

Haptic Experiences Shape Student-Generated Gestures While Learning with Computational Environments

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Abstract: In science education, gestures have emerged as a valuable tool for both students to represent their reasoning and educators to assess learners' developing knowledge. One reason is that gestures afford representing dynamic causal reasoning, a fundamental aspect of understanding various natural phenomena. However, gestures inherently lack feedback mechanisms and are possibly epiphenomenal to learning. We address these limitations by pairing haptic physical models with a computational NetLogo simulation designed to support students in comprehending dynamic interactions within complex systems. In this study, we investigated the impact of haptic learning experiences and computational environments on student-generated gestures. Our findings revealed that haptic learning experiences augment the computational environments by providing students with sensory feedback. This, in turn, leads to a shift in students' gestures, as they transition from representing aggregate patterns, such as quantity and motion, to individual interactions between physical entities and forces.

Introduction

Many natural phenomena involve multiple interacting forces that produce dynamic equilibrium. Computational simulations often use visual representations to depict the sub-microscopic motions and interactions between entities that produce dynamic equilibrium. Nevertheless, sub-microscopic forces often appear unnoticed by students when they depict molecular phenomena in drawing (Cooper et.al., 2017). In response to this problem, we sought to assess student-generated gestures after learning with a computational simulation. Despite the sub-microscopic view that computational simulations grant, the present investigation seeks to determine the role that haptic training plays in learning from simulations. We reasoned that both simulations and gestures fail to afford students a feeling for intermolecular forces—we therefore designed an intervention that guided students' perception of these forces by using concrete haptic technologies that produce *magnetic* forces.

Gesture affords representing dynamic causal reasoning

Scientists have long relied on external representations to comprehend and convey scientific ideas (Crick & Watson, 1954). In the realm of science education, educators often investigate how students utilize external representations to understand complex scientific concepts. Diverse modes, such as physical or virtual representations, emphasize distinct aspects of phenomena, thus making some ideas more conceptually salient than others (Rau, 2020). However, many scientific phenomena and concepts involve spatiotemporal information and require students to comprehend a sequence of dynamic causal relationships. Consequently, there is a need for a mode of representation that enables students to effectively depict, reason about, and communicate these complex dynamic interactions.

A substantial body of evidence supports the notion that gestures afford the representation of dynamic causal reasoning (e.g., Alibali et.al., 2014). For example, representational gestures serve as manifestations of crucial spatiodynamic characteristics that may not be effectively conveyed through other modalities (Scherr, 2008). Professional chemists use representational gestures in laboratory settings to aid in theory development (Becvar et al., 2005). In science education, educators employ gestures as a valuable tool to facilitate student learning. For instance, Mathays et al. (2019) have suggested that representational gestures function as epistemic tools for middle school students, aiding in the development of mechanistic explanatory models. Moreover, gestures offer valuable insights into the mechanics of knowledge transfer, serving as a natural mode of communication that often necessitates minimal instruction. Consequently, gestures have exhibited their effectiveness as assessment tools, enabling the evaluation of students' developing representational competence, as illustrated by Lira & Stieff (2018).

Computational environments support students' learning about complex systems

Although gestures prove to be a valuable tool for learning and assessment, it is worth noting that they often appear to be epiphenomenal (Stieff et al., 2014). In other words, students frequently employ gestures in conjunction with other forms of external representation that are often assumed to be the primary driver of their conceptual understanding. Moreover, gestures alone do not provide the tactile or interactive feedback one experiences when interacting with physical objects or digital interfaces (Bivall et al., 2011).

One solution involves designs that present multiple representations (Kozma & Russell, 2005). This approach aligns with the conceptual salience argument (Rau, 2020), which posits that when students struggle to discern a particular entity or property within a system, the learning environment should make that content manifest regardless of the representation format (e.g., visual, tactile, and so forth) used. The key is to identify the mode that effectively highlights for students the neglected concept within the complex system.

Computational environments like NetLogo (Wilensky, 1999) provide design solutions that address students' tendency to overlook critical entities, properties, or influences. These environments allow students to monitor how individual entities within the system move and reorganize as the system evolves. As a central principle, this approach encourages students to focus on the individual level rather than solely on the aggregate level (Sengupta & Wilensky, 2009). It prompts students to explore the interactions between individual entities.

Haptic experiences shape student-generated gestures

Despite the visual affordances that computational simulations provide to students, their emphasis on visualization, though pedagogically important, often falls short in conveying to students a feeling of causal forces between entities within the system. Numerous studies have highlighted the challenge of reasoning about intermolecular forces in chemistry and related domains (Cooper et al., 2017; McLure et al., 2021).

We introduce a version of an emerging approach that addresses this challenge: student-generated gestures paired with haptic feedback coupled to a computational environment. This design creates a hybrid learning space where learners can gesture while receiving guided feedback, transforming their gestures into meaningful sensory experiences (Lindgren, 2015). Haptic technologies have been effectively used in various work, learning, and training scenarios (Escobar-Castillejos et al., 2016). For instance, Bivall et al. (2011) demonstrated that adding a haptic interface—providing somatosensory information about virtual objects through force and tactile feedback in a 3D model—enhanced students' comprehension of complex molecular interactions.

Although haptic experiences have proven valuable for science learning, they are typically not designed to support representational gesturing and conceptual development. Haptics, however, hold the potential to guide a person's movements in representing sub-microscopic entities and processes that surpass human sensory capabilities (Bivall et al., 2011). Therefore, in this study, our aim was to determine how augmenting computational simulations with physical haptic models delivers to students new representational forms and concepts. More specifically, we sought to understand how these haptic experiences influence the gestures students generate as they engage with the computational environment.

Investigation context and research questions

We introduce a complex system situated at the intersection of life and physical sciences: the Resting Membrane Potential (RMP). The term "resting" denotes a state of dynamic equilibrium, where two opposing processes occur at equal rates but in opposite directions. The membrane potential represents an electrical driving force, quantified as voltage, which prevents ions from diffusing until they reach equal concentrations. This concept holds broad significance across various STEM fields, serving as the physicochemical foundation for homeostasis, motoric action, cell-to-cell signaling, and consciousness.

The challenge for students lies in recognizing two processes operating at both the individual and aggregate levels within the system. One is a physical force, while the other is a probabilistic process influencing ion movement. The probabilistic process is simple diffusion—ions display random movement, tending to occupy fluid compartments with higher occupancy. However, the cell membrane is selectively permeable, allowing ions to pass with their charge. This charge separation generates an electrical driving force, permitting fewer than 1% of ions to diffuse (Bialek & Botstein, 2004). To predict or explain the RMP, students must reason about the two interacting influences. The RMP requires students to recognize that individual ions possess two distinct physical properties, each exerting an influence on the motion of the ion.

Although computational visualizations effectively convey the random process and the individual entities involved, it falls short in representing the physical force between entities that simultaneously affect their motion. Therefore, we aimed to augment the computational visualization by introducing haptic models that simulate the

electrical attractive force. The combination of visual and haptic feedback provides students with a more immersive and salient learning experience. Thus, in this investigation, we ask:

1. What representational gestures do students produce while learning about RMP in computational environments?
2. How do haptic learning experiences re-shape student-generated gestures within the context of a computational learning environment modeling RMP?

Method

Participant population and recruitment

We recruited 50 undergraduate students ($n=50$), comprising 5 male and 45 female individuals, who were majoring in Biology and Psychology at a R1 Midwestern university. Recruitment was conducted via a University mass email. To gather demographic information from participants, we administered questionnaires, which included inquiries about their academic year, major, and the number of courses they had completed related to the Resting Membrane Potential (RMP) and associated content. All participants had previously completed at least one physiology course that covered the concept of electrical potentials in biological cells.

Research design, procedure, and rationale

This research is part of a larger study. We implemented three distinct instructional conditions and randomly assigned participants to one of these conditions. All participants were subsequently presented with the same computational simulation, with the objective of examining how different modes of instruction promote subsequent learning with the computational simulation.

Upon obtaining informed consent, participants were subjected to a pretest featuring specific tasks including drawing and writing. Subsequently, students were randomly assigned to one of three conditions:

1: *Equation Instructional Condition (Control Group, $N=15$)*: In this condition, we instructed students using equations, a symbolic representation that conveys aggregate quantities. This condition approximates the common instruction in students' physiology courses.

