Investigating the Proposed Affordances and Limitations of the Substance Metaphor for Energy

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Abstract: This study explores the proposed affordances and limitations of the substance metaphor for energy in the context of a computer simulation that illustrates processes of energy transfer and transformation. We examine data from eight interviews conducted with introductory physics students as they used the simulation. We empirically explore the hypotheses that (i) student and (ii) instructional use of the substance metaphor promote specific affordances, such as energy conservation, transfer, and localization, and specific limitations, such as locating potential energy in a single object and appropriating material qualities to energy. We find that the frequency of both affordances and limitations increases when the simulation embeds an explicit substance metaphor and that the affordances and limitations more often co-occur with students' substance metaphor use. However, in all cases, the number of instances of affordances is greater than that of limitations, which suggests that the substance metaphor is beneficial to instruction and student discourse.

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INTRODUCTION

The substance metaphor for energy is the subject of much discussion and debate in the literature [1]. In particular, some researchers argue that learners naturally tend to embed new physics ideas into an already-developed substance ontology [2,3]. This is a cause for concern for researchers who claim that many physics concepts belong to an ontologically-distinct category from material substances and that supporting this ontological mismatch may lead to misconceptions [4]. For example, embedding energy, a purely mathematical quantity [5], in a substance ontology may compromise learner understanding. Proponents of this argument highlight the following limitations of the substance metaphor for energy [1, 5,6]:

(i) Energy does not share all qualities of substances (*i.e.*, having mass, volume, or being affected by Newtonian gravity)
(ii) Potential energy is not located in a single object
(iii) Energy is frame-dependent
(iv) Energy can be negative

This line of reasoning implies that the substance metaphor should be avoided in instruction on concepts like energy, lest misconceptions result.

Other researchers argue that both experts and novices use the substance metaphor for energy, and productively so [6-9]. These authors claim that the advantages of the substance metaphor, including that:

(a) Energy is conserved
(b) Energy transfers among objects
(c) Energy is localized, even if spread out
(d) Energy can be located in objects
(e) Energy can change form
(f) Energy can accumulate in objects

outweigh its limitations and that this metaphor may in fact be necessary for describing certain attributes of energy [1,6]. This line of reasoning implies that energy instruction should intentionally embed the substance metaphor in order to capitalize on its affordances [9].

The literature proposes these affordances and limitations theoretically, as logical extensions of the metaphor itself. This paper begins to empirically explore these proposals in the context of interviews with introductory physics students as they interacted with the "Energy Forms and Changes" (EFAC) PhET simulation (phet.colorado.edu), which has the option to show a substance-like representation of energy and is therefore particularly well-suited to the exploration of hypotheses about the substance metaphor for energy. We particularly look for confirming and disconfirming evidence for the hypotheses that (I) instructional tools that explicitly embed the substance metaphor for energy and (II) student use of the substance metaphor for energy promote the particular affordances and limitations described above.

ENERGY FORMS AND CHANGES PHET SIMULATION

The EFAC PhET simulation models a system in which energy is transferred between objects and changes form within objects. The simulated system is comprised of a source of energy (*e.g.,* the sun), an energy converter (*e.g.,* a solar panel), and a receiver of energy (*e.g.,* a light bulb). Students may select among sources, converters, and receivers using buttons at the bottom of the screen. The key feature of the simulation for our investigation is the "energy symbols," small blocks that move through the system as energy is transferred and that change color as the energy is transformed. The symbols can be turned on or off by checking a box in the simulation.

INTERVIEW METHODS

The participants in this study were recruited from Seattle Pacific University's first-quarter calculus-based introductory physics course. Eight students, representing a range of course grades and backgrounds, were individually interviewed as they used the EFAC simulation. This sample was one of convenience; students self-selected to participate in interviews rather than complete a similar homework assignment. Such a sample is appropriate for the purpose of exploring whether the assumption that the substance metaphor logically promotes certain affordances and limitations bears out. In the interviews, students were instructed to explore the features of the simulation, but they were asked not to check the box labeled "energy symbols." After several minutes of questioning without the symbols, students were instructed to turn on the symbols.

Interviews were semi-structured; questions were largely based on individual student responses to the simulation and varied from interview to interview. Questions asked before the symbols were turned on included: (i) Can you describe the process of heating the water/lighting the light bulb? (ii) What kinds of energy are involved and what is your evidence for them? (iii) How would you describe energy based on the sim? Questions asked after the symbols were turned on included: (iv) What do you think the energy symbols represent? (v) Can you say anything quantitative about energy in the simulation? (vi) How would you describe energy based on the sim?

