How freshmen generate evidence for reasoning in physics and non-physics tasks?

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We explore students' sources of self-generated evidence and their meta-cognition when they solve physics and non-physics questions. Our sample comprises 50 freshmen taking or having taken introductory physics. Each student participated in a one-hour interview to complete five open-ended reasoning questions taken from published instruments. Two questions are non-physics that deal with correlation of variables. The three physics questions pertain to the topic of energy. Results indicate that for the non-physics questions, the students mainly used given information in the task as source of evidence. They realized that everyday experiences or assumptions were informal ideas and hence assigned them less weight in generating the evidence. For the physics questions, the students did not realize that they used informal ideas. They packaged informal knowledge in the form of formal physics knowledge. These outcomes may be explained by the ease with which the students dealt with the context of the questions coupled with a high cognitive load associated with processing multiple pieces of information when students tackled qualitative questions.

I. INTRODUCTION

Reasoning skills are essential for effective sense-making, problem solving and decision-making. In science, reasoning has been defined in various ways. Its definition varies from being simplistic, as thinking about and/or with scientific knowledge [1], to being more elaborate by focusing on the hypothetical-deductive nature of thinking [2]. Reasoning ability has been identified as a key skill that students are expected to develop and apply in the practice of science [3]. It is also regarded as a crucial predictor of learning [4]. However, studies have reported that undergraduate students tend to have poor reasoning skills regardless of their years of study, majors or types of institutions [4,5].

Our study is based on Kuhn's framework [6], which defines scientific reasoning as the conscious intent to seek novel and/or additional information in order to enhance knowledge and comprehension. It emphasizes the importance of cognition for scientific reasoning to occur i.e., the conscious awareness or intent to widen one's knowledge and understanding. The process of theory-evidence coordination, which is the core of Kuhn's framework, is explicit and intentional.

We report one aspect of our project, specifically how students self-generate evidence in two contexts, non-physics and physics questions. Two reasons motivated this research. First, context plays a central role in learning [7] and reasoning ability has been found to be related to content learning [8]. As such, we assume that there is a possible link between context and students' reasoning ability. Second, not much is known about how physics students think and reason with particular physics concepts to generate an answer when tackling qualitative and conceptual physics problems. There is a paucity of studies documenting students' reasoning ability in the physics context [4,5] and they have used standardized tests or questionnaires with a multiple choice format. For our study, we address the following research questions: (i) What sources do students use to generate evidence when handling physics and non-physics questions?; (ii) How does students' meta-cognition compare between answering physics and non-physics questions? We define evidence as the information students provide to justify and expand on their *initial and spontaneous* predictions about a situation. We provide a definition for sources of evidence in the next section (see Section II).

II. METHOD

We used five questions taken from published instruments that have been previously validated. In the original instruments, the questions were in the multiple-choice format, which we believe may limit students' thinking. In this study, we are interested in the students' self-generated evidence. So, we adapted the questions into the open-ended format to solicit diverse, authentic responses. Q1 [in Fig.1], taken from Han [9] and Q2 borrowed from TIMMS [10] are non-physics questions pertaining to correlation of variables. Q1 deals with the connection among three variables namely, thickness of fishhooks, length of fishing rods and fishing locations, to the number of fish caught. Q2 involves comparing the change in population between two countries over the next 10 years. The students have to consider the relations among birth rate, death rate, oil consumption, food production and surface area of the two countries, and link them to the change in population. Q3, Q4 and Q5 are questions of energy topics selected from the Energy Assessment Questionnaire [11]. We chose the topic of energy because it is an important concept that cuts across multiple disciplines of physics, chemistry and biology [1]. Knowledge of high school physics should suffice to answer these questions. Q3 is concerned with the work done on a person in an elevator moving upwards at constant speed. The students have to generate an answer about the amount of work done on the person. Q4 deals with the work done on a box moving on a frictionless surface until it is stopped by a person. The students have to provide a response about the amount of work done on the box for the entire process. Q5 [Fig.2] involves comparing the kinetic energy of two pucks of different masses. An example of a non-physics (Q1) and of a physics question (Q5) is in Fig. 1 and Fig. 2 respectively.