2: *Aggregate Haptic Instructional Condition ($N=15$)*: This condition introduced students to magnetic models, which simulate the phenomenon and provide haptic feedback on the attractive force experienced. The magnetic models used are sourced from 3D molecular design Water Kit (<https://3dmoleculardesigns.com/>). This instructional condition provides students with iconic representations of the phenomenon at an aggregate level, as it did not explicitly direct their attention to the attractive forces between individual magnetic models.

3: *Individual Haptic Instructional Condition ($N=20$)*: In this condition, students were directed to interact specifically with two magnetic models representing positive and negative ions, focusing on the force of attraction between them. This condition provides students with iconic representation of the phenomenon at the individual level. Each condition lasted an approximate duration of 10 minutes.

Following these instructions, all participants were guided through an interpretation of a computational environment constructed in NetLogo. They were instructed to predict, explain, and reflect upon three phases in the evolution of the Resting Membrane Potential (RMP). Our aim was to help them differentiate between aggregate motion and individual interaction. This phase of the study also took approximately 10 minutes. Subsequently, participants completed a posttest that included the same drawing task and additional written and calculation items. The whole posttest lasted about 25 minutes. Participants received compensation of 20 USD for their participation and were subsequently dismissed.

Qualitative analysis of students' gesture production

One of us (XT) conducted a qualitative analysis of students' spontaneous representational gestures throughout the three distinct learning phases in the experimental protocol. The first phase was determined by the instructional condition to which students were assigned, involving either the equation, aggregate haptic, or individual haptic learning phase (*initial instruction phase*). The second phase involved students experiencing the NetLogo simulation, during which they were tasked with making predictions based on the simulation's visualization (*NetLogo prediction*). The last phase also involves the NetLogo simulation. In this phase, students received feedback on their predictions, and they were subsequently prompted to articulate their understanding of the phenomenon simulated by NetLogo (*NetLogo explanation*).

The emergent categories for students' representational gestures were derived through an inductive approach and included *entity*, *aggregate state*, *motion*, and *interaction*. Categorization of students' gestures was based on a combination of gesture characteristics, including their shape, position, and movement, in conjunction

with the accompanying speech content (see Lira & Stieff, 2018). For instance, if a student raised their left hand with the palm facing themselves and fingers pointing to the right, moving horizontally to the right side while stating, “the potassium ions will *leave* the cell,” this gesture would be coded as “motion.” This categorization arises from the congruence between the students' gesture and speech, which jointly illustrate diffusion, a specific form of motion. Fifteen percent of total gestures were independently recoded by a second coder. Gesture coding inter-rater reliability, assessed with Krippendorff's alpha, yielded a substantial agreement level ($\alpha = 0.804$). A breakdown of each category's definitions and illustrative examples can be referenced in Table 1.

Table 1
Definitions and Examples of Gesture Categories

	Individual Entity	Aggregate State	Motion	Interaction
Definition	The gesture & speech represent the individual entities	The gesture & speech represent the position/quantity/structure of entities	The gesture & speech represent a process that involves motion	The gesture & speech represent the force between entities
Example	 Chloride Ion	 Equal Quantity	 Diffusion	 Attraction

Individual Entity

Entities are the fundamental components in the system essential for the scientific phenomenon. In our problem space, the key entities are the potassium and chloride ions. Students frequently employ a closed fist or comparable hand shapes that resemble circles to represent these ions.

Aggregate State

The category "Aggregate State" comprises a range of gestures intended to represent the system's aggregate level. A common gesture within this category involves students depicting the quantity of ions within a given space. For instance, students often use both hands with palms facing down on the desk to visually illustrate that the potassium ions will be evenly distributed between the intracellular and extracellular fluid of a cell.

Motion

Students utilize hand movements, involving either one or both hands, to signify motion. Diffusion reflects the most prevalent form of motion. Students employ sweeping or fluctuating hand movements to illustrate the process of ions diffusing from the intracellular fluid of a cell to the extracellular fluid, or vice versa.

Interaction

In this study, gestures that represent interaction are the primary phenomenon of interest. Students employ various gestures to depict the interactions between ions. The most prevalent interaction gesture involves students facing their palms toward themselves, with the fingers of each hand pointing towards one another and interlocking (similar to those reported by Scherr, 2008). Students convey interaction by bringing two fists together to show the attractive force between potassium and chloride ions.

These four gesture categories were tallied based upon their frequencies. Note, however, that the *quantity* of gestures produced by a student does not necessarily correlate with their developing conceptual understanding or performance. A student who generates ten gestures is not inherently "better" than a student who gestures once (Goldin-Meadow & Alibali, 2002). Nevertheless, we counted the frequency of gestures produced by each student to gain insight into the relative proportions of each gesture type to understand the entire data corpus.

Results

Students shifted from gesturing to represent aggregate states of the phenomenon to gesturing to represent individual entities interacting after learning with the computational simulation

Following a systematic analysis of students' representational gestures, we observed a transition from the gestural representation of aggregate-level phenomena, such as *motion* and *aggregate state*, to a focus on individual-level

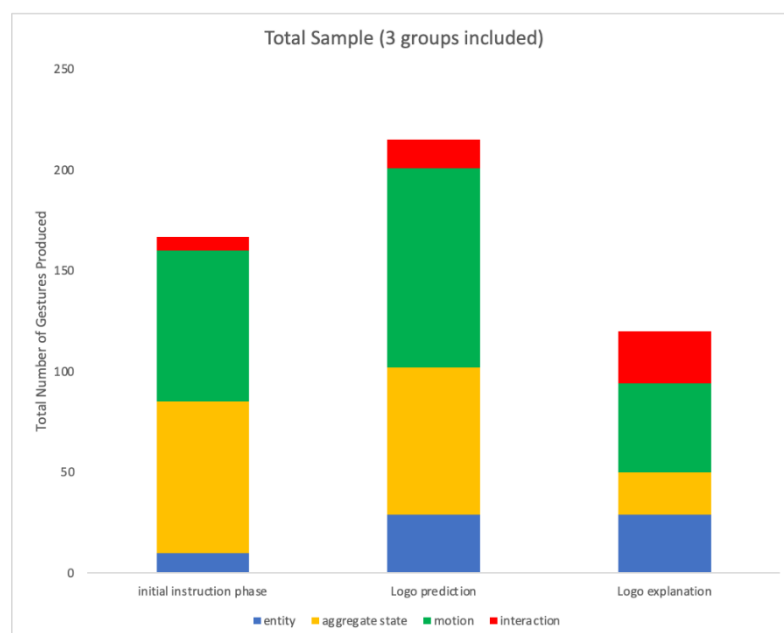
interactions, which involves *entities* and *interactions*. Figure 1 presents the frequency of each type of gesture produced by all students, irrespective of initial instructional conditions, at each protocol phase.

In the first two phases (initial instruction phase and Logo prediction), many gestures depicted motion and aggregate state. However, in the final phase (Logo explanation), there was a substantial reduction in *aggregate state* gestures, accompanied by a proportional decrease in *motion* gestures. Meanwhile, *entity* gestures increased from the initial instruction phase to the NetLogo prediction phase and remained consistent during the Logo explanation phase. Notably, gestures representing *interactions* between entities displayed a consistent upward trend throughout all three learning phases.

This pattern suggests that regardless of students' initial instructional condition, computational environments encourage students to shift from representing aggregate patterns to representing the underlying individual interactions that drive the emergence of said aggregate patterns. Students transitioned from gesturing about the visually salient facets of the phenomenon, such as quantity and movement, to gesturing to represent less salient mechanistic causes, i.e., intermolecular forces.

Figure 1

The Frequency of Each type of Gesture Produced by all Students Trrespective of their Instructional Conditions at Each Phase During the Protocol.



Despite visualizing individual entities in the complex system, we knew that the computational environment fails to represent the interactions between these entities. Therefore, we next turn our attention to the different instructional conditions prior to the computational experience so that we might determine the source for how students transitioned to representing molecular interactions.

Haptic learning experiences enable students to construct embodied representations of the interaction between individual entities

Figure 2 illustrates the number of students in each instructional group who produced “interaction” gestures during each learning phase. Across all three groups, there is an increase in the number of students producing “interaction” gestures during the NetLogo explanation phase as compared to the initial learning phases. This pattern suggests that the learning experiences we provided encourage students to reflect upon their latter learning with computational simulation. This reflective experience prompted students to search for causal interactions as we have reported previously (Lira, 2020).

