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Intuition and Reasoning: What Can We Learn from Cognitive Psychology?

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Students tend to rely on intuitive reasoning, rather than formal physics knowledge, even after they have successfully used this knowledge in similar situations. This approach often leads to erroneous conclusions, which may be frustrating for both students and their instructors. Research from cognitive psychology suggests that intuition is an integral part of human cognition and cannot be turned off. In fact, intuition provides an entry point into any reasoning path. In this paper, we briefly introduce a set of theoretical ideas from cognitive psychology referred to as the dual-process theories of reasoning (DPToR) that describe interactions between intuition, reasoning, and formal knowledge. We illustrate how student reasoning in an introductory algebra-based mechanics course could be interpreted through the lens of DPToR and suggest implications for instruction.

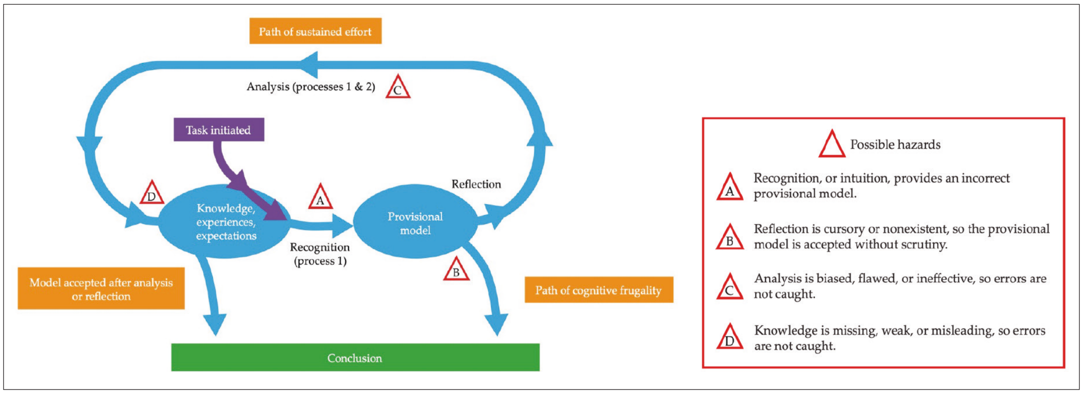

Fig. 1. A model of pathways predicted by DPToR. When faced with a problem (purple box), students unconsciously develop an intuitive mental model [labeled "Recognition (process 1)"] based on previous experiences and knowledge. There are several hazards (labeled A–D) that may be present on reasoning pathways. Reproduced from Ref. 6 with the permission of AIP Publishing.

Nic and Sam review materials on forces and Newton's laws. Nic says, "Next problem involves a block sliding down the incline. The incline is not frictionless. We are supposed to determine how the force of friction will change, if at all, after the angle of the incline is increased." Sam replies, "Let's skip this problem. We practiced solving several problems like this in class and on homework." After a few seconds, Nic replies, "Yep, if the angle of the incline is increased, the block moves faster, so it must be producing more friction." Sam nods, and the students move on.

Experienced instructors often witness situations similar to that illustrated in the opening vignette. The discussions may vary slightly. Nic may have predicted that, since the object is now sliding faster, the friction must decrease. Alternatively, Sam may have said that the friction is unchanged because the surfaces remained unchanged. Regardless of the final answer, one facet of many student conversations like the one above remains the same: novice learners tend to jump to conclusions without applying formal knowledge and skills acquired in class to verify the validity of their initial (often intuitively appealing) answers.

For instructors, these observations may be very disheartening. After significant efforts dedicated to planning lessons, guiding students through activities, and helping them learn how to apply physics concepts in a variety of situations, instructors may feel discouraged. Our students often feel frustrated as well. Some students comment that "physics is too hard" and "no matter how much I study, I never do well." Decades of work in cognitive psychology, however, suggest that reasoning patterns such as those highlighted in the vignette are entirely normal and often unavoidable for novice learners.[1,2] In our research into student reasoning in physics, we found that DPToR provide a valuable lens for understanding reasoning pathways in physics, both productive and unproductive. In addition, DPToR allow us to pinpoint mechanisms contributing to reasoning difficulties in physics and to identify reasoning hazards that one needs to navigate on the way to a correct conclusion.

Dual-process theories of reasoning

According to the DPToR, there are two cognitive processes involved in human reasoning. Process 1, often referred to as the heuristic process, is fast and automatic. Process 2, the analytic process, is slow, deliberate, and rule-based.[1–5] Figure 1 illustrates reasoning pathways due to the interactions between the two processes.[6]

When a reasoner is presented with a problem, process 1 immediately and subconsciously develops a mental model of (or a way of thinking about) the situation based on previous knowledge, experiences, and contextual cues. This provisional mental model is often referred to as intuition or a "gut feeling." Herbert Simon defined intuition as "nothing more and nothing less than recognition."[7] Experts, with their diverse repertoires of experiences, may quickly recognize a given situation accurately. For novices, accurate recognition is often still a challenge. It is critical to note that process 1 cannot be turned off. Whether we want it or not, a quick provisional mental model serves as an entry point into all reasoning paths. If the provisional model is incorrect, it presents the first setback on a path to a correct conclusion, as shown by hazard A in Fig. 1.

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Once the provisional model is formed, it becomes available for examination by the slow and deliberate process 2, which may or may not intervene (as indicated by the junction in Fig. 1). If a reasoner feels confident in their intuitive idea, process 2 may be entirely circumvented. In this case, process 1 produces a final, intuition-based response. This direct path from a quick provisional model to a conclusion is often called the path of cognitive miserliness, reflecting the human tendency to spend the least amount of time necessary on a given task. This path, however, could be entirely appropriate or even necessary. The repeated application of skills and formal knowledge helps develop the quick recognition needed for expertise or expert intuition. An expert may not need to check for the validity of a provisional model if it is based on knowledge automated by this repeated application. Such automation may even be necessary on tasks that require more computationally expensive procedures. For example, most adults do not need to verify that 3 + 3 = 6 while solving a more complex mathematical problem. For these reasons, we prefer the term *path of cognitive frugality*, as indicated in Fig. 1.[6] Knowing when it is appropriate to be cognitively frugal and when the engagement of process 2 is required is critical for productive reasoning. A quick acceptance of an erroneous provisional model that leads to an incorrect conclusion is represented by hazard B.

If hazard B is avoided, the provisional model becomes available for analysis by slow and deliberate process 2. However, reasoning errors often remain undetected due to hazards C and D. Instead of scrutinizing a provisional model, process 2 often looks for evidence to support what the reasoner already believes to be true, thus engaging in confirmation bias. In addition, process 2 tends to simplify the problem by making unjustified assumptions, which leads to analytical errors. These possible reasoning biases are represented by hazard C. Even if that hazard is avoided and a possibility of an error is detected, if a reasoner does not possess strong enough formal knowledge to check for the validity of their provisional model, an incorrect intuitive model persists and yields a final response, as indicated by hazard D. If the provisional model is rejected (i.e., hazard D is avoided), then the reasoning cycle repeats, and the first provisional model is replaced with a new one. As a result of these cycles, a reasoner may reach a correct conclusion.

Reasoning in physics

From our experiences as instructors and researchers focusing on the student learning of physics, we see evidence of student reasoning pathways consistent with the DPToR.[3–6] For example, consider again the block-on-the-ramp problem introduced in the vignette and shown in Fig. 2. This problem was given to algebra-based introductory students (N = 122) in a web-based format as a practice assignment before a course exam. A block is sliding down a ramp positioned at a 20° angle. Students predicted how, if at all, an increase in the angle would affect the magnitude of the force of friction between the block and the ramp and explained their reasoning. In addition, students were prompted to answer two follow-up questions. First, students were asked to predict what answer other students, who may have used intuitive reasoning, would give. Next, the students commented on whether they used intuitive or formal reasoning. The purpose of these follow-up questions was to provide an opportunity for the students to slow down, reflect on their answers, and consider alternative solutions. Student responses were not graded based on correctness; instead, students received credit based on their effort.

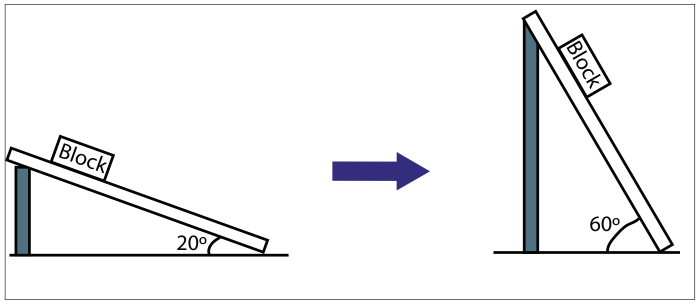

Fig. 2. The block slides on the ramp. Students determine how the force of friction between the block and ramp changes, if at all, after the angle is increased.

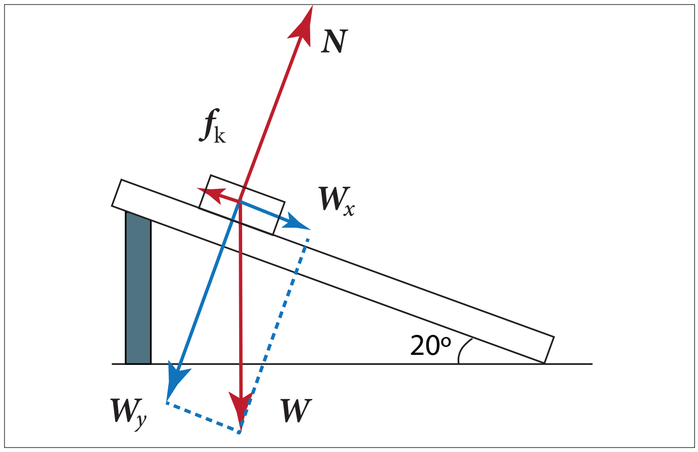

Fig. 3. Free-body diagram for the block.

To answer correctly, a student needs to recognize that (1) the problem concerns a force of kinetic friction, $f_k = \mu_k N$, where μ_k is a coefficient of kinetic friction and N is a normal force between the block and the ramp; (2) an increase in the angle of the incline decreases the y-component of the weight force, as shown in Fig. 3; and (3) the normal force must be proportional to the y-component of the weight and therefore must also decrease. These steps lead to a conclusion that f_k decreases as well.

Although this problem is typical for algebra-based courses and students in our study practiced solving similar problems, only ~16% arrived at a correct answer with correct reasoning. As illustrated by the examples below, most students appeared to succumb to one (or more) reasoning hazards.

Hazards A and B: Incorrect intuitive model and no evidence of reflection

Anna (all names are changed) wrote, "As the angle of the ramp increases, the block will slide faster down the ramp creating a greater frictional force. ... I believe I used formal reasoning, because I imagined what a block would do sliding down a ramp if I tilted it upwards." It appears that Anna entered an incorrect reasoning path by erroneously recognizing the problem as being "about the motion" of the block as opposed to “about the forces that cause the motion.” Most experts would avoid hazard A by immediately recognizing that this type of problem requires a free-body diagram and an application of Newton’s laws. However, a significant number of students (~20%) responded like Anna. They seemed to visualize the motion of the block (an observable behavior) and inferred a change in the force of friction based on that visualization. Although Anna claimed that she used formal reasoning, her response does not contain any physics concepts or any other evidence that she attempted to reflect on her intuitive response by engaging in process 2.

Brian’s argument was similar to Anna’s. However, he arrived at the opposite conclusion that the force of friction decreases “because as you tilt the ramp higher, the block will have a faster velocity causing the block to have less friction.” Even though an intuitive model can erroneously lead to a correct conclusion, as it did for Brian, it is misleading, as shown by Anna, and incorrect. We argue that students should become explicitly aware that reasoning approaches based solely on visualization of an experimental outcome are not reliable, although they may be appealing for novice learners.

Hazard C: Reasoning biases

Dan erroneously concluded that the friction would increase by arguing that “There are two types of friction forces, kinetic (sliding) and static friction. If you think of a ramp, if you increase the ramp height the kinetic friction increases because it is more likely to slide. It would increase the tangent of the angle.” This response suggests that Dan’s provisional mental model is similar to Anna’s and is based on the intuitive notion that a faster-moving object causes a force of friction to increase. Unlike Anna, Dan appears to be looking for formal knowledge to support what he believes to be a correct answer (i.e., confirmation bias), thus struggling to avoid hazard C. Dan’s reflection on his response is consistent with this interpretation. He stated, “The formal class of physics helped by logically reason out the problem, however, you have to think of how things actually work in the world too.” Dan seemed to recognize that reasoning in physics requires a carefully constructed argument, but he struggled to connect what he learned in the class with his ideas about “how things actually work.” It may also be the case that Dan’s relevant knowledge was weak or missing, which may have prevented him from avoiding hazard D to catch his mistake.

If a student’s intuitive mental model is consistent with the correct response, then confirmation bias may assist in constructing a correct argument. For example, Clara argued that “As the angle increases the gravity component acting on the block will decrease which will decrease the normal force, which in turn decreases the frictional force.” Later, she revealed that “It made sense that the friction would decrease, so I came up with a formal reason for why that might be true.” We recognize that for Clara’s response to be considered correct with complete reasoning, the student must explicitly mention the *y*-component of the weight. However, this response illustrates the student’s self-reflection on her reasoning process that could be described as “answer first, reasoning next.” Prior research suggests that students are significantly more successful at building an argument to support a correct known answer than at creating an argument to arrive at that answer.[3]

About 10% of students included reflection statements like Clara’s: “I started with intuitive and then confirmed it with the formal,” or “I used formal reasoning to prove my intuitive.” It appears that these students are aware that they tend to come up with an answer first and only then construct an argument to rationalize it. Since the intuitive process 1 cannot be turned off, the emergence of an intuitive response is unavoidable. However, students also need to learn how to check for the validity of their intuition-based responses. Being attentive to the human tendency to engage in confirmation bias may help students refine their general approaches to reasoning and learn about the importance of considering alternatives when engaged in decision-making.

Process 2 may also be impeded by different reasoning biases represented by hazard C such as analytical errors. For instance, novices tend to make unjustified assumptions that simplify their arguments. For example, Naresh argued (see Fig. 4) that “For F_{net} in the X direction, you need the friction force and the sin(theta) times the force due to gravity to equal ma. So, by increasing the angle, the force due to gravity will increase, so the friction force must decrease.”

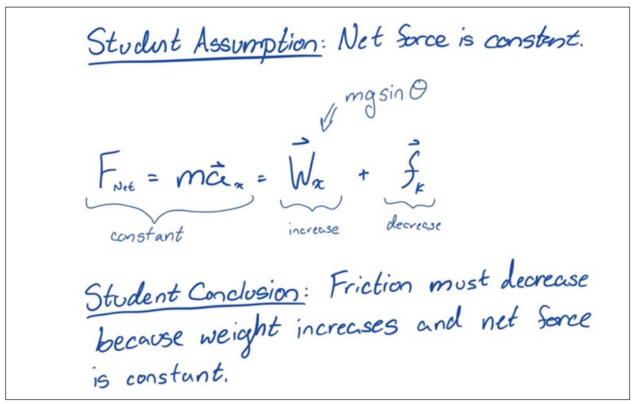

Fig. 4. Student reasoning based on an incorrect assumption.