INTERVIEW ANALYSIS

We coded student interviews for (i) instances of students' substance metaphor use and (ii) instances of each affordance and limitation defined in the Introduction. In the tradition of similar physics education research studies on metaphor use [6,10,11], we assume that the structure and content of students' discourse constitutes evidence for the metaphors they are using and provides insight into their understanding of energy. Student statements referring to energy as "in" an object, to an object as "having" energy, to energy as "transferred" or "released from" objects, or similar treatment of energy as a material substance were coded as instances of substance metaphor use. Student statements reflecting the particular affordances and limitations articulated in the Introduction were coded as instances of these. A single phrase or sentence often expressed more than one category of affordance or limitation, or more than one instantiation of the substance metaphor. In such cases, a single statement or sentence received more than one code (or count, in the case of metaphor use). Transcripts were coded separately by the two authors, and their minor differences were resolved by discussion. Example student statements follow, listed by affordance or limitation code (instances of substance metaphor language are italicized):

<u>Affordance (a)</u>: "It's conserved…they just don't disappear."

<u>Affordances (b), (c), and (d):</u> "…So *it starts here, then transfers to there, the wheel transfers its energy to this thing*…"

<u>Affordance (e):</u> "It turns into electrical energy and then heats up the water and becomes thermal energy."

<u>Limitation (i):</u> "...mechanical energy, *when it hits*, um, what is this called? Water wheel?"

<u>Limitation (ii):</u> "… you can't really put a number on the amount of potential energy someone *has*."

Three questions emerged from our exploration of the hypotheses proposed in the Introduction:

Question 1: Does use of an instructional tool that embeds the substance metaphor for energy promote particular affordances and limitations? If so, we expect the frequency of both affordances and limitations to be greater *after* the energy symbols are turned on than before. To explore this question, we counted the number of occurrences of each affordance and limitation across participants (1) before and (2) after the symbols were turned on. Numbers were normalized according to the time spent in interviews before and after the energy symbols, giving a frequency.

Question 2: Does student use of the substance metaphor promote particular affordances and limitations? If so, we expect that both would more often co-occur with substance metaphor language than without. To explore this question, we compare the number of instances in which an affordance or limitation occurs concurrently with substance language to the number that occur without use of such language.

Question 3: Do we see plausible qualitative connections between (1) hypothesized causes (use of the simulation with the symbols on and student use of the substance metaphor) and (2) hypothesized effects (specific occurrences of affordances and limitations)? To explore this, we attended to the content and timing of student utterances, looking for confirming and disconfirming evidence of possible causal connections.

RESULTS

We separate the results according to the questions we articulated in the previous section:

Result 1: Does the frequency of affordances and limitations increase after the energy symbols are turned on? With the exception of energy transfer [(b)], the frequency of all **affordances** increased when the energy symbols were turned on (Fig. 1). We note that the increase in average frequency of conservation [(a)], localization [(c)], and transformation [(e)] was especially prominent. These results suggest that the energy symbols promote affordances (a) and (c)-(f).

Both **limitations** (i) and (ii) increased in average frequency from before the introduction of the energy symbols to after (Fig. 2). We note a pronounced increase in the average frequency of limitation (i)—attributing material qualities to energy—and a much smaller increase in limitation (ii)—locating potential energy within an object. There were no instances of limitations (iii) and (iv) – treating energy as frame-dependent or responding as though energy cannot be negative. The frequency of every limitation is lower than the frequency of affordances (a)-(e), both before and after the energy symbols were turned on. Thus although there do seem to be some limitations associated with the presence of the energy symbols, these are outnumbered by the affordances.

Result 2: Do the affordances and limitations more often co-occur with substance metaphor language? Language about transfer, localization, and location in objects more often co-occurred with substance metaphor language than without (Fig. 3). For example, one student said: "We physically see that there are *energy units going out into the atmosphere* [affordance b, d]… I can maybe even calculate how much energy is lost here, or how much *energy that I put in from here* is really going into here [affordance b, c]." (Substance metaphor language italicized.) In contrast, language about energy transformation more often occurred in the absence of substance metaphor language, such as in statements like: "…this mechanical is turned into electrical and electrical is turned into thermal." Language about energy conservation was just as likely to occur with substance metaphor language as without. The low number of instances of affordance (f) makes a pattern difficult to distinguish.

Limitations (i) and (ii) more often co-occurred with substance metaphor language than without. However, the discrepancy between instances of limitations with substance language and without is smaller than that for affordances. For example, while there was approximately one more instance per student of limitation (i) with substance metaphor language than without, there were approximately seven more instances per student for affordance (c) with substance metaphor language than without. Thus, although there do seem to be limitations associated with substance metaphor language, the affordances outnumber them.

Result 3: Is there qualitative evidence to support the conclusions we might draw from frequency counts and instances of co-occurrence? Qualitative evidence from our interviews further corroborates our sense that

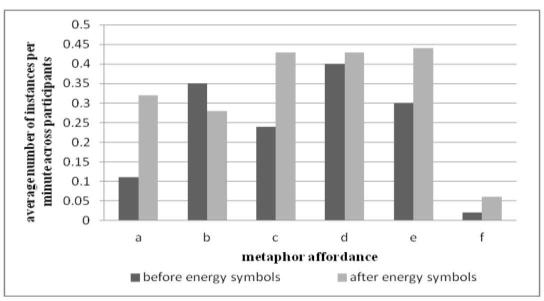

FIGURE 1: Average frequency of each affordance before and after energy symbols were turned on.

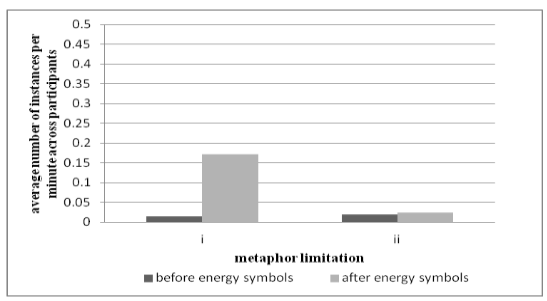

FIGURE 2: Average frequency of each limitation before and after energy symbols were turned on.

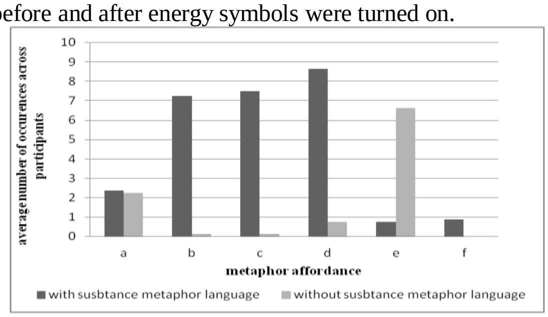

FIGURE 3: Occurrence of individual affordances with and without substance metaphor language.

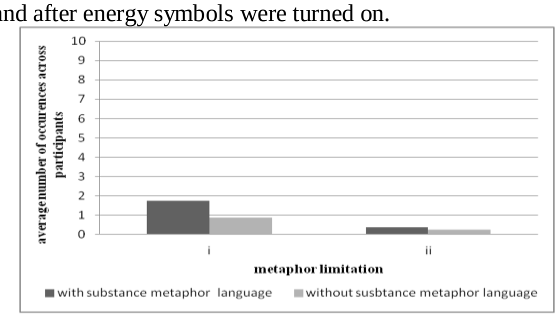

FIGURE 4: Occurrence of individual limitations with and without substance metaphor language.

the explicit embedding of the substance metaphor promotes affordance (a). We see this in the *timing* of student statements – several students discussed conservation of energy *immediately* after turning on the symbols – and in students' articulation of what the symbols represent – chunks or units of energy that are not spontaneously created or destroyed. Thus, the energy symbols may prompt thinking about conservation of energy, as in the following dialogue:

> **Interviewer:** …Do you think that they [the energy symbols] help you like describe the concept of energy to someone in any way?
>
> **Student:** I think they do...that I guess shows the transfer from one type of energy into another, and I guess it seems like it's conserved... I mean you do lose some, there still remains like energy forms…it shows the transfer…it remains, the amount of energy being used, but in a different type of energy.

Most of the limitations that emerged during the interviews were connected to the attribution of material qualities to energy. Yet many of the students qualified their statements by saying that they did not actually think of energy as a tangible "thing," or by arguing that energy can really only be described in an abstract way. One student repeatedly referred to energy as "molecules" after the energy symbols were turned on; however, when asked what the energy symbols represented, she responded, "not molecules! Um, how about units of energy?" The same student said, "Now I can see that there's certain molecules of energy, or not molecules!" While both of these statements were coded as limitation (i), clearly the student is not associating the energy symbols with actual molecules. Statements such as "I don't really think of energy as a tangible thing," and "[Energy is] not actually like physical... it's not a physical object but an amount of…work being done or something that can be transferred," show that students were conscious of the immaterial nature of energy despite the metaphor they used. In other words, the content of their speech suggests that the substance metaphor does not cause students to attribute inappropriate material qualities to energy.

CONCLUSIONS

Previous literature on the use of the substance metaphor for energy suggests that instruction that embeds this metaphor logically promotes certain affordances and limitations. Based on our exploratory study, we find that embedding a substance metaphor in an instructional representation for energy coincides with an increase in the likelihood that students discuss certain attributes of energy, especially conservation. Moreover, students often mentioned that the energy symbols employed by the EFAC simulation illustrated conservation of energy. We also observe that turning on the symbols in the EFAC sim coincides with an increase in the frequency of limitations, but the frequency of limitations is much lower than that of affordances, and we do not see a noticeable difference in the numbers of limitations that co-occur with substance metaphor language and those that do not. Furthermore, students' qualification of their use of substance language suggests that they are aware of the limitations of this metaphor.

Our analysis thus paints a more complex picture than treating specific affordances or limitations as logical extensions of the use of the substance metaphor. The relative frequency of affordances and limitations suggests that this metaphor for energy may be more helpful than harmful; however, our small sample size and sampling technique limits our ability to make population-level claims. Our qualitative evidence also raises questions about whether or not the limitations proposed in the literature are truly evidence of compromised learner understanding; students who attributed material qualities to energy often qualified their statements by reflecting on its abstract nature.

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