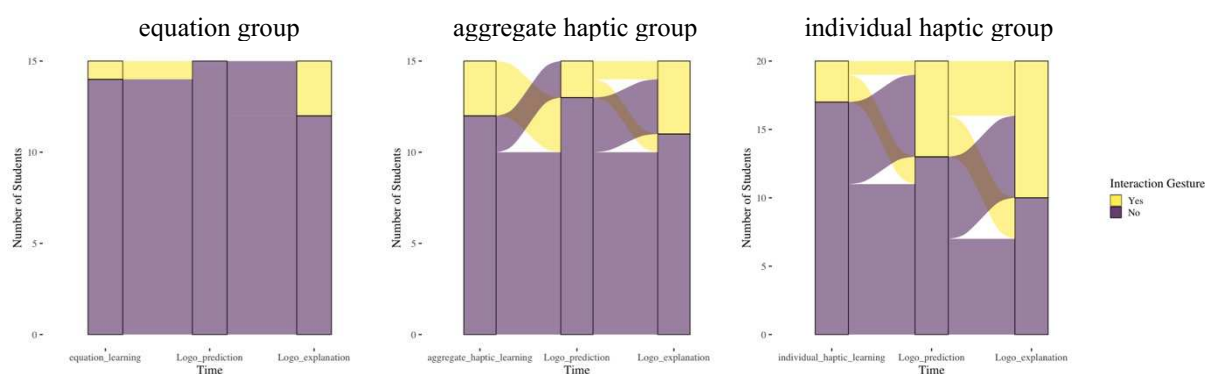
However, the prevalence of students using gestures to represent interaction differs across conditions. Within the equation condition, a minority of students gestured to depict causal interactions. In contrast, the

aggregate haptic group exhibited a larger proportion of students who displayed interaction gestures. Within the individual haptic group, this proportion elevates to half the group.

This trend suggests that even though computational environments invite students to cue knowledge of molecular interactions, haptic learning experiences augment these environments by prompting more students to consider these invisible forces as causal factors. Students' consideration manifests in their gestures and talk. Thus, the learning experiences that incorporated both the computational simulation and tangible haptic models provided an opportunity for students to recognize invisible causal interactions that they otherwise fail to consider.

Figure 2

The Number of Students Who Produced Gestures that Represent Interactions at Each Learning Phase Analytically Decomposed by Instructional Group

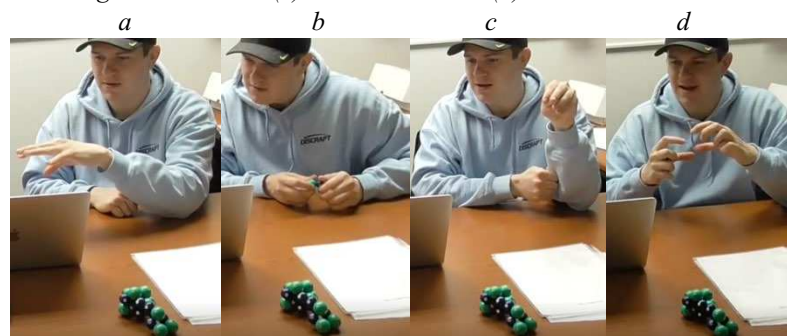


Greg's shift in reasoning and gesture production after his haptic learning experience

Next, an illustrative episode shows how haptic and computational learning experiences cued student's prior knowledge and prompted him to embody the interactions between ions and represent it through gestures. Greg, who was instructed with the individual haptic model, did not initially produce interaction gestures during first haptic instruction phase. But he began gesturing about the interaction in both the Logo prediction and Logo explanation phases. While observing the simulation, Greg was asked about what "potential" means. Greg replied, "There is going to be a lot more potassium leaving the cell because there are more potassium molecules in the intracellular fluid." Simultaneously, he made a motion gesture with his left hand, moving it from left to right (Figure 3a). Subsequently, he added, "The potassium will still move back into the intracellular fluid. Just because of the channel being open." As he said this, his right hand moved from right to left. Here, Greg's description underspecifies the mechanism that underpins the phenomenon, i.e. the interaction between ions. Instead, he only described the phenomenon based upon his direct visual observation. However, note that during his explanation, Greg held the magnetic model of potassium in his left hand and chloride in his right, casually bringing the magnets together (Figure 3b).

Figure 3

After the Haptic Learning Experience, Greg Shifted from Gesturing about Motion (a) to Gesturing about Entities (c) and Interactions (d).



