

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Abstract: Engaging students in epistemic practices, including explanation, modeling, and sense-making more generally, has become an important focus of science education. This paper draws from two theoretical frameworks: *epistemic forms and games* and *knowledge in pieces*, to create a framework for building fine-grained models of the knowledge involved in scientist and student engagement in epistemic games. The *epistemic system* framework features two main components: one perceptual and one cognitive. The perceptual component includes the perceptual strategies the individual uses to extract raw information from the world. The cognitive component includes the knowledge the individual uses to make sense of that raw information and turn it into an epistemic artifact (e.g., an explanation or model). The paper presents two case studies to demonstrate how the epistemic system framework can be used to model student engagement in both informal and formal epistemic games.

Introduction

Engaging students in epistemic practices has become a central focus of science education (Duschl, 2008). Epistemic practices are knowledge-building practices of science. They include theory-building practices, such as modeling and explanation. They include empirical practices, such as representing, analyzing, and interpreting data. They include practices that bridge theory and data, such as argumentation. In general, these practices engage students in sense-making and support their construction of knowledge through the same practices that scientists use in their construction of formal knowledge (Schwarz et al., 2017). Engagement in epistemic practices can help students develop content understanding of scientific phenomena, as well as skills for engaging in scientific practices. Importantly, constructing knowledge through epistemic practices challenges students' beliefs about who has the authority to generate and evaluate scientific knowledge (Ford & Foreman, 2006; Manz, 2015).

A number of research programs have sought to characterize students' engagement in epistemic practices in the context of classroom activities (Lehrer & Schauble, 2000). Some of this work has characterized the nature of student participation in computational modeling (Wilensky & Reisman, 2006). Another strand of work has examined elements of students' mechanistic reasoning in the context of modeling and explanation activities (Krist et al., 2019; Russ et al., 2008). Yet other work has examined the knowledge students have about the nature of scientific products and practices, including their epistemic considerations when constructing and critiquing explanatory models (Berland et al.; 2016), their meta-modeling knowledge (Schwarz & White, 2005), and their criteria for scientific models (Pluta et al., 2011).

These characterizations provide a good foundation for understanding student engagement in epistemic practices. diSessa has articulated a need for building knowledge-level characterizations of student engagement in knowledge-construction activities (diSessa, 2014). Such characterizations would include fine-grained models of cognitive processes underlying individuals' participation in and learning through epistemic practices. Such models can help us understand the knowledge and cognitive dynamics involved in the construction of new knowledge. This, in turn, can inform the design of instruction that effectively helps students learn scientific material through participation in epistemic practices. This paper introduces a framework for modeling the knowledge leveraged by individuals engaged in epistemic practices, including informal sense-making and more formalized scientific knowledge-building processes.

Theoretical foundations

The theoretical framework introduced in this paper integrates ideas from two existing theoretical frameworks. The first, *epistemic forms and games* (Collins & Ferguson, 1993), is concerned with characterizing formal knowledge-building practices. The second, *knowledge in pieces* (KiP; diSessa, 1993), is concerned with modeling, at a fine grain size, the structure and dynamics of both naive and expert knowledge. Synthesizing the two frameworks enables the construction of fine-grained models of the structure and dynamics of knowledge involved in both informal and formal knowledge-building processes.

Epistemic forms and games

Collins and Ferguson (1993) introduced the construct "epistemic games," to characterize the knowledge-construction activities of scientists and other scholars. Example epistemic games include building stage models of development, hierarchical lists of related entities, and computational models. Each epistemic game is played to produce a particular epistemic artifact, which is a specific instantiation of a general epistemic form. For example, in the case of the "stage model of development" game, the target form is a stage model and a resulting artifact might be a stage model of cognitive development. In the case of the "hierarchical list" game, the target form is a list organized by a hierarchy of categories and a resulting artifact might be a taxonomy of mammals in the animal kingdom. In the case of the "computational modeling" game, the target form might be an agent-based computational model and the resulting artifact might be a model of predator/prey dynamics.

