Do Our Words Really Matter? Case Studies From Quantum Mechanics

D. T. Brookes, E. Etkina

Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Rd, Piscataway, NJ, 08854

Abstract. To understand the role of language in learning physics, we will treat it as one possible representation of a physical model. We will then present a theoretical framework that enables us to identify physical models encoded in language. We will present data showing that physicists use linguistic representations to reason productively about physical systems and problems. We will also present a case study and supporting evidence to argue that these linguistic representations are being used and applied by physics students when they reason. Sometimes students misapply and overextend these linguistic representations. This study allows us to understand and account for some student difficulties.

INTRODUCTION

What do students do when they learn physics? Lemke suggested that students primarily practice *representing* ideas. They encounter many different representations of physics knowledge: graphs, equations, tables, pictures, diagrams, and words. These representations of physics ideas are each by themselves incomplete. It takes an act of assimilating, coördinating, and moving easily between many different representations in order to create understanding. The first ability students have to develop is the ability to represent ideas and move between representations. Lemke suggests that students do not interact with knowledge, but interact with representations of knowledge [1]. In this paper, we want to examine the role of one particular representation, namely words, either written or spoken.

Sutton has suggested that physicists speak in *metaphors* that encode *analogies* [2, 3]. For our purposes we will define an analogy as a comparison between two different conceptual systems where the limitations of the comparison are made explicit. A metaphor is a similar comparison, but made as a statement of fact. When a person uses a metaphor unconsciously, she/he may not consider the limitations of the comparison. The idea that language is made up of a system of unconscious metaphors was systematized by linguists Lakoff and Johnson and gave birth to the field of cognitive linguistics. Cognitive linguistics will form the theoretical framework of our analysis [4].

For example, Schrödinger based his wave equation on an analogy to geometrical and wave optics. Now physicists often talk about "*diffraction* of electrons" and "the *wave* function of the electron". The language suggests a metaphor, THE ELECTRON IS A WAVE, without making the underlying analogy (its applicability and limitations) explicit. Physicists are definitely aware that what they say may have the potential to mislead and confuse students. (See, for example, [5, 6, 7, 8, 9, 10, 11].) Much of this research has been focused on students' difficulties with the vernacular of physics. Our aim is to extend these ideas and build on Sutton's work by looking more closely at the role of metaphors in physics. (See Hypotheses and Methodology.)

Our research questions are (1) how does language function as a representation of knowledge in physics, and (2) how may students be using and misusing linguistic representations when they reason? To answer these questions we will use data from three sources. To answer question (1) we will study language in Quantum Mechanics (QM) textbooks and interviews with professors talking about QM. To answer question (2) we videotaped a student study group working on QM homework problems.

HYPOTHESES AND METHODOLOGY

If we consider language to function as a representation of a physical model, then what is it representing and what is its role as representation? We suggest the following:

1. Cognitive linguists have hypothesized that language is comprised of systems of metaphors. We will apply this hypothesis to the language used to describe ideas and models in physics. We will attempt to identify systems of metaphors that physicists use when they talk and write about physical systems.

2. Sutton has already suggested that metaphors encode analogies. On the basis of our study of physicists talking about QM, we take this further by suggesting that metaphors encode two types of explanatory analogies: analogies currently used in the practice of science (e.g., the *wave* model of QM particles), and defunct analogies (e.g., the *planetary* model of the atom). Metaphors also encode descriptive analogies that do not explain a phenomenon (e.g., the POTENTIAL WELL metaphor, which is the central example of this paper). Such descriptive metaphors function as ways of conceptualizing and talking about physical systems.
3. On the basis of the evidence presented below we hypothesize that metaphors encode productive modes of reasoning. We observed that physicists use metaphors, rather than analogies, when they speak and reason productively about familiar physical systems. The applicability and limitations of these modes are well understood by the physics community, but are seldom made explicit.
4. While physicists seem to be able to use linguistic representations as metaphors productively, Sutton has suggested that students might take metaphors literally and miss limitations and applicability of metaphorical systems. Possibly some of students' difficulties may be explained as difficulties interpreting metaphors used by physicists. Because metaphors appear as statements of fact (a statement of "is" rather than "is like") they obscure the original analogy that had specific limitations and applicability. Thus part of learning physics involves a process of exploration where students will necessarily over-extend and misapply the metaphorical systems they hear and read when reasoning about physical systems. If this idea is correct we expect to see examples of such over-extension and misapplication when analyzing students' discourse. In other words, instances where they take the metaphorical language, interpret it as "literal" and apply the literal interpretation to solve a problem.