Later, when asked to predict ion movement and elaborate on his previous prediction, Greg shifted to reasoning about molecular interactions that describe ionic motion and the underlying causal mechanisms that produce it. He explained, "Inside the cell would become more negative because more potassium would move out. There'd be more chlorides in the intracellular, making it more negative. To maintain charge balance, we'd need more positive ions to move back into the cell." While predicting, Greg raises up his right fist as a potassium ion, and left fist as chloride ion, bringing his left fist close to his right fist to represent the attraction force (Figure 3c). Here, Greg embodied the ions with his fists and gestured to depict the interaction between the entities. Finally, towards the end of the Logo explanation phase, Greg explained the halt in potassium diffusion, stating, "...the ions want to stay together." He illustrated the attraction force by extending his thumb and index fingers, symbolizing two ions sticking together, *but now without the magnetic models* in either of his hands (Figure 3d).

Greg's transition in reasoning and gesture production suggests that the haptic sensation of attraction led him to identify the key properties of ions (charges) and reconstruct explanations based on these individual entity properties. As Greg first casually interacted with the magnets and experienced the attraction, it is likely that his preexisting knowledge of the RMP coordinated with the haptic forces his hands experienced, thus enabling him to identify dynamic equilibrium's underlying causes. This characterization is plausible because *after* interacting with the haptic model, Greg spontaneously used representational gestures to illustrate the interaction between entities but now *without the models held in his hands*.

Discussion

In this empirical study, we introduced haptic models and incorporated subsequent computational learning experience to support students' learning of RMP. We consider gestures as a medium for students to both convey their conceptual understanding and for us to assess their developing knowledge. Specifically, we analyzed students' spontaneous gestures to assess how haptic intervention prepares students' learning within the subsequent computational environment. We found that (1) computational environments induced a shift in students' gestures, transitioning from representing aggregate states and motion to representing individual entities and interactions. And (2) Students displayed a higher propensity to produce interaction-representing gestures after learning with the haptic model, particularly when their attention was explicitly directed towards the interactions between two haptic models.

These findings illustrate a potential pathway for designing multi-modal instructional tools that support students' dynamic causal reasoning in science domains. At initial phases of the protocol, students produced a great proportion of representational gestures to depict motion and aggregate states. This pattern is consistent with prior literature where some of students demonstrated "slippage between levels" (Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999), meaning that learners tend to cue knowledge due to salient macro-level phenomena in the world or in representations of it. Here, the motion of entities and their aggregate patterns such as quantities are salient dimensions of the phenomenon—especially when it is represented visually. Students tended to draw from their repertoire of intuitive knowledge and represent the macro-level phenomenon that they observed from the external visualization. Thus, despite the "glass box" approach of computational simulations, the motion and aggregate patterns of entities tend to be more salient than the individual entities themselves. For example, Greg's initial explanation and gestures primarily focused on visual cues from the screen—such as the concentration gradient and ions' movements. Despite his prior haptic learning experience, his initial reasoning did not incorporate the haptic feedback into his explanation. This result doesn't necessarily imply a lack of salience or significance in haptic experiences. Rather, it suggests that as learners interact with the computational environment, the visual simulation tends to take precedence over their prior engagement with the haptic model. This claim is supported by Greg's transition in both his verbal reasoning and gesture production. As he engaged with the haptic model and observed the simulation concurrently, he shifted to reasoning about interactions between individual entities, supplementing his speech with representational gestures that re-represented the invisible interacting forces between physical entities.

Greg's case illustrates the potential learning mechanisms that underly the pattern among students who had haptic learning experiences as their initial instruction. In comparison to students instructed with equations, those who used the haptic model were more inclined to use representational gestures to convey ion interactions while learning with the computational environment. It appears that haptic feedback cued learner's underlying knowledge of RMP, prompting them to use their prior knowledge to interpret the computational simulation and construct dynamic representations of aspects of the phenomenon that were not visually represented. Hence, our

current direction is on the development of haptic gloves equipped with force feedback linked directly to the computational environment. This approach aims to offer students an immersive learning experience by combining visual and haptic feedback in real-time. We see this route as a fruitful path towards shifting more students toward a meaningful understanding of the physical interactions that produce emergent properties in complex systems.

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