The epistemic form can be thought of as a template, with slots that need to be filled out to answer a question driving a particular inquiry. The form constrains the game, as it is played to fill out the template slots. Collins and Ferguson unpack the example of inquiry inspired by the question "What is the nature of X?" The answer to this question might be embodied by the form of a list of elements of the nature of X. The list is a template with slots that should be filled with distinct characteristics of X. The corresponding "list" game is played to fill out this template. The game is characterized by moves such as adding new elements to the list, subtracting ill-fitting or redundant elements, merging similar elements, splitting elements into distinct sub-elements, and possibly transferring the inquiry to a new template and engaging in a new epistemic game as a result. For example, a scientist might ask the question: "What is the nature of the Zebrafish?" They might list characteristics such as "lives in freshwater," "belongs to the minnow family," "originates in both tropical and subtropical climates." As their list grows, the scientist might decide to change their epistemic form and game slightly and organize their list's elements in categories, such as physical attributes, habitat, and behaviors.

Collins and Ferguson present a non-exhaustive list of types of epistemic forms and games. They divide games into structural, functional, and process games, and list examples for each category. For each example game, they describe the form, its corresponding constraints, and the basic moves by which the game is played. The theoretical framework presented in the present paper is designed to characterize an individual's epistemic game, connecting the activity of their game with their target epistemic form.

Knowledge in pieces

Knowledge in pieces (KiP; diSessa, 1993) is a cognitive theory of knowledge and learning. In contrast with cognitive perspectives that view the knowledge of an individual as a unitary structure consistently used across contexts (Wiser & Carey, 2014), KiP views the knowledge of an individual as a complex system of elements that are drawn into networks in response to the sense-making demands of a given context.

From a KiP perspective, the naive knowledge system consists of elements that are activated inconsistently across contexts, while the expert system has more consistent connections between elements and contexts. In the naive system, elements may be activated in contexts where they are productive as well as in contexts where they are not productive. In the expert system, elements are activated reliably in contexts where they are productive. The transition from novice to expert (i.e., learning) is viewed as a gradual tuning to expertise, through which the individual's knowledge system is reorganized and refined. Elements of prior knowledge that were unproductive in one context may be repurposed and used productively in a new context. For this reason, KiP views a learner's prior knowledge as rich with potentially productive *resources* for the construction of more formal knowledge. This sets KiP apart from "misconceptions" perspectives, which view learners' commonsense conceptions as obstacles to learning (McClosky, 1983). While "misconceptions" perspectives view students through a deficit lens, KiP views students through an anti-deficit lens (Adiredja, 2019).

A primary goal of KiP is to build theoretical machinery for modeling the structure, dynamics, and development of an individual's knowledge system. Towards this aim, a number of scholars working within the KiP paradigm have developed new ontologies of knowledge elements and knowledge structures, which bring knowledge elements together synergistically to accomplish particular goals.

Knowledge elements

KiP researchers have proposed elements belonging to a number of different knowledge ontologies. Conceptual knowledge elements have been proposed to account for individuals' intuitive sense of mechanism and their sense of satisfaction with explanations or predictions of phenomena. This category of elements includes *phenomenological primitives* (p-prims; diSessa, 1993). A well-documented p-prim called "Ohm's p-prim" captures the intuition that "greater effort leads to greater result." An individual might draw on this intuition when asked to provide an explanation for why they are able to push a couch across the room with greater speed, saying: "Because I pushed harder." *Epistemological resources* have been proposed to explain how individuals understand the nature of knowledge. This category of knowledge includes ideas about the origins of knowledge and the nature of its validity, as well as epistemic forms and their associated entry conditions and constraints (Hammer & Elby, 2002). Epistemological resources for understanding the nature of knowledge include ideas such as "knowledge must be transferred from one person to another" and "anyone can make up a new idea." In addition to conceptual and epistemological resources, a category of knowledge has been proposed, which facilitates the enactment of *epistemic game moves* (Swanson, 2023).

