Determining how context matters in an algebra-based physics class

Tyler Garcia and Mila Kryjevskaia
Physics, North Dakota State University, 1340 Administration, Fargo, North Dakota, 58105

The Dual-Process Theory of Reasoning (DPToR) is one of the theoretical frameworks used to examine students' reasoning in physics. So far, this framework has mainly been employed to analyze student reasoning in introductory calculus-based physics courses. In this study, we apply the framework and its corresponding methodology to explore student reasoning in algebra-based courses primarily taken by students majoring in life sciences. Additionally, we redesigned a set of traditional physics tasks to incorporate more familiar and relevant contexts for life science majors. Both the original and modified versions require the application of the same physics knowledge and skills but differ in context. The aim was to investigate how, if at all, these contextual modifications affect reasoning. The results largely replicate those documented in calculus-based physics courses, showing no observable effects of contextual changes on reasoning patterns. This finding highlights the robustness of the reasoning mechanisms described by DPToR.

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I. INTRODUCTION

The Dual-Process Theory of Reasoning (DPToR), developed in cognitive psychology, provides a framework for examining domain-general reasoning processes [1, 2]. In recent years, physics education researchers have successfully applied DPToR to investigate student reasoning in physics, particularly within calculus-based introductory courses for engineering and physical science majors [3–8]. In this study, we build on and extend this approach to explore student reasoning in algebra-based physics courses, which are primarily taken by life science majors.

Universities across the country offer courses designed to teach physics to biology majors and premedical students, often referred to as "Intro Physics for Life Science Students (IPLS)" [9, 10]. These students usually take physics to fulfill premedical requirements, such as those established by the Medical College Admission Test (MCAT), which emphasize physics competencies aligned with reasoning and application rather than rote memorization [11, 12]. A report by the Association of American Medical Colleges and the Howard Hughes Medical Institute also outlines the competencies required by medical workers, including the topics and mathematical skills taught in a physics class [13]. However, IPLS courses often face challenges related to both relevance and engagement. In fact, there is a persistent perception that physics is disconnected from biology and medicine [9, 10]. This disconnect is further aggravated by curricular structures and advising practices that postpone students' exposure to physics until after key biology coursework [9].

To address these challenges, some researchers and instructors have advocated for reforming physics courses for life science majors to align the content more closely with life science applications [9, 14]. Such efforts, supported by initiatives like the Living Physics Portal [15], indicate that life science students perform better and have more positive attitudes when physics is taught using biologically relevant contexts.

Building on this work and research on reasoning through the lens of the Dual-Process Theory of Reasoning, this study investigates whether problems designed in contexts more relevant to life science majors alter students' reasoning approaches and enhance their performance. We adapted a set of research-based and research-validated physics questions by redesigning them in contexts relevant to life sciences while maintaining the underlying physics concepts and the reasoning necessary to answer the questions correctly. Students in a large-enrollment IPLS course were randomly assigned to receive either the original (traditional physics context) or modified (life science context) version of each question. This methodology enabled us to examine the student reasoning in IPLS courses through the lens of DPToR and to investigate the impact of a more relevant context on student reasoning.

In the following sections, we outline the DPToR framework and its relevance for analyzing student thinking in IPLS settings. We then describe the study design and the analysis of student responses. Finally, we examine the results of contextual framing on students' reasoning and discuss implications for instruction in life science-oriented physics courses.

II. THEORETICAL FRAMEWORK AND MOTIVATION

The Dual-Process Theory models reasoning as the interaction between two cognitive processes. Process 1 is fast, automatic, and operates with little conscious control. In contrast, Process 2 is slow, deliberate, and governed by rules and logic [1, 2, 16, 17]. When students are presented with a physics task, Process 1 rapidly generates a mental model based on contextual cues and prior experiences [16, 17]. This initial response is often referred to as intuition. We agree with Simon's concise definition of intuition as pattern recognition, which draws not only from everyday experiences but also on formal knowledge acquired through instruction [18, 19]. This perspective helps explain why expert intuition tends to be more accurate than that of novices. Experts have a broad base of experience and well-organized, practiced knowledge. They often recognize a given situation accurately and apply the correct knowledge automatically and effectively [20].

Novices, on the other hand, are still developing accurate pattern recognition. Their quick, intuitive mental models are prone to error, which can immediately set them on an unproductive reasoning path. A key characteristic of Process 1 is that it is always active and cannot be turned off. We perceive the world around us through the lens of Process 1.

The role of Process 2 is to monitor, evaluate, and override the initial output of Process 1 when necessary. However, successful engagement of Process 2 is not guaranteed, and its effectiveness depends on several factors. If a reasoner is highly confident in their intuitive response, they may bypass Process 2 altogether, accepting the initial response as final without further consideration [21]. Even when Process 2 is engaged, its effectiveness may be limited by cognitive biases. For example, if we are confident in our intuitive response, we tend to seek evidence that supports our initial beliefs rather than questioning them (i.e., confirmation bias) [22]. Moreover, if we lack strong or coherent formal knowledge, we may be unable to recognize errors, generate better alternatives, or make an informed choice between competing lines of reasoning [23]. In such cases, reasoners often abandon effortful reasoning and default to the more compelling, but potentially incorrect, intuitive responses [24].

Consider, for example, a task presented in Figure 1 in which a magnet weighing 1 N is attached to a side of a refrigerator. The magnet remains at rest while a hand applies a 0.5 N force from below. The students are asked to determine the direction of the frictional force (fr) exerted by the refrigerator on the magnet. Prior research has consistently documented low success rates on this task among students in introductory calculus-based physics courses at multiple institutions [17, 25]. Even after instruction on forces and Newton's laws, only 20% to 40% of students correctly recognize that the frictional force must point upward. Since the mag-

net remains at rest ($F_{net} = 0$), the upward frictional force must combine with the upward applied force by the hand to balance the downward weight.

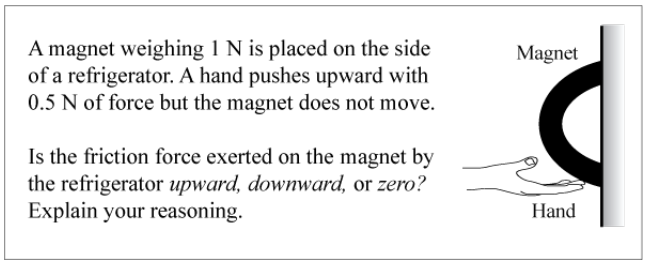

FIG. 1. *Magnet on a refrigerator* task

Most students instead argue that the frictional force must oppose the applied force by the hand, concluding that it points downward. Notably, this incorrect reasoning is often produced by students who otherwise demonstrate proficiency in applying Newton's 2nd law to similar problems involving objects at rest or moving with constant velocity [25]. This suggests, through the lens of DPToR, that such errors do not necessarily stem from a lack of knowledge but instead illustrate the strong grip of intuitively appealing yet inappropriate mental models. On this specific task, experts are likely to recognize the applicability of Newton's 2nd law immediately. Novices may instead recognize this task as "being about friction," which cues a familiar and intuitively appealing mental model in which friction opposes the applied force. This mental model, although relevant to many other tasks, is unproductive and misleading in this scenario.

The intuitive appeal of this model can inhibit engagement of the more effortful, analytical Process 2. Students may accept their initial judgment without checking for consistency with Newton's 2nd law, exploring alternatives, or questioning why the weight of the magnet appears unaccounted for. Even when students experience doubt, the abstract and seemingly irrelevant context of a magnet stuck to a refrigerator may hinder their motivation to engage in deeper reasoning. Students may dismiss their uncertainty and accept the intuitive response as correct, attributing any confusion to the belief that "physics rarely makes sense" [24].

These findings, along with existing research on student reasoning in IPLS courses and the impact of context on reasoning, prompted us to pose the following research question: Would redesigning traditional physics tasks to include contexts more relevant to life science majors alter underlying reasoning mechanisms and improve students performance?

From the perspective of DPToR, it could be argued that presenting a task in a more familiar and relevant context may improve reasoning through the following mechanisms. First, the familiarity of the context may enhance the accuracy of the mental model created by Process 1 through more effective situation recognition. Second, the relevance of the context may also boost the productive engagement of Process 2: if a problem feels familiar, relevant, and less intimidating, students may be more likely to reflect on their initial response, identify possible inconsistencies, and persist in their reasoning rather than dismissing any "reasoning red flags" under the assumption that "physics is just weird." Finally, familiar and relevant contexts can reduce cognitive load, freeing up cognitive resources for reasoning instead of sorting through the provided information. Overall, contextual relevance *may* support both Process 1 and Process 2 functions, ultimately leading to better problem-solving outcomes in IPLS settings.

At the same time, we acknowledge several limitations to this argument. Any improvement in reasoning or performance may be attenuated (or even reversed) if the course is taught predominantly through traditional physics contexts while assessments are framed in life-science-relevant scenarios [26, 27]. In such cases, students may be more attuned to superficial features rather than deep structural elements of problems, rendering Process 1 even less effective at recognizing the task as, for example, requiring application of Newton's 2nd law [28]. While students may still be more motivated to persist in Process 2 reasoning, they might also be more inclined to embrace intuitively appealing incorrect mental models due to heightened confidence in their thinking within a more familiar context. Finally, even when a context is aligned with students' disciplinary identity, if the situation itself is unfamiliar, it may increase cognitive load and thereby hinder reasoning. These concerns are consistent with long-standing findings in STEM education and cognitive science that highlight the difficulty of transferring knowledge across domains or contexts [25, 29, 30].