To identify instances of a particular metaphor in language we will use the *base* space of the analogy (a term coined by Gentner [12]) as the basis for identifying the presence of a metaphor in language. For example, if we consider the metaphor THE ELECTRON IS A WAVE, the *base* space of the original analogy is wave optics, which uses terms such as "diffraction", "polarization", "wave", "frequency", "wavelength", and so on. (The base space itself can be identified by analyzing the writings of the analogy's progenitor. In this case, Schrödinger elaborated the analogy in his second paper on the wave function [13].) The following is an example of how this analogy transformed into a metaphor in the language of physicists: "You send in *polarized* electrons to the left and you send them into a Stern-Gerlach apparatus. . . " (Prof. C. from our interview study).

RESULTS AND ANALYSIS

Metaphors in QM: Role and Function

In our analysis of physicists talking about QM, we used the tools of cognitive linguistics to identify many coherent metaphorical systems in use. The example considered in this paper is the POTENTIAL WELL metaphor. In our framework, this metaphor encodes a descriptive analogy between potential energy graphs *(target)* and a water well or bucket of water *(base)*.

Original Descriptive Analogy

> "Because of the Pauli exclusion principle, the electrons must be spread over the available states; but they settle down to the states of lowest energy, so that as more electrons are added, the energy levels in the band fill up like a bucket fills with water." [14]

In this example Peierls makes the analogy explicit. The way he uses it shows that this analogy has a descriptive role.

Modern Language

When physicists speak of "potential *well*" and "energy level", they give energy an existence as water. When physicists speak about quantum particles "*leaking* through a barrier", they give the quantum particles an existence as water. When physicists speak of a "potential *well*", "potential *step*", "potential *barrier*", "confinement", "trap" etc. . . they give the potential energy graph an existence as a physical object. According to Lakoff and Johnson, metaphorical systems are comprised of one or more *ontological* metaphors that endow the concepts described by the metaphors with an existence [4]. (Ontology is the study of the nature of existence.) From the language examples above, we can identify two ontological metaphors: (1) ENERGY/QM PARTICLES ARE WATER, (2) THE GRAPH IS A PHYSICAL OBJECT OR CONTAINER. Together, these two ontological metaphors constitute a metaphorical system that we shall call the POTENTIAL WELL metaphor. This system refers not only to these two metaphors, but also to any metaphors built on this ontology, grounded in the notion of the graph as a physical object.

Productive Modes

We have observed physicists reasoning productively with this system of metaphors. From the discourse of professors and textbooks we identified the presence of many productive modes for the POTENTIAL WELL metaphor. These productive modes can be used to reason about physical situations or simply represent *ways of talking* about physical systems. We present three examples:

1. The notion of squeezing the walls of the well forces the water upwards, thereby raising and spacing out the "energy levels." Prof. A: "... when you have a confined system, ... [the momentum of the particle is] going to set the scale for what ... the magnitude of the energy is, *so as you confine it more and more, your zero point energy is going to go up and up.*"
2. The idea of water taking up space and filling up the well/bucket can be used to understand the behavior of fermions. We already observed Peierls make this analogy explicit [14]. The following is an example of Prof. B. using the mode metaphorically: "if you have fermions then... you have to keep *stacking the fermions into levels which get more and more elevated in energy* ... "
3. The idea of the potential energy graph behaving as a physical container or barrier preventing the escape of the particle leads to the ideas of "tunneling" or "leaking". In describing α-particle decay, Feynman et al. write: "This is called the quantum mechanical '*penetration* of a *barrier*.' " Later when describing how it happens to the α-particles, they write: "... they start out with the energy *E inside* the nucleus and *'leak' through* the potential *barrier*." [15]

Student Difficulties

A study group of four junior physics majors in their first QM course, agreed to be video taped while working on problems. This problem was from French and Taylor[16]. The question can be paraphrased as: "Suggest classical wave analogs of an electron beam scattering off a potential down step." Notice here the POTENTIAL WELL metaphorical system serving a specific function: namely, it describes the shape of the potential energy graph ("potential down step").

> S1: Well, there wouldn't be reflection in particle physics on a down-step right? Or even, I don't think even on an up-step...
> S3: No, there's reflection on an up-step, total reflection.
> S1: Not classical though, right?
> S2: Not if its less than the energy though.
> S1: It just slows it down.