Knowledge structures

An important knowledge structure developed within the KiP paradigm is the *coordination class*. Coordination classes were invented to model knowledge systems used by individuals when obtaining measurable information from the world, such as force or velocity (diSessa & Sherin, 1996). Coordination classes are knowledge systems that feature two components, one perceptual and one cognitive. The perceptual component consists of the sensory machinery used by an individual to attend to objects and events and extract raw data from the world. This component has been called *readout strategies*, because it consists of the perceptual strategies the individual uses to “read out” data from the world. The cognitive component consists of the knowledge used by an individual to direct their attention to particular objects and events, and the knowledge they use to infer the desired information from the extracted data. Because it includes knowledge supporting an individual’s ability to infer information from the world, the cognitive component has been called the *inferential net*. The combination of readout strategies and inferential net used by an individual to obtain a particular kind of measurable information from a particular context is called a *concept projection* (diSessa & Wagner, 2005). An individual may have multiple concept projections for obtaining the same information from different contexts. The greater number of contexts for which the individual has productive concept projections, the greater their expertise regarding that information.

A concrete example may be helpful for illustrating the different components of a coordination class. Imagine an individual trying to determine which of two vehicles travels with greater speed around a track. The individual’s inferential net includes knowledge that directs their attention to the relative positions of the vehicles, because their knowledge contains ideas about the connection between position and speed, as well as the knowledge that the vehicles began to move at the same moment from the same initial position. Their readout strategies extract data that Vehicle A is further away from the initial position than Vehicle B. Their inferential net then draws on knowledge relating speed to change in position with respect to change in time, helping the individual infer that Vehicle A must be traveling faster. The particular readout strategies and inferential net used by the individual in this situation would be the concept projection they used to determine which vehicle moved with greater speed.

The knowledge structure introduced in this paper is similar to the coordination class in that it features both perceptual and cognitive components. While coordination classes are knowledge structures used to obtain measurable information from the world, the knowledge structure proposed below is activated when an individual engages in an epistemic game, whether it be informal sense-making or a more formalized process such as scientific theory building. I present this knowledge structure, which I call an *epistemic system*, next.

Epistemic systems

The epistemic system framework incorporates elements from both epistemic forms and games and KiP. Drawing on epistemic forms and games, it aims to characterize individuals’ informal sense-making and formal knowledge construction as engagement in epistemic games. It draws on elements of KiP to characterize both the informal and formal knowledge involved in the enactment of epistemic games at a fine grain size. It uses coordination class theory as a reference model and likewise has two components: one perceptual and one cognitive. The perceptual component is the same as in the coordination class model: it consists of the *perceptual strategies* (e.g., sense of sight and touch) which mediate an individual’s perception of particular objects and events in the world, allowing them to extract raw data about those objects and events. The cognitive component is much the same as the coordination class model, only it specifies that the knowledge the individual leverages can be further broken down into different kinds of knowledge, each of which serves a different purpose. The cognitive component as a whole is referred to as the individual’s *meta-epistemic competence*, indicating a space of knowledge that serves different functions in an individual’s epistemic game.

An individual’s meta-epistemic competence includes resources related to *epistemological* and *conceptual knowledge*, and *epistemic game moves*. As in the case of the coordination class model, knowledge in this space guides the individual’s attention to particular objects and events. In the epistemic system framework, it is the epistemological knowledge of the individual that focuses their attention and motivates their extraction of raw data. This is because their epistemological knowledge includes knowledge of both informal epistemic forms (e.g., intuitive expectations for what comprises a satisfactory explanation) and formal epistemic forms (e.g., a stage model), which motivates their inquiry and guides it towards a particular end goal. The individual’s conceptual knowledge is used as raw material for generating explanations, and as a benchmark for comparison and assessment of the reasonableness of given explanations or phenomena. Their epistemic game moves are used to fill out the epistemic form by connecting conceptual knowledge elements and evaluating and refining the knowledge network they are building. As in the case of the coordination class, an individual may draw on a different combination of perceptual and cognitive components in enacting the same basic epistemic game in different contexts. Each unique combination is referred to as an *epistemic projection*.