Thus, in this study, we seek to understand whether and how contextual relevance affects student reasoning processes, while taking into account particular instructional circumstances as outlined in Section III.

III. METHODOLOGY

A. Task Design

The challenges of adapting traditional physics problems to better align with disciplinary interests are well recognized [9]. Identifying contexts that require the application of basic physics principles appropriate for introductory courses without excessive adjustments proves to be difficult. Preserving the authenticity of the new context is also important. If the revised scenario feels contrived or biologically implausible, it may undermine student motivation and hinder their reasoning even further.

To address these challenges, we collaborated with researchers in biology education to redesign four traditional physics scenarios by incorporating contexts more relevant to IPLS students. This process was iterative and included steps to establish evidence for content and face validity. In this paper, we focus on one set of these tasks, specifically the traditional physics scenario depicted in Figure 1. Notably, the patterns of student responses reported here were largely

replicated across the other task sets, which are not discussed in this paper.

The *Magnet* task was replaced by a gecko clinging to a vertical surface as shown in Figure 2. The biomechanics of gecko adhesion are not only well-grounded in physics but also relevant to various current research areas, including biomedical engineering (e.g., the development of gecko-inspired adhesives and medical bandages) [31].

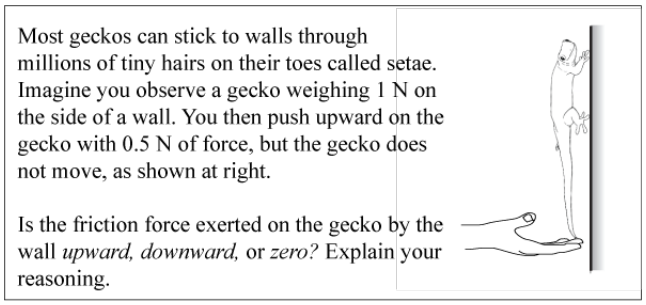

FIG. 2. *Gecko on a wall* task

We note that the modified task differs not only in context but also in structure. The *Gecko* task includes additional information to situate it within a biological context. Specifically, it introduces the adhesion mechanism through setae, whereas the *Magnet* task does not explain the nature of the magnetic interaction between the magnet and the refrigerator surface. One might argue that students in the first semester of an introductory course may lack the background to reason effectively with magnetic forces, which are typically covered in the second semester of the introductory sequence. As a result, they may not be able to apply Newton's 2nd law correctly in this situation. However, careful analysis of student written responses and interview data across multiple institutions and instructional settings offers no evidence to support this concern. As discussed earlier, the majority of calculus-based students respond based on the intuitive notion that friction opposes the applied force by the hand, showing no indication that they attempted to apply Newton's 2nd law but did not persist in this line of reasoning due to possible confusion about magnetic interactions. Nevertheless, we are interested in probing whether replacing the magnetic context with the gecko adhesion scenario would yield any improvement in student performance.

B. Instructional settings and data collection

The study was conducted in the first semester of an introductory algebra-based physics course, predominantly taken by life science majors, with a small fraction of students pursuing a degree in another unrelated field like construction management engineering. The course was taught by an experienced instructor with a background in physics education research. However, the course was not explicitly designed to incorporate context-relevant activities for life science majors. As such, before the tasks were administered, students had not encountered the context of gecko adhesion during instruction.

Both tasks were given during week 16 of the semester, following all relevant physics instruction on forces and Newton's laws. The tasks were administered outside of class in an online format. Students earned credit based on their effort in answering questions rather than the correctness of their responses. All students were randomly assigned to consider either the traditional version of the questions (*Magnet* task) or the modified version (*Gecko* task). We received a total of 148 responses, with 72 students responding to the traditional task and 76 to the modified task.

IV. RESULTS AND DISCUSSION

A two-proportion Z-test was used to compare correct response rates between the original and modified task versions. This test is appropriate for large, independent samples ($N > 50$) and yields a Z-score with a corresponding p-value. A result of $p < 0.05$ is considered statistically significant [32].

	Magnet (N = 72)	**Gecko (N = 76)**
Upward	39%	37%
Downward	44%	46%
Other Reasoning	4%	6%
No Reasoning	12%	11%

TABLE I. Performance on the *Magnet* and *Gecko* tasks

Student performance on the *Magnet* task is nearly identical to that on the *Gecko* task, as shown in Table I (Z-score = -0.26, p = 0.79). The small differences in performance are neither statistically nor instructionally significant. Additionally, the patterns of students' reasoning approaches appear to be remarkably similar. Below, we present illustrative examples of student reasoning for each task.

Approximately 38% of the students provided correct responses and supported their answers with reasoning based on the requirement that the forces must be balanced for an object to remain at rest.

> *Gecko Response:* The friction force must balance the net vertical force and the net vertical force is the difference between the gecko's weight and the applied force upwards.
>
> *Magnet Response:* The net force on the magnet is downward and since the magnet is not moving, the force must be opposite of the net force.

Although these students' use of the term "net force" is not entirely accurate, they understood that since the object remained at rest, the friction force must balance the vector sum of all other vertical forces acting on the object: the weight and the force by the hand. These responses demonstrate productive engagement with formal physics knowledge and are therefore considered correct.

In contrast, a majority of the students (44%-46%) argued that the force of friction must be downward, as illustrated by the two representative responses below.

> *Gecko Response:* The static friction is opposing the force from you pushing upward on the gecko.

> *Magnet Response:* The friction force would have to be going opposite the pushing force to cause it not to move.

As expected, these students reasoned that friction opposes the applied force by the hand, an external agent that actively and visibly acts on the object. These responses are consistent with the reasoning observed in prior studies, suggesting that the initial output of Process 1, based on this incorrect model, was likely accepted without further examination. Although this model can lead to correct reasoning in some situations, the students did not account for all relevant forces acting on the object. The visual salience of the hand pushing upward likely cued this intuitive response, overshadowing more deliberate reasoning based on net force and force balance.

A smaller group of students provided responses that did not fit into any common reasoning category or lacked explanation. These responses revealed difficulties with basic conceptual understanding of friction or Newton's 2nd law. For example, one student stated that the force of friction in the magnet scenario is "zero because it doesn't move," indicating a belief that friction only acts on a moving object.

The comparable performance on these two tasks suggests that a possible lack of background knowledge on magnetic interactions is not a likely cause of student reasoning difficulties on the *Magnet* task. Instead, our findings consistently align with DPToR-predicted reasoning mechanisms: students often rely on salient task features that elicit strong intuitive responses, which are subsequently accepted without thorough evaluation.

The lack of a significant difference in student performance between the original and modified task versions also suggests that altering the context *alone,* without incorporating similarly contextualized activities in instruction, is likely insufficient to produce measurable improvements in student reasoning. Still, we remain optimistic. First, the challenge of transferring knowledge across different contexts and domains is well-documented in STEM education [25, 29, 30]. Performance often drops on novel, discipline-relevant tasks (e.g., the *Gecko* task) that require transfer from traditional contexts (e.g., the *Magnet* task). The comparable performance on the *Gecko* task, which requires transfer, suggests that further improvement is achievable. This improvement, however, may require more consistent and deliberate integration of life-science relevant activities into classroom instruction, which could boost student motivation and help improve reasoning (and performance) even further (see, for example, [10]).

Based solely on written responses, we cannot determine with certainty whether the reasoning processes predicted by DPToR were affected by the change in context. To explore this in more depth, future research involving think-aloud interviews and student reflections with more complex alternate-context questions will be necessary.

V. CONCLUSION AND FUTURE WORK

We applied the Dual-Process Theory of Reasoning to examine student thinking in an algebra-based introductory physics course, focusing on tasks known to elicit strong, intuitively appealing but incorrect responses. Our primary goal was to probe whether modifying traditional physics tasks to incorporate contexts more relevant to life science majors would affect student reasoning. The results suggest that changes in context alone may not be sufficient to produce significant improvements in reasoning, especially when such contextualizations are not integrated within broader instructional practices.

The patterns of incorrect reasoning previously documented in calculus-based courses were replicated with IPLS students. This suggests that certain scenarios consistently elicit intuitively appealing yet incorrect responses, which students often accept without engaging in more deliberate reasoning. These patterns appear to be consistent across student populations and possibly even task contexts, reinforcing the robustness of the underlying cognitive mechanisms described by DPToR.

Moving forward, future studies should explore the effects of systematically incorporating biologically relevant tasks into instruction. Additionally, think-aloud student interviews and real-time reflections may provide valuable insights into how context affects the outcomes of the intuitive process 1 and the engagement of process 2. Ultimately, while contextual relevance shows potential for boosting engagement and enhancing learning experiences, improving reasoning will likely require more than just relevant context. Significant improvements in student reasoning will likely require instructional strategies that explicitly support students in recognizing intuitive responses, critically evaluating them, and, if necessary, replacing them with formal reasoning. Without such intentional support, even contextually relevant tasks are unlikely to produce lasting changes in students' reasoning habits.

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