In this opening exchange we can observe S1 talking at cross purposes with S2 and S3. S2 and S3 seem to be imagining a classical particle approaching the step and bouncing back (later dialogue show that they do not really shift from this literal view of the situation), while S1 seems to be thinking of a wave approaching with energy greater than the energy of the step. As we see later, S1 is reasoning from a picture of a surface water wave passing over a step in a river or sea bed.

> S1: Not quite sure what the wave analogs would be. If I had to guess I'd say it would be like sound, like those things that male cheerleaders have, like big cones.
> S4: Megaphones?
> S1: Yeah. 'Cause I think, you know,... basically a step up or step down in resistance. But I am not quite sure what we are supposed to say about that.

This is the first example of an analog from S1. It is interesting that S1 sees the key as a change in resistance, yet he still is the one who proposes a physical form (consistent with the ontology of the graph as a physical object) surrounding the medium rather than a change in the medium itself (which would represent a more obvious change in resistance for the wave).

> S2: So they're saying that there would be reflection on a potential up-step like a...
> S1: Yeah, just like a sound, or a water wave or something.
> S1: Um, well 'cause I know on a potential up-step,... like if you just had... water and you had, you know, deeper part and a shallower part, and you had a wave, some of it would reflect back.

Here S1 misapplies the metaphor of a physical object again and proposes a second analog based on the physical form of the graph rather than a change in "density" or "tension" of the medium. Actually a physical step on a river bed could be a valid example if S1 connected it to a model of how the resistance experienced by a surface wave attenuates with the depth of the water. He does not, and this explains his uncertainty below.

> S1: So that's not too hard to see. But like, I would guess that the same thing would happen if you had a down-step, but that's not something like I really, I could vouch for. Like I think they're looking for stuff that like most people know.
> S2: Is that what it's saying? Its coming at it

with every energy, like continuous energies, like around the step?

S2's statement is interesting. The use of "at" and "around" are examples of grammatical *location* and suggest the metaphor: THE STEP IS A PHYSICAL OBJECT. S1 shows he is still on the right track when he says:

S1: I think they're just asking for like, examples from... in real life from when a wave... goes into a space of less resistance and has reflection back.
S4: So in classical what would happen at a potential down-step?
S1: A potential down-step?
S2: It would just keep going...
S1: ...It would just speed up. At a potential up-step it would just slow down.

DISCUSSION AND CONCLUSION

One alternative hypothesis to explain the difficulties presented above could be that the students are unable to interpret the physical meaning of the potential energy graph or are simply not understanding the situation. However, S1's ability to interpret potential energy graphs correctly (S1 sees that the potential step corresponds classically to a change in speed of the particle) and articulate the key to the analogy discounts this hypothesis. The data shows that his inability to come up with a productive analog must be based on other factors. Our framework explains how S1 is distracted by applying an overly literal interpretation of the POTENTIAL WELL metaphor in an inappropriate situation. We see that a way of talking (i.e., describing the potential graph as a "step") seems to be interacting with students' reasoning. Our analysis shows that the students in this group are searching in the category of "physical objects" for an analogy, in accordance with the underlying ontological metaphor THE POTENTIAL ENERGY GRAPH IS A PHYSICAL OBJECT rather than searching in a more productive category.

As a control we posed the same problem to professors in the interview study. They all responded that an analogy of an electron beam scattering off of a potential down step is light traveling from a medium with greater index of refraction to a medium with a lesser index of refraction. When asked why changing media was a good analog, most were unable to explain, but continued to elaborate their answer. Only one professor was able to explain why this was a good analogy. "I know because we've thought about these things before and its just been classified in that category." (Prof. E.) We see from this statement that physicists are able to search for an analog in a category of analogous *processes* rather than analogous *objects* [17]. Our data indicates that physicists are able to make the distinction between the process (the event itself) and the medium (object/matter) in which the process occurs.

We have shown how physics professors can use metaphorical systems to reason productively in certain situations while students take the same representation and apply it too literally and inappropriately in other situations. Strange ideas like the megaphone make sense if we understand the underlying ontology of the graph, spoken of as a physical object. We think that the example of student discourse presented above is a typical example of students' difficulties arising from linguistic representations. If teachers are unaware of the difficulties students experience interpreting our metaphorical language, it leaves them less able to understand, interpret, and facilitate student learning.

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