How system elements might work together in the case of informal epistemic games

In the case of informal epistemic games, the system elements work together to support the individual's sense-making activity. For example, imagine that one morning, an individual walks barefoot across a lawn towards a building. As they approach the building, they notice their feet becoming wet. They wonder why their feet have become wet, while just a moment before their feet were dry. Let us examine the activity of their epistemic system from this moment forward. Epistemological elements within their meta-epistemic competence make them feel there must be a plausible explanation for this phenomenon. This drives them to seek a causal explanation (an intuitive epistemic form), which directs their senses to aspects of their environment where they anticipate they might find clues. Through their sense of touch, they extract information that the grass closest to the building is quite wet and coldest in temperature. Through their sense of sight, they can see that this grass is in the shade produced by the building. The grass just beside the shaded region is in the sun, it is still damp but not as cold or wet. Just a few steps further out the grass is dry and warm. The individual enlists epistemic game moves to compare the wet and dry regions. They determine that the shaded regions are wettest and coldest, regions nearest to the shade but in the sun are damp and slightly warm, and regions far from the shade and in broad daylight are dry and warm. The individual draws on conceptual knowledge, which tells them that sunlight causes water to evaporate and that as the sun rises, the shade caused by the building shrinks and grows closer to the building. By synergistically drawing on their perceptual and cognitive components, the individual takes in the phenomenon and makes sense of it. They produce the explanation that as the sun has been rising, the shaded region of grass beside the building has been shrinking, leaving the grass driest in spots furthest from the building, wettest closest to the building where it is still covered in shade, and somewhere on a gradient between wet and dry between these two zones.

How system elements might work together in the case of formal epistemic games

A formal epistemic game can also be modeled using the epistemic system framework. In this case, the individual's *epistemological resources* would also include a formal epistemic form, which would guide the individual's knowledge construction. For example, the individual may be interested in creating a computational agent-based model to explain the dry-to-wet gradient of the grass on their morning walk to work. The agent-based model would act as a template with slots to be filled, guiding their epistemic game. Specifically, these slots would prompt the individual to name the agents in the model (e.g., photons and water droplets), to specify their initial conditions (e.g., photons leave the sun with some range of energy values, water droplets are randomly distributed across grass blades and have some range of initial energy values), and to specify their behaviors (e.g., photons leave the sun and travel in a straight line, water droplets absorb photons, gain energy, and fly away from the grass in random directions with varying probabilities). Needing these particular pieces of information might cause the individual to seek out particular data, drawing perhaps on their memory of the different entities in their morning stroll, and the warmth of the sun and the cold wet grass under their feet. They might use epistemic game moves to compare the relative temperatures and moisture levels of the grass in the sun with the grass in the shade, and their conceptual knowledge might allow them to make decisions about assigning initial energy levels to the photons and water droplets in the model, based on their temperatures. By orchestrating the perceptual and cognitive components of their epistemic system, the individual engages in a formal epistemic game of building a computational agent-based model, which simulates and validates their informal sense-making.

Methodology

Data featured in the following section were taken from a larger study, which investigated students' engagement in an 8th grade science elective course that focused on the generation, evaluation, and refinement of pattern theories (Swanson, 2019). The kinds of patterns featured in the course were patterns in behaviors or processes that led systems to change over time, including threshold and equilibration. These kinds of patterns can be found in phenomena across domains, from physical to psychosocial. For example, a pattern of threshold can be recognized in a tipping point of a tower of blocks, as well as the limit of a person's patience.

The course, called the Patterns class, was implemented and refined across four iterations. Data from the final implementation are reported in this paper. This implementation occurred in a middle school located in an economically depressed neighborhood of the U.S. West Coast. It was the primary curriculum of an 8th grade science elective course, which had traditionally been used as an enrichment period for students who had scored above average on tests of basic math and the English language. The course met for 40 minutes, 3 times a week over the entire school year, for a total of 52 hours. Twenty-one students participated in the course (11 girls, 10 boys). The majority of the students spoke English as a second language and had immigrated to the U.S. from Central America and Mexico. The author was the primary teacher of the course.

The Patterns class engaged students in a simplified version of theory building, in which students generated, evaluated, and refined pattern theories. Their theories were simply descriptions and/or explanations of the patterns they found in multiple phenomena. For example, for the pattern of threshold, one student's pattern theory read: “Adding more until you get a reaction.” The course guided students’ exploration and articulation of four patterns: threshold, equilibration, exponential growth, and oscillation. Data from the equilibration unit are presented in this paper. For each pattern, students explored two example phenomena and then wrote their first theory draft. They then evaluated their theory against a third example and wrote a second draft. They then generated examples of phenomena from their own lives that followed the pattern, evaluated their second drafts against these, and wrote third draft theories. Through cycles of generation, evaluation, and refinement, the students iteratively revised their pattern theories and their thinking.

Data were collected in the form of video footage, student work, and teacher/researcher reflections. Two video cameras captured each session. One was positioned at the front of the room and captured the students working at their tables or participating in class discussions. The other camera was positioned at the back of the room and captured presentations made at the front of the room by the students or teacher, and what was written on the white board. Student work was collected at the end of each class session and scanned or photographed and then returned to the students at the start of the next class period. The teacher wrote reflections at the end of each period, noting anything that stood out from that day in terms of student thinking, activity design, and classroom management.

Data were analyzed using knowledge analysis (KA), a suite of techniques developed for analyzing data through a knowledge-in-pieces lens (diSessa et al., 2016). Reflecting its KiP orientation, KA views data through a cognitive lens, with a goal of modeling the structure, dynamics, or development of individuals’ knowledge systems. Analyses are typically focused on characterizing these phenomena at a fine-grain size. Knowledge structures are therefore described in terms of the smaller elements of which they are composed and the systems’ dynamics and development are described in terms of smaller moves made in an individual’s reasoning or the piecemeal shifts in thinking that occur at fine time-scales. Knowledge analysis often moves in a bottom-up direction, with a goal of inventing new models to characterize what the researcher sees in the data. Below, Patterns class data are analyzed through a fine-grained lens to model the structure of the epistemic system students draw on when engaging in informal and formal epistemic games. For the informal epistemic game, video footage of a whole class discussion is analyzed. For the formal epistemic game, student work is analyzed. Pseudonyms are used in the place of student names.

Findings

I present examples of both informal and formal epistemic games enacted by students in the Patterns class. For each example, I present data and then use the epistemic system framework to characterize the epistemic projection of one student.

Informal epistemic game

The example of student engagement in an informal epistemic game is drawn from a whole-class discussion, which occurred near the beginning of the equilibration unit. The discussion followed an activity in which the students investigated a glass of cold milk warming to room temperature. The graph of the milk’s temperature over time showed that the milk warmed fast at first, and then slowed down as the milk reached room temperature. The class discussion focused the students on generating a causal explanation for the “fast-then-slow” warming phenomenon. Just prior to the discussion, the teacher had asked the students to write down their initial explanations.

The teacher seeded the discussion by reading aloud each of the students’ explanations, leaving them anonymous. She then asked them to consider one idea in particular: “Because it was getting to room temperature at the end, so it was slowing down. It’s like a race, when you’re getting to the destination you start to slow down.” The students debated the idea, pushing the student who had written it to unpack his thinking and explain why approaching room temperature would cause the milk to slow down. This student was Alvaro, though, due to the anonymity of the activity, no one knew this but he and the teacher.

