Toward Meaning and Scientific Thinking in the Traditional Freshman Laboratory: Opening the "Idea Space"

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Abstract. Experimentation appears to be an ideal context in which several key aspects of scientific thinking can be addressed. However, the traditional freshman laboratory does not appear to be successful in doing so. This paper argues that this has much to do with the way in which tasks are formulated. We propose a simple descriptive model based on the notion of the "idea space" that can be used to analyze task formulation that can promote meaningful critical thinking. A number of factors that affect the size of the idea space are discussed, such as conceptual metaphor and the perceived nature of questioning from a socio-cultural perspective, described in terms of knowledge and information flow.

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INTRODUCTION

It is common cause among scientists and science educators to espouse "scientific thinking" as a central component of the scientific enterprise. In physics for example the phrase "thinking like a physicist" [1] is often used as a shorthand to describe skills, abilities and attitudes that are felt necessary for students to become successful at physics. While there is a vast literature on scientific thinking (the phrase critical thinking is often used interchangeably) in which the notion is problematized in detail we simply note three aspects [2] that are pertinent to the present discussion in which the freshmen laboratory will provide a context.

- An attitude of "productive skepticism"
- An understanding of the central role of empirical evidence
- The ability to think probabilistically

While the idea that elements of scientific thinking should be part of the curriculum and its outcomes is commonplace, how to do so successfully has been a challenge. Part of the reason for this is that the way in which information is structured and delivered in courses often sends a meta-message to students that is at odds with traits such as the above. For example, in a recent study with first and second year psychology students, the second year students who had several issues regarding scientific thinking addressed in a research methods course showed improvement in their scientific thinking ability after the course, the first year students showed a decrease in scientific thinking after their course [2]**.** This finding is in keeping with the analysis of Finster who applied Perry's model [3] to the context of chemistry teaching [4,5] in which he pointed out that part of the problem was that knowledge was presented in a binary manner i.e. as right or wrong. Such an underlying message tends to work against scientific thinking.

One curriculum area in physics that would appear to lend itself to addressing some of the aspects of scientific thinking is the freshmen laboratory: the items mentioned above lend themselves to being addressed through experimental investigations. This has indeed been shown to be possible through the adoption of several curricular materials that are successful in using experimentation to move students toward this goal [6-8]. However, these approaches require substantial buy-in for their adoption and are not likely to be the norm in the near future. On the other hand, there is little evidence that the more widely used traditional freshman laboratory has been able to affect the scientific attitudes of students in such a positive manner. We suggest that this is due to the fact that the way in which traditional laboratory tasks are formulated also promotes binary thinking. Thus, a standard template for experiments involves the following structure each of which is framed in unitary (prescribed) or binary (right/wrong) terms. Thus, we find

- An "aim" [goal of replicating an authoritative law or physical constant]
- A prescribed method [known recipe]
- Findings [statement of facts]
- Conclusion [aim realized or not]

- Discussion [factors that affected the experimental process]

While the last step appears to open up the process for critique it is very difficult for students to do so meaningfully. In effect students have to proceed from ideas that are triggered by right / wrong thinking to a much larger landscape of ideas but for which there are no obvious cognitive triggers.

We suggest that traditional laboratory tasks have the potential to be recast in forms that provide the necessary triggers to open the "idea space" that will allow for a measure of scientific thinking to take place while carrying out the laboratory experiment. We therefore propose a model based on the notion of the "idea space", as discussed below, that can be used as a rough guide in adapting existing materials. In particular, we suggest that there are factors that control the idea space and that identifying these factors and then paying attention to them in task will help to promote scientific thinking.

THE 'IDEA SPACE'

Consider a simple question: do you want coffee or tea? Comment on your choice? The implications of this question are that there are two choices and commenting is quite likely to lead a rather uninspired comment such as "I prefer tea to coffee," regarding the choice made. By contrast, consider the following formulation: think of all of the beverages that are available in the world and then choose the one you would like to drink now; explain to your friend why you chose this one. In this case the answerer is much more likely to come up with a range of ideas and by association various parameters such as how hot, how sweet, how thick, how bubbly etc. There is no longer an expectation of a specific 'correct' answer; the topic is open for discussion, and puts the answerer in a frame of expanding upon the ideas rather than possibly justifying their choice when asked the follow-up of commenting on their choice. The ensuing conversation with the friend is also more likely to have a greater measure of richness.

The concept of an 'idea space' as introduced intuitively through the above example can be considered as an abstract cognitive space into which ideas or resources [9] are recruited and that, expressed geometrically, the size of the space is structured by factors which are governed by contextual triggers.

A Toy Model for Critical Thinking

Using the 'idea space' as the central notion we propose a toy model for conceptualizing student access to scientific thinking skills. If a question or task is posed to a student in way that that closes the idea space or leads to a small idea space, there will be fewer resources to draw from and fewer opportunities for making inferences and associations, leading to the construction of meaning that will be very limited or highly specific. With limited meaning construction, there is less scope for critical thinking which requires reflection of the ideas at hand. If instead, the question (or task) opens the idea space for the student, there will be more resources to draw on, more inferences and associations and a better chance of constructing meaning that is applicable at a more general level. Thus, reflection will more likely involve meaningful engagement with specific elements associated with scientific reasoning.

Therefore a key task is to identify and understand what impacts the size of the idea space. The following is not meant to be an exhaustive list but an indication of the types of factors that impact the idea space.

- Conceptual Metaphor
- Language (voice, audience)
- Framing
- Attitudes/fear

As can be seen these range from issues central to cognitive science/linguistics to socio-cultural considerations. While the PER literature often deals separately with one tradition or the other, each productive frameworks offers different insights, and they merge at this critical juncture of opening students' space for drawing on productive resources. We will address each of these factors below.

Conceptual Metaphor

Over the past two decades cognitive linguistics has shown convincingly that metaphor is not merely linguistic but both deeply conceptual and embodied [10,11]. In short, the way we think about abstract domains depends on (source) metaphors that are usually grounded in bodily experience and are then mapped in both simple and complex ways to a new (target) domain. For example, the notion of data is central to experimentation and the way it is processed and turned into knowledge is a cornerstone of science. Over several years work that has been carried out at the University of Cape Town in collaboration with the University of York (UK) in this area has indicated deep differences in the way students think about data and how addressing these issues can significantly improve student understanding (see for example recent references [12,13].

To demonstrate the principle, consider the following example: you have collected a number of wooden beads of different colors and are now asked to produce an 'average color' bead from this collection. It

is clear that "applying the formula for the average" is problematic as whatever the result may be thought to be there is no bead that can be produced that will correspond to this outcome. Operations are constrained to identifying discrete colors, to counting how many of each color there are, and to being challenged about what single-colored bead best represents the group. The conflict between the question posed and the metaphor causes the answerer to be uncertain about how to proceed or if forced to proceed to do so having to abandon sense-making. Consider, instead, that the beads in question are made of soft clay. In this case creativity quickly takes over and the idea of blending all the clay together and then <u>creating</u> an 'average bead' of the same size as the original beads provides a logical answer. Questions such as "calculate the uncertainty" can easily be mapped onto the clay-bead metaphor while the wooden-bead metaphor poses rather difficult problems if the answer expected is to be judged according to the usual rules for data analysis in the freshmen laboratory!

Language: the role of audience

At the University of Cape Town and Oregon State University we have conducted experiments to understand the role of audience in student writing [14,15]. In the latter experiment we found that writing is highly dependent on the student's perceived audience. In the former experiment, this effect was explicitly studied by designing an instrument asking students to report on the results of a posited measurement task to three different audiences, namely, their instructor (lecturer), a laboratory write-up, and an intelligent friend who knows mathematics but has not studied physics (Bugs). In the instrument a specified mass of powder is purported to be weighed out by the student in question who having achieved the specified mass on a particular scale then proceeds to check the mass of the sample on five similar scales, providing 6 different readings. The instrument then requests the student to state what they would report regarding the mass of the sample.

- *"What would your words to the lecturer be"?*
- *"What would your words to Bugs be"?*
- *What would you write down in a report?*

It was found that in a sample of 50 students only 13 students reasoned in the same way across all three audiences. More surprisingly, student answers matched more between Bugs and the laboratory report than they did when the audience was the lecturer. A selection of students was interviewed to understand why they reported differently to different audiences. An excerpt from one interview quote explains our finding:

> **"**…because when I speak to the lecturer I don't say everything. I stand to be corrected. I don't want to come across as if I know it and whatever. I want him to sort of push me… give me a nudge in the right direction… but if like a friend comes to me I be like ok I also know something about unc..standard uncertainty and whatever and what not and that kind of thing….so if I'm speaking to a lecturer and my friend it will be two totally different answers".

Of particular note is her statement "I stand to be corrected" the import of which is to close the idea space. We elaborate further on this aspect from the perspective of the dynamics between a questioner and an answerer and the exchange of knowledge and information.

Knowledge/Information Flow: fun or fear

We start here by noting that a question whether it be directly asked in a face to face situation or whether it is implicit in a task involves an Answerer [A] - Questioner [Q] System. We define "Downhill" K/I flow as going from [A] who knows more to [Q] who knows less. This is a normal situation, such as when a child asks a parent to explain a phenomenon. The child is curious, and the parent is perceived to know more, so the parent [A] welcomes the opportunity to share what they know with their child [Q]. The converse, "Uphill" K/I flow is a judgmental situation. In this case, knowledge goes from [A] who knows less to [Q] who knows more AND will pass judgment on [A] based on the given answer. This can be realized in a fun situation, such as a quiz show, where [A] enjoys trying to earn positive judgment from [Q]. However, for many students this represents a fear-based situation which is typical of tests and examinations. In the table below some of the attributes and attitudes that accompany the triggering of the two modes (downhill and uphill) of knowledge or information flow are contrasted from the perspective of the Answerer.

TABLE 1. Details of K/I Flow

Downhill K/I Flow: "Normal" for [A]	**Uphill K/I Flow: "Judgmental" for [A]**
I am the expert	I am the novice
I know more	I know less
I feel good/warm	I feel nervous/fearful
I could be regarded more highly	I could be judged badly
Low social stakes	High social stakes
OPENS THE IDEA SPACE FOR THE ANSWERER	CLOSES THE IDEA SPACE FOR THE ANSWERER

It is clear from Table 1 that the Answerer who perceives a "normal" knowledge flow situation is not, on the whole, likely to have a negative experience as opposed to the uphill situation where strong negative emotions can be experienced.

EXAMPLE

We propose that the IDEA SPACE formulation gives simple yet very powerful messages about how to reform laboratory tasks. Consider two ways of formulating a standard physics lab. In one case, the students are asked: find the (accepted) value of 'g'. In this fairly standard lab, students are put in an uphill flow, they are expected to find a value that matches the authoritative value and their work will be judged strictly on whether it matches (is right) or not. The same lab could be given as follows: the university astronomers club is troubled by the fact that their apparatus used to measure 'g' gave a value in disagreement with the standard accepted value. Investigate the apparatus and report back to your peers in the astronomy club regarding their findings. Here students are put in the downhill flow.

Traditional labs typically include the following steps:

- Aim: to show / prove / verify / establish / find a well known law / principle / constant
- Method: series of instructions / steps / (recipe)
- Results: successful or not? [right or wrong]
- Conclusion: the aim was / was not achieved

There are meta-messages in this standard formulation of lab tasks:

- There are authoritative laws, constants out there.
- Replication = success (right)
- Non-replication = failure (wrong)
- Reinforcement of the dualist regime in the Perry Scheme of thinking [3]
- Message leads to a "SMALL IDEA SPACE"
- Critical Thinking requires a "BIG IDEA SPACE"
- Idea Space related to "size" of meaning constructed.

These messages are not present in the revised lab.

Concluding Remarks

Laboratory investigations should lend themselves to enhancing scientific thinking but there is little evidence that traditional labs achieve this. The way in which traditional tasks are formulated closes down the "idea space". Factors affecting the size of the idea space include e.g. metaphors for data, aspects of language (such as audience) and the perception of whether or not the situation in terms of knowledge flow is a threatening one from a socio-cultural perspective. The present analysis is offered as a tool for applying to formulations of tasks in order to judge whether or not the formulation can lead to enhancing scientific thinking.

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