1. Tom, Jerry and Dan go fishing together most weekends. They often use the same type of fishing tools and have similar skills in fishing (i.e., they often each catch a similar number of fish every time). On their last fishing trip, they had selections of different rods and fishhooks, and they each picked a different location to fish. They fished for a total of two hours and the number of fish they caught during this period is shown below.

		Tom	Jerry	Dan
Conditions	Fishing rods	Long	Long	Short
	Fishhooks	Thick	Thin	Thin
	Locations	Point A	Point A	Point B
Number of fish caught during the two-hour		15	15	8

a) What will you say about the link between each of the three conditions and the number of fish caught?

b) Why do you say that?

FIG 1. An example of a non-physics question.

5. On a frictionless table, you launch two pucks by pushing them against identical springs through the same amount. The two pucks have the same shape and size but the mass of puck 2 is twice the mass of puck 1. The pucks are released and propelled towards the finish line.

a) What will you say about the kinetic energy of puck 1 compared to the kinetic energy of puck 2 at the finish line?

b) Why do you say that?

FIG 2. An example of a physics question.

Overall, the non-physics and physics questions are similar in the sense that they both allow students to invoke their everyday knowledge to find an answer. Also, they both involve the idea of correlation of variables. Ideally, the physics questions should be solved by using the concept of energy conservation. However, there is a possibility for students to use equations related to work, kinetic energy and Newton's Second Law to seek relations among different variables. These alternative approaches are acceptable but reveal the different sources of information that students were looking for.

Our sample comprises 50 freshmen who either had recently completed or were taking an introductory physics course at the time of the study. In addition, they all had taken high school physics. Data were collected after the students had covered the topic of energy in their introductory physics course. Each student participated in a one hour individual interview. During each session, the student was given 30 minutes to complete the five questions. Individual interviews immediately followed and lasted a maximum of 30 minutes. Examples of interview questions are: (a) Can you elaborate on how you come up with your answer? (b) Which information did you use and why? (c) Is there anything else that you thought about but did not write down? (d) I am sure you have given more thoughts to this question. Can you tell me the additional ideas that came to your mind when you were thinking about this question? (e) Do you find the questions easy or difficult to tackle?

The interview responses were analyzed thematically for the sources of evidence and students' meta-cognition. For sources of evidence, we coded if the students considered: (i) only the information given in the task, (ii) only formal knowledge i.e., concepts learnt in class, (iii) only informal knowledge i.e., knowledge acquired outside class including everyday experiences, assumptions and intuitions, and (iv) information given in the task or formal knowledge combined with informal knowledge. We combined categories (iii) and (iv) as we were mainly interested in whether or not the students referred to their informal knowledge. For meta-cognition, we looked at whether or not the students realized that they used informal knowledge when generating their evidence. We focused on whether they explicitly said that they used or did not use informal knowledge. We also examined whether the students discarded or used the informal knowledge after they mentioned it. Finally, we considered the students' actions when they had to choose between two self-generated responses, one based only on information given in the task or only on formal knowledge and the other involving informal ideas. Two researchers independently coded the students' interview responses. The inter-reliability rate varied between 86% - 89% for the five questions. Any difference in coding were discussed and resolved.

III. RESULTS

1. Source of evidence

Table I presents the percentages of students classified according to the different sources of evidence for the non-physics and physics questions. In some cases (24% for Q1 and Q5, 22% for Q3 and 18% for Q2 and Q4), the students generated two responses for a question. To compile the results for this section, we only considered the students' first answer. Their second answers were generated while they were elaborating on the first one.

TABLE I. Source of evidence for non-physics and physics questions (N = 50)

	Non-physics questions		Physics questions		
Source of evidence	Q1	Q2	Q3	Q4	Q5
Given information	94%	84%	-	-	-
Formal knowledge	-	-	48%	30%	50%
Informal knowledge	6%	16%	52%	66%	50%
Uncodeable	0%	0%	0%	4%	0%

For the non-physics questions, most students (94% for Q1 and 84% for Q2) solely used information given in the question as the source of evidence. A low percentage of students (6% for Q1 and 16% for Q2) generated evidence based on information given in the questions together with informal knowledge. For Q1, the students brought in their fishing experiences that did not match with the given information, as typified by the following quote: "*If you change the rod length, it changes the size of fish caught and* *not how many fish you catch. Location affects the number of fish caught. It determines the density of the fish, the ecosystem of the pond. Fishhook has no effect since Jerry and Dan had a thin one and their number of fish caught didn't match*." For Q2, the students made assumptions about the effect of the variables (birth and death rates, oil consumption, food production and the geographical areas) on the population of the two countries: "*Country 2 is dense, about 20 people/km^2. The denser the country, the more people would move out for better living conditions. Country 1 produces twice as much food as country 2. It is less dense and is an urban area given it consumes more oil. All these are pull factors of people from country 2 to country 1*."

For the physics questions, the students mainly brought in informal knowledge combined with their formal knowledge as a source of evidence (52% for Q3, 66% for Q4 and 50% for Q5). A typical response from Q3 is: "*No work is done on the person. Work is only being done on the elevator. Work is force applied to an object. Here, there is force of the pulley pulling the elevator, and there is gravity. These forces act on the elevator, not the person. The person is in the elevator and is not affected by any forces. When I stand in the elevator, I just stand there. I am stationary. There is nothing happening other than I am going up, because the elevator is going up*." The student referred to the formal knowledge of work being done on an object when a force is applied to it. The student also provided an everyday example of being in an elevator and explained that one is not physically moving. Instead, it was the elevator that was in motion carrying one upwards. This informal idea was then transferred and applied to the physics situation. For Q4, an example of student response is that "*[t]he amount of work done is negative, as if you are acting on something, and your work was positive, it would move it, but the person is stopping the box and the velocity goes down to 0. There had to be something that took its velocity to 0, so you have to subtract, like this work would have to be negative*." The student used (notably in an acceptable manner) the informal idea of addition and subtraction to think of work in relation to energy. Although the intuitive thinking of subtracting "something" from the box to stop its motion did not strictly match the formal reasoning in physics that should involve the relations among work, energy (specifically kinetic energy) and speed, it did serve well as an initial conceptual representation of the phenomenon. For Q5, a quote exemplifying the use of informal knowledge is: "*When you release the springs, the same amount of energy is transferred from each spring into each puck. But the effect the energy has on the individual puck is different* [...]. *You hit a baseball, you do the same exact swing, same bat* [;] *it will go the same distance. But a bowling ball weighs more than the baseball. It will not go far or travel as fast as the baseball. Here the energy has a greater effect on puck 1 as it is smaller. The same amount of energy on puck 1 will push it further than same amount of energy on puck 2. So puck 1 has a higher potential energy to move. The potential and kinetic energies of the system are conserved. So, higher potential energy is going to end with high kinetic energy*." The student used the formal knowledge of energy conservation and referred to an everyday example of hitting a baseball and a bowling ball. The student alluded to the informal idea that lighter objects move faster and farther compared to heavier ones when the same force is exerted on them. As such, even if the springs transfer the same amount of energy to the two pucks, the puck with less mass (puck 1) will have a greater amount of potential energy as it moves faster and farther compared to the heavier puck (puck 2). Since energy is conserved, the puck with the greater amount of potential energy will have a greater amount of kinetic energy.

2. Meta-cognition

Table II presents the number of students who realized and did not realize that they included informal knowledge when generating their evidence for the non-physics and physics questions.

TABLE II. Students' meta-cognition for the non-physics and physics questions.

	Non-physics questions		Physics questions		
Students' meta-cognition	Q1 (N = 14)	Q2 (N = 29)	Q3 (N = 26)	Q4 (N = 33)	Q5 (n = 29)
Informal knowledge with realization	14	24	2	0	0
Informal knowledge without realization	0	0	24	33	29
Cannot be determined if informal knowledge includes realization	0	5	0	0	0

For the non-physics questions, the students realized that they brought in their informal knowledge to generate their evidence. First, they explicitly said that they used their fishing experience (Q1) or made assumptions about the effect of the variables on the countries' populations (Q2). An example of a response (from Q2) is: "*Birth and death rates are directly related to population change, but the others I'll be making a lot of inferences and assumptions trying to interpret that into the population change*." Second, although the students mentioned informal knowledge, they did not include their everyday experiences or assumptions to formulate their answer; for example, here is a quote for Q1: "*We can't really figure out one variable with two variables. We need to run multiple trials,* [...] *isolate variables if you are trying to look for one,* [and] *all the other conditions have to be the same* [...]. *But fishing involves weather and pond conditions. I grew up fishing. If it is cold and chilly, the fish will be in the sun. Towards midday when it is hot, they'll be in the shade*." Last, when the students generated two responses, they discarded the answer based on assumptions in favour of the response based on information given in the question. An illustration from Q1 is: "*There's a link, definitely here* [long rod and location affecting the number of fish caught]. *But, then, this link* [only location affecting the number of fish caught] *applied to my outside information,* *which I am not very confident about, as I realize I took a lot from my outside information which might have skewed my answer. I'm taking my outside information and using it for the information that I haven't been given here*."

For the physics questions, the students did not realize that they used informal ideas that they often combined with their formal knowledge. First, they usually brought in an example of an everyday situation that was similar to the one given in the question and compared them. Their reasoning in the everyday situation was transferred and applied to the physics question. Second, their everyday experience of force and quantity prevailed and was integral in generating the responses. For example (Q3): "*The force of gravity is acting down, and it is trying to make the person come down. But the force pulling up is overcoming the force of gravity. It has to be greater than the force of gravity for the person to go up. Since the upward force is greater, the amount of work done is positive*." In this case, the upward force is the winning force. It has a larger magnitude to counteract the opposing force of gravity and move the person upwards. The student also associated "greater force" to a positive quantity. Lastly, when the students generated two responses, one using formal knowledge and the other involving informal ideas, they either had no preference for either response or chose the answer involving informal knowledge as a final answer. A quote (from Q4) highlighting no preference for any answer is: "*Both* [answers] *I'm not confident. The more I think into it, the more I'm pulling out physics information. It's a lot harder to think about than with the fishing problem.*" A typical quote for students choosing the answer involving informal knowledge (from Q5) is: "*I'll go with the second one as I thought of pushing a boulder and a stone and how that* [kinetic energy] *would be different even if I put the same force on it* [boulder and stone] *which is the same thing here*."

IV. CONCLUSIONS

The study shows that students predominantly generated evidence based on the given information in the non-physics questions. Often they realized that they used informal knowledge to generate evidence. However, for the energy related physics questions the students tended to combine informal knowledge with their learned formal concepts for reasoning. Interestingly, they appeared to package their informal ideas in the form of formal physics knowledge. These outcomes may be explained by the ease with which the students deal with the context of the questions as well as by the cognitive load for processing multiple pieces of information when tackling qualitative questions. As evidenced by the above results, most students (62%) stated that the non-physics questions are easier or more straightforward than the physics ones. The physics questions require knowledge of energy and understanding of energy conservation in the physics context. Research has shown that students are better at manipulating equations and numbers, they prefer the formulaic plug-and-chug problem solving approach and are more familiar with and confident in solving quantitative physics problems than solving qualitative problems [12]. If students lack confidence in their ability to handle qualitative questions and in their understanding of concepts, there may be an increase in cognitive load associated with processing information. They will not have enough space in their working memory to think about whether or not they are using informal ideas. They will not have the cognitive capacity to assess the usefulness of the informal knowledge to generate an answer provided it logically makes sense to them. The non-physics questions do not require conceptual knowledge or understanding specific to physics. Therefore, there may be less cognitive load associated with processing information. The students have enough space in their working memory to bring in informal ideas and assess their relevance

An implication of these outcomes is that it is crucial for students to differentiate between and connect their informal and formal knowledge when solving physics questions, reasoning and sense-making. Moreover, students should be familiarized and exposed more to qualitative physics problem solving where they can reflect on conflicting ideas and evaluate their relative validity and significance.

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