> Leo: Why would you slow down when you’re about to finish a race? It doesn't make sense.
> Teacher: Does anyone want to try and make a guess why?
> Alvaro: Say there’s a wall. Are you going to run straight into it Leo?
> Leo: Well, I’m not gonna go slower though, because then I'll lose.
> Alvaro: Like no-no-no-no-no! Like, say you're winning ‘cause you’re going as fast as you can, then when you’re gonna reach the wall, don't you start to like kinda? <stomps feet on ground slowly>

Alvaro had barely defended his analogy to Leo, when Michelle challenged it on the basis of its fit with the milk scenario.

> Michelle: Is there a wall?

> Alvaro: Yes, there's a wall.
> Michelle: There is no wall.
> Alvaro: There is a wall.
> Michelle: Where?
> Teacher: Alvaro, what would the wall be in the case of the milk warming up?
> Alvaro: The room temperature.

Because the debate had interrupted his causal explanation, the teacher asked Alvaro to summarize it for the class.

> Alvaro: You're like running, like fast as you can, 'cause like just straight, and then you're like gonna run into the wall, you're not going to keep going the same speed <turns to Leo> dude, you're just going to […] You have to slow down to stop.

Alvaro's epistemic projection

Epistemological resources. Alvaro's epistemological resources frame the task at hand, orienting his attention and motivating his activity. In this segment of transcript, Alvaro hears Leo and Michelle challenge his explanation for the fast-then-slow warming. He is motivated to defend his ideas and craft a satisfactory causal explanation for his classmates. This intuitive epistemic form drives Alvaro to understand the problems his classmates have with his original explanation and to modify it accordingly.

Perceptual strategies. Alvaro's goal of crafting a satisfactory causal explanation orients his attention to both his original explanation and the phenomenon he is trying to explain. He may be attending to the explanation that is written on the board, or he may be attending to his memory of it, which may include details that he has not publicly articulated. As for the phenomenon he is trying to explain, he may be focused on the graph or data table representing the temperature over time, both of which are drawn on the board. It is also possible his attention is focused on a memory of his participation in an activity in which he walked out the temperature of the milk as it warmed to room temperature (see Swanson & Trninic, 2021, for the details of this activity). From the objects of his attention, Alvaro's perceptual strategies enable his extraction of the information his explanation must account for: the milk is warming quickly at the start and then slows down as it approaches room temperature.

Epistemic game moves. Alvaro employs a number of epistemic game moves in his attempt to make his explanation sensible to his classmates. His initial hypothesis had explained the slowing of the milk's warming in terms of a race analogy. Leo challenged his analogy on the basis of its logic, questioning why a runner would slow down at the end of a race. Alvaro recognized the problem with his logic and modified the analogy so that it was logical, by making the race end at a wall. Alvaro's moves suggest that he had knowledge facilitating their enactment, specifically knowledge enabling his evaluation of the logic behind his original explanation and recognition of its shortcoming, and knowledge enabling his evaluation of his proposed modification to the analogy. When Michelle challenged the analogy by pointing out a missing mapping (asking Alvaro what the wall was in the case of the milk), Alvaro clarified the mapping, stating that the wall in the case of the milk was room temperature. Again, Alvaro's moves suggest underlying knowledge, specifically knowledge facilitating his evaluation of the mappings between the race analogy and milk scenario and his identification and evaluation of the mapping implicit in his explanation.

Conceptual resources. Alvaro draws on several conceptual resources in attempting to make his explanation sensible to his classmates. These likely include knowledge of what it is like to run a race both in the open (where you wouldn't need to slow down to stop) and what it is like to run a race to a wall (where you would hurt yourself if you didn't slow down to stop), and an intuition which may be a p-prim: "you have to slow down to stop [without the outside force of a wall]." This logic is at the heart of his explanation for why the milk is warming more slowly as it approaches room temperature and it is the key behavior illustrated by the race analogy. He draws on these conceptual resources in constructing his original explanation, and in modifying and more clearly articulating his explanation in response to his classmates' criticisms.

The analysis of this example shows how the perceptual and cognitive elements of Alvaro's epistemic projection worked together to help him clarify the sensibility of his explanation for why the milk warms fast-then-slow.

Formal epistemic game

The example of a formal epistemic game is drawn from students' second draft pattern theories, which were written towards the middle of the equilibration unit. Their construction of pattern theories is considered a formal epistemic game, as they were aiming to produce artifacts that followed a formal epistemic form. Second drafts were written following their exploration of the examples: cold milk warming, hot tea cooling, and particle diffusion. For his second draft theory, Emre wrote:

Fast then slow, fastest, faster, fast, slow, slower, slows, stop, slows down b/c reaching equilibrium goes fast in the beginning because it has more room to cover.

Emre's epistemic projection

Epistemological resources. Emre's epistemological resources frame his task, orienting his attention and motivating his activity. In this case, his epistemological resources include a formal epistemic form given to him by his teacher: the form of a pattern theory. This form is a template for a description of a behavior common to the behavior he had explored thus far (including the cold milk warming, hot tea cooling, and particle diffusion).

Perceptual strategies. The pattern theory form motivates Emre's engagement in an epistemic game of pattern-theory building. This goal orients his attention to the three phenomena he has observed. In particular, it directs his attention to the behavior demonstrated by each phenomenon, as opposed to their surface features.

Epistemic game moves. Emre employs epistemic game moves in his attempt to find a behavior that is common to the three examples. These moves likely involve knowledge facilitating his comparison of the three example phenomena, and his identification of similarities in their behavior.

Conceptual resources. Emre draws on several conceptual resources in articulating his pattern theory. The idea that the milk "slows down b/c reaching equilibrium" might be indicative of a conceptual resource like the one Alvaro shared during the cold milk discussion that one has to slow down to stop. "Goes fast in the beginning because it has more room to cover" might be representative of another intuition, or a collection of intuitions, that indicate the further one is from one's destination causes one to move more quickly (see Swanson & Collins, 2018, for a discussion of the conceptual elements drawn together in this reasoning).

The analysis of this example shows how the perceptual and cognitive elements of Emre's epistemic projection worked together to help him write his second draft pattern theory. A notable difference between Emre's epistemic projection and Alvaro's is the nature of the epistemic forms employed by the students (the former responding to a formal epistemic form and the latter responding to an informal epistemic form).

Discussion

The paper presented a theoretical framework for characterizing student engagement in epistemic games. The framework synthesized ideas from two existing theoretical frameworks: epistemic forms and games and knowledge in pieces. Like epistemic forms and games, the framework is meant to characterize an individual's knowledge-construction process. Like KiP, the framework is meant to characterize the structure and dynamics of the individual's informal and formal knowledge at a fine grain size. The resulting framework, called epistemic systems, features two basic components: one perceptual and one cognitive. The perceptual component consists of the perceptual strategies the individual draws on to extract raw data from the world. The cognitive component consists of the individual's meta-epistemic competence, which includes resources related to *epistemological* and *conceptual knowledge*, and *epistemic game moves*. These resources orient and motivate the individual's attention to their task, and facilitate their enactment of the epistemic game. The epistemic system framework is introduced and used to produce fine-grained models of instances of both informal and formal epistemic games.

The paper makes a theoretical contribution to literature concerned with characterizing the nature of scientist and student engagement in epistemic practices. As well, it extends the theoretical machinery of knowledge in pieces, producing a framework that researchers can use for modeling individuals' engagement in epistemic games ranging from formal modeling to informal explanation and sense-making. The epistemic system framework is still in its infancy. Future directions include further investigation of both scientist and student engagement in epistemic games, with the aim of refining the framework. Of specific interest is investigation of the dynamic interplay between the different kinds of knowledge elements belonging to meta-epistemic competence, to understand more clearly how the different kinds of knowledge elements interact in an individual's knowledge-construction processes. Finally, it is well known that many epistemic games are not played by individuals in a vacuum, but rather, are distributed among individuals and materials (Dunbar, 1997). Therefore, understanding how epistemic systems can be used to model distributed epistemic games would be beneficial.

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