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Lisa Goodhew
Seattle Pacific University

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INVESTIGATING THE PROPOSED AFFORDANCES AND LIMITATIONS
OF THE SUBSTANCE METAPHOR FOR ENERGY

by

LISA GOODHEW

FACULTY ADVISOR, AMY ROBERTSON

SECOND READER, STAMATIS VOKOS

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Approved _____

Date _____

ABSTRACT

This study explores the instructional advantages and disadvantages of representing energy as a material substance; this is done in the context of a computer simulation that illustrates processes of energy transfer and transformation. These affordances and limitations have been proposed in science education literature as extensions of the substance metaphor itself, but there is little empirical evidence to support them. This study is intended to provide preliminary empirical evidence for these affordances and limitations. We examine data from eight interviews conducted with students from Seattle Pacific University's introductory physics classes as they used the simulation. We explore the hypotheses that (i) student and (ii) instructional use of the substance metaphor promote specific affordances and limitations mentioned in the literature. We compare the language used and the affordances and limitations demonstrated by students as they interact with two forms of the simulation: one with an explicit substance metaphor and one without.

INTRODUCTION

“There is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same...Since it is an abstract idea, we shall illustrate the meaning of it by an analogy.” –Richard Feynman, *The Feynman Lectures on Physics*

One possible analogy for energy is that of a material substance. For example, we often talk about energy “in” gasoline or the energy that a person might “have.” With this kind of language, energy is modeled as a tangible thing. The consequences of using this analogy in instruction have been debated in the literature on the subject: there are those who contend that energy is fundamentally different from a material substance and representing it as such will only lead to misunderstandings, and there are others who contend that the substance metaphor can be used quite productively in instruction. The study of how best to teach the concept of energy in classrooms is the focus of Seattle Pacific University's Energy Project; the Energy Project's research suggests that there is pedagogical value in representing energy as a quasi-material substance. In light of these findings, the University of Colorado's PhET (Physics Education Technology) project has developed a computer simulation, “Energy Forms and Changes,” based on the representation of energy as a substance. This study investigates the affordances and limitations of this metaphor, as demonstrated by physics students, when it is used in such a representation of energy.

In one sense, the substance metaphor is just one of many possible ways to represent an abstract concept; in another sense it is unique because of the way it relates the abstract with human experience. One of the most obvious aspects of being human is that it involves being an embodied individual, and the analogy of a tangible object resonates with this essential characteristic of humanity. Perhaps this is why the literature reports that students naturally tend to describe abstract concepts in terms of material substances (Lakoff & Johnson, 1980). The substance metaphor may also be especially powerful because it enables the human mind to view an abstract concept in terms of the things it understands most deeply, its own lived experiences.

It is not only abstract physics concepts that I see the substance metaphor as a particularly powerful illustration for. Throughout scripture God manifests Himself to humanity in the form of something physical, be it a burning bush, a cloud of smoke, the Ark of the Covenant, or ultimately in the person of Christ. Is this not a glorious example of the substance metaphor? In light of the ideas about the substance metaphor that I have developed as a result of this project, I have gained new insights into the character of God. In His desire to develop a relationship

with humanity, God chose to make Himself known to us in a way that is most natural and accessible to the human mind. (Even here, I employ this metaphor by describing God as a “him”) Thus, “The Word became flesh and dwelt among us” (Jn. 1:14, RSV). My investigation of the substance metaphor in the context of energy has shown me a new beauty in the incarnation: what better way could God have used to communicate himself to us than through this metaphor?

To understand the world as profoundly wonderful is, I believe, part of the task of the Christian scholar. Through this project I have developed a new appreciation for the complexity of people’s thoughts and ideas and a deeper understanding of how I think. At the same time I have gained a new perspective on the incarnation of Christ which has enriched my faith. Each of these things have increased my conviction that the world is truly a wonderful place. I see this as an example of how faith and reason feed into each other, more closely resembling two sides of a seamless whole than two separate entities. St. Augustine sums this up when he says, “Intellege ut credas, crede ut intellegas.” I seek both to understand in order that I might believe, and to believe in order that I might understand.

While my Christian perspective supports the substance metaphor strongly, I feel it is important to make clear that it was never my intention in conducting this study to prove that the substance metaphor is helpful for conceptualizing the abstract concepts in physics. It has been my aim to investigate the issue in a way that is faithful to the discipline, takes seriously both the advantages and disadvantages of the substance metaphor, and ultimately draws conclusions based on the empirical evidence offered by the investigation.

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

Lisa M. Goodhew and Amy D. Robertson

Department of Physics, Seattle Pacific University, 3307 Third Avenue West, Suite 307, Seattle, WA 98119-1997

Abstract: This study explores the proposed advantages and disadvantages 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 compare language used and affordances and limitations demonstrated by students as they interact with two forms of the simulation: one with an explicit substance metaphor and one without. We report that the frequency of affordances demonstrated is greater than the frequency of limitations in all cases. Frequency of affordances and of limitations increases with instructional use of the substance metaphor; certain affordances and all limitations occur more often with student use of the substance metaphor.

Keywords: conceptual metaphor, energy, PhET simulations

PACS: 01.40.Fk

INTRODUCTION

The substance metaphor for energy is the subject of much discussion and debate in the literature.¹ Some researchers argue that many physics concepts² belong to a category that is ontologically distinct from material substances and that supporting this ontological mismatch may lead to misconceptions. It has been argued that learners naturally embed new physics ideas into an already-developed substance ontology.^{3,4} If energy, being a purely mathematical quantity,⁵ is embedded into a substance ontology, student understanding may be compromised. Proponents of this argument highlight the following limitations of the substance metaphor^{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.^{6,7,8,9} These authors claim that the advantages of the substance metaphor, including that¹:

- (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.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. We particularly look for confirming and disconfirming evidence for the hypotheses that (I) instruction that explicitly embeds 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 were individually interviewed as they used the EFAC simulation. 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? The 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

The method of analysis we use is based on the perspective that the structure and content of students’ language gives insight into their understanding, a method common in literature on different metaphors and ontologies for energy in instruction.^{6,10,11} The interviews were coded for (i) instances of students’ substance metaphor use and (ii) instances of each affordance and limitation defined in the Introduction. 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 differences were resolved by discussion. Example student statements are as follows, listed by affordance/limitation code (instances of substance metaphor language italicized):

Affordance (a): “It’s conserved...they just don’t disappear.”

Affordances (b), (c), and (d): “...So it starts here, then transfers to there, the wheel transfers its energy to this thing...”

Affordance (e): “It turns into electrical energy and then heats up the water and becomes thermal energy.”

Limitation (i): “...mechanical energy, when it hits, um, what is this called? Water wheel?”

Limitation (ii): “... 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:

Hypothesis 1: If it is true that instruction that explicitly embeds the substance metaphor for energy promotes particular affordances and limitations, we expect the frequency of both affordances and limitations to be greater *after* the energy symbols are turned on than before. To explore this hypothesis, 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.

Hypothesis 2: If it is true that student use of the substance metaphor promotes particular affordances and limitations, we expect that both would more often co-occur with substance metaphor language than without. To explore this hypothesis, we compare the number of instances in which an affordance or limitation occurs concurrently with substance language to the number that occur without such language.

Hypothesis 3: If these two hypotheses are correct, we expect to 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 hypothesis, 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 hypotheses we articulated in the previous section:

Question 1: Does the frequency of affordances and limitations increase after the energy symbols are

turned on? Conservation, transfer, and localization are mentioned more frequently with the energy symbols present, while location in objects, transformation, and accumulation are not. For some students, the frequency of **affordances** increased with the introduction of the energy symbols; for others it decreased; for others the frequency remained essentially the same (Fig. 1). Individual affordances and limitations show different trends: some increased when the energy symbols were introduced and others remained fairly constant. The number of instances of affordances (a) and (c) tended to increase for all students; the frequency of affordance (b) increased for most students. The introduction of the energy symbols did not seem to have any noticeable effect on the frequency of affordances (d), (e), and (f). These results suggest that the symbols promote affordances (a), (b), and (c).

Although there do seem to be some limitations associated with the presence of the energy symbols, these are greatly outnumbered by the affordances. For every student whose talk included **limitations** of the substance metaphor, there was an increase in frequency from before the introduction of the energy symbols to after (Fig. 2). This was true for both limitations (i) and (ii); there were no instances of limitations (iii) and (iv). However, the frequency of limitations was much lower than the frequency of affordances for every student, both before and after the energy symbols were introduced. Students tended to demonstrate a total of less than five of each individual limitation, while they often demonstrated a total of 5-10 instances of each individual affordance in the time period after the

symbols were turned on.

Question 2: Do the affordances and limitations more often co-occur with substance metaphor language? The substance metaphor co-occurs with language about transfer, localization, and location in objects. Language about energy transformation, in contrast, is not strongly associated with the substance metaphor. **Affordances** (b), (c), and (d) were much more likely to co-occur with substance metaphor language than without during our interviews. (Fig. 3.) For example: “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, affordance (e) more often occurred in the absence of substance metaphor language, such as in statements like this one: “... this mechanical is turned into electrical and electrical is turned into thermal.” Affordance (a) 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 of limitation (i) for each student with substance metaphor language than without, there were approximately seven more instances per student for affordance (c) with

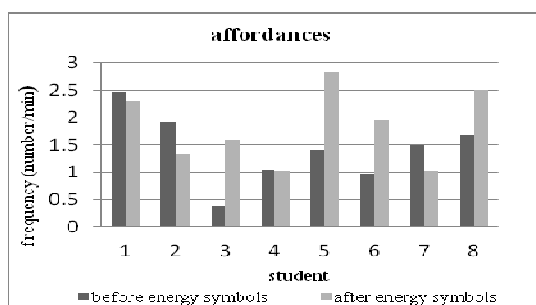


FIGURE 1: Frequency of affordances for individual students before and after energy symbols were turned on.

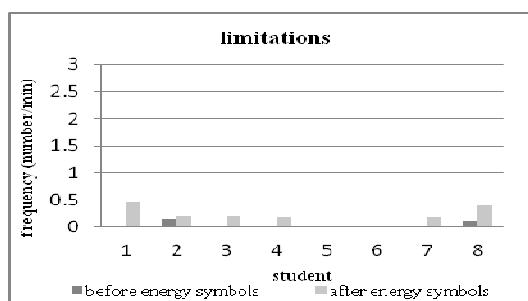


FIGURE 2: Frequency of limitations for individual students before and after energy symbols were turned on.

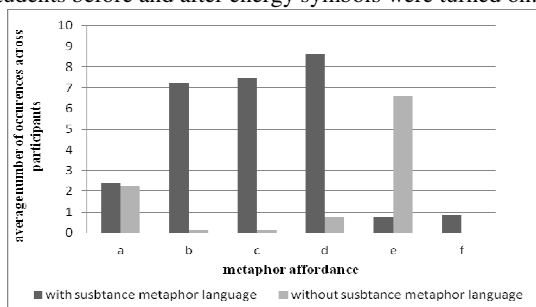


FIGURE 3: Occurrence of individual affordances with and without substance metaphor language.

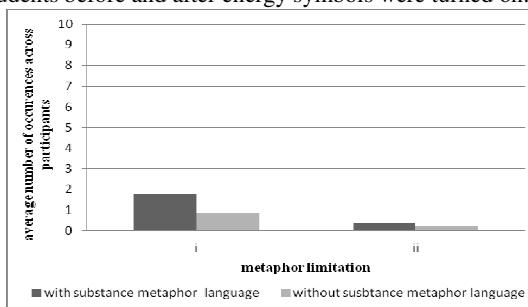


FIGURE 4: Occurrence of individual limitations with and without substance metaphor language.

substance metaphor language than without. Thus, although there do seem to be limitations associated with language about the substance metaphor, these are greatly outnumbered by the affordances.

Question 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 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 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 use of the substance metaphor for energy raises the question of whether or

not instruction that embeds this metaphor promotes certain affordances and limitations. Based on this 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. However, 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. The limitations associated with the substance metaphor, while real, occur much less frequently than the affordances. Furthermore, students’ qualification of their use of substance language suggests that they are aware of the limitations of this metaphor. We conclude that the substance metaphor is helpful for instruction and discussion, both in the representation used by the simulation and in the language used by students.

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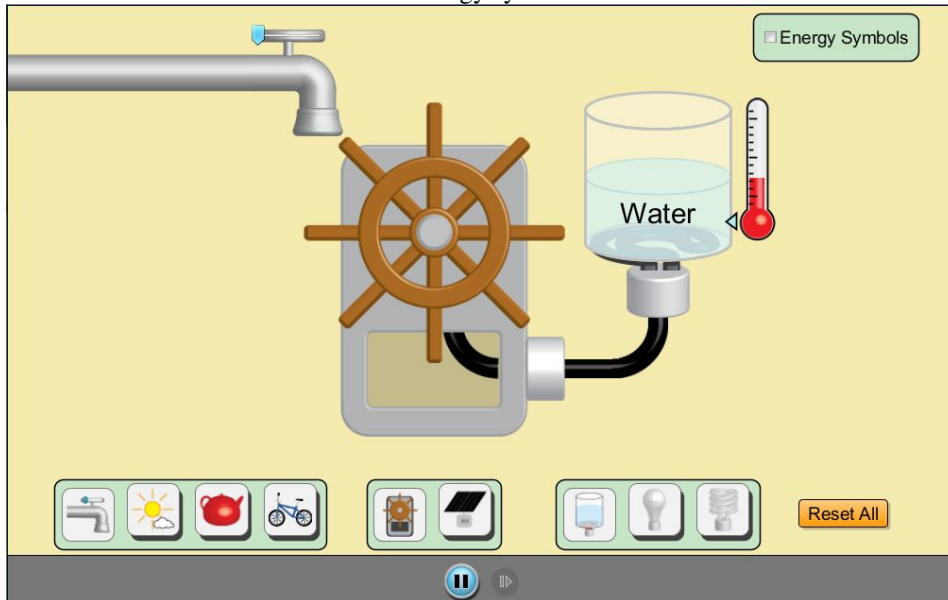
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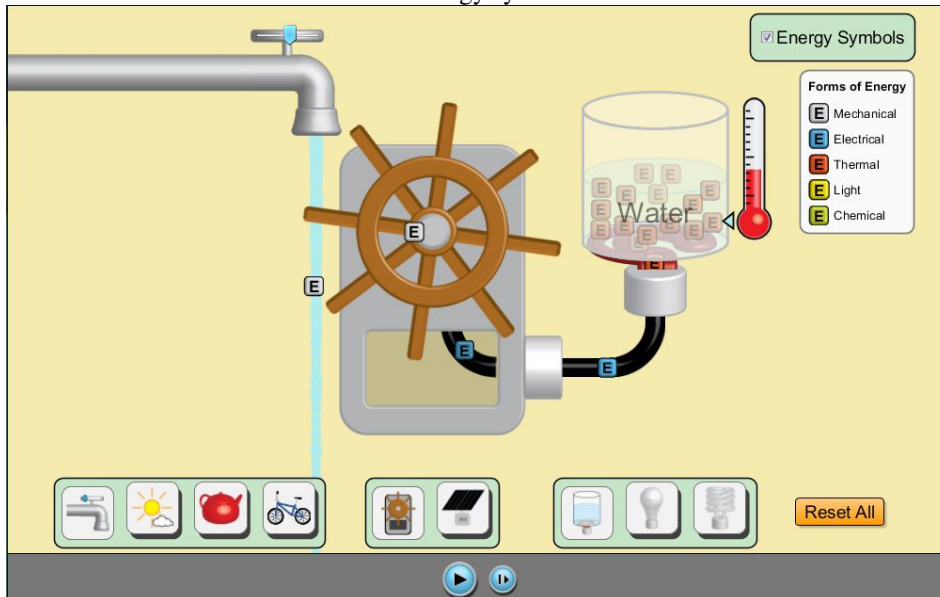
Appendix I: The Energy Forms and Changes Simulation.

These figures have not been included in the body of the text due to constraints of space, but nonetheless provide useful background for understanding the study that this work discusses. The simulation used in this study has two settings: one with an explicit energy representation (energy symbols on), and one without (energy symbols off).

The EFAC simulation shown without energy symbols:



The EFAC simulation shown with the energy symbols on:



The EFAC simulation can be found online at phet.colorado.edu.

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