Tiana provided a similar argument and later revealed, “I am assuming F_{net} is the same in both situations because I’m given no information. Therefore, in order to compensate for a larger $F_{gravity}$ value, $F_{friction}$ must decrease.” These students attempted to apply formal knowledge learned in class but chose a computationally complex path. Instead of considering an alternative solution, they made an inappropriate assumption, which allowed them to apply the compensation reasoning, yielding a response with incorrect reasoning but a desirable answer. About 7% of the students explicitly mentioned that making the assumption was necessary to proceed with the formal solution. It is also possible that their relevant formal knowledge was not strong enough (hazard D) to recognize and overcome the analytical bias (hazard C).

Hazard D: Relevant knowledge is absent or weak

It is indisputable that strong analytical skills alone are not enough to reach a valid conclusion.[3] If the relevant knowledge is absent or weak, a reasoner is not likely to catch a mistake in their provisional model or override an error, even if hazards B and C are avoided. Charlie predicted that many students who applied intuitive thinking would give a response similar to Anna's by visualizing a faster-moving block producing a greater force of friction. He also recognized that this approach is dangerous: "I first thought about it using intuitive knowledge, but then I thought a little more because I have made that mistake many times in physics class and have finally learned and then came up with my second answer using formal reasoning." Despite Charlie's quite sophisticated reflections on reasoning, his final response was incorrect: "The coefficient of kinetic friction stays the same, so that wouldn't change it. The normal force would also stay the same because it's the same mass and the same acceleration due to gravity." Charlie made a common mistake by treating the normal force and the weight force as if they were Newton's third law "action–reaction" force pair. About 25% of responses contained mistakes similar to Charlie's, indicating weak or absent relevant knowledge.

Successful error detection and override

If a student avoids all the hazards described above, they may recover from an erroneous model. Many physics instructors would probably agree that the most joyous instructional moments involve witnessing students detecting and successfully overriding a mistake in their reasoning. However, it is uncommon for students to discuss such processes in their written responses to classroom assignments. Still, as instructors, we may be able to prompt introspection by asking follow-up questions. For example, one student, Igor, initially concluded that as the angle of the ramp increases, "the friction force does not change because the two surfaces have not changed at all. The only thing that the normal force is not as large and cannot counteract gravity as well so the block may slide off the ramp." Upon reflection, Igor was able to catch his mistake. He noted, "The friction force changes. The coefficient of friction does not change. I messed up that last question. … If you look at the [friction] equation you can deduce that with the normal force decreasing the friction force would reduce." Igor was able to override his original answer by recovering from a common (but intuitively appealing) response. Quick follow-up questions appeared to be enough to nudge him to reevaluate the relationships among μ_k, N, and f_k.

Conclusions

When students perform poorly on a task, an instructor needs to diagnose the roots of their errors. The presence of formal knowledge is undoubtedly necessary for productive reasoning but not sufficient. Students must also be able to navigate reasoning hazards on their path to a correct conclusion. Some students appear to produce a final judgment based on highly appealing intuitive ideas without checking their validity. Other students attempt to engage in formal reasoning but often succumb to reasoning biases. Interpreting student responses through the lens of the dual-process theories can help physics instructors identify reasoning hazards and help students develop strategies to avoid them. It is important to highlight that DPToR is not in opposition to other theoretical frameworks used by physics education researchers to examine student thinking in physics (e.g., p-prims and resources).[8–11] In fact, we argue that DPToR takes these ideas into account, while the model in Fig. 1 allows for visualization of various reasoning paths and identification of reasoning hazards.

We also argue that helping students become aware of the dual nature of human reasoning may have benefits that extend beyond improved performance in physics. Students often share that they find "physics to be too hard" and that "the correct answer is always the opposite of what I think, so I guess I am just not good at physics." Such negative attitudes toward our discipline and unfavorable students' beliefs in their own capacity to succeed are detrimental to our efforts to increase participation in STEM. Instruction that makes reasoning pathways and associated hazards visible to the students may help create a learning environment that normalizes the process of reflection on one's reasoning, error detection, and correction. It may help students recognize that making and correcting mistakes is a natural and necessary part of learning and should not be perceived as inadequacy and failure. Instead, these experiences should serve as a motivation for learning how to navigate reasoning hazards successfully.

Acknowledgments

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