Intuitive ontologies for energy in physics

Rachel E. Scherr*, Hunter G. Close†, and Sarah B. McKagan*

** Department of Physics, Seattle Pacific University, Seattle, WA 98119*
† Texas State University – San Marcos, San Marcos, TX 78666

Abstract. The nature of energy is not typically an explicit topic of physics instruction. Nonetheless, participants in physics courses that involve energy are frequently saying what kind of thing they think energy is, both verbally and nonverbally. Physics textbooks also provide discourse suggesting the nature of energy as conceptualized by disciplinary experts. The premise of an embodied cognition theoretical perspective is that we understand the kinds of things that may exist in the world (ontology) in terms of sensorimotor experiences such as object permanence and movement. We offer examples of intuitive ontologies for energy that we have observed in classroom contexts and physics texts, including energy as a quasi-material substance; as a stimulus to action; and as a vertical location. Each of the intuitive ontologies we observe has features that contribute to a valid understanding of energy. The quasi-material substance metaphor best supports understanding energy as a conserved quantity.

Keywords: energy, embodied cognition, metaphor, ontology
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INTRODUCTION

The nature of energy is not typically an explicit topic of physics instruction. Nonetheless, participants in physics courses that involve energy are frequently saying what kind of thing they think energy is, both verbally and nonverbally. Physics textbooks also provide discourse suggesting the nature of energy as conceptualized by disciplinary experts. We use linguistic analysis to identify the ontologies expressed in learners' and experts' statements about energy [1-6]. Each of the ontologies we observe has features that contribute to a valid understanding of energy. The quasi-material substance metaphor best supports understanding energy as a conserved quantity [6-9].

THEORY AND METHODS

The data for this investigation includes audio-video recordings of naturally occurring classroom events. The practice of using rich records of naturally occurring activities as evidence of student knowledge promotes and supports the point of view that learning and expertise show best in what students do and say to learn together [10]. This investigation also uses data from physics textbooks [11,12], which present physics discourse endorsed by disciplinary experts.

An embodied cognition theoretical perspective enables us to identify ontologies in discourse. The premise of this perspective is that we understand the basic kinds of things that may exist in the world (ontology) in terms of sensorimotor experiences such as object permanence and movement [4]. Abstract ideas, such as time, are expressed with embodied metaphors: for example, we might say that we are "halfway through" the year, as though a year had spatial extent and we were moving relative to it. Human use of embodied metaphor is natural, unconscious, and pervades our talk; we normally express conceptualizations of events, activities, emotions, ideas, and so on as being entities or substances. Embodied metaphors are often especially evident in the verbs and prepositional phrases used together with the terms of interest. For example, to say someone is *in* trouble or *close to* graduation conceptualizes these states as being locations, and to say that someone *got* an idea or *has* a headache poses these attributes as being possessions [4].

Influential work in cognitive science has demonstrated that ontological categorization is key to understanding physics concepts [1-3]. This tradition has claimed that novices misunderstand concepts such as heat, light, and electric current as having matter-like ontologies, whereas experts properly categorize them as emergent processes [1-3,5]. The authors make the stronger claim that matter and process ontologies are cognitively mutually exclusive, and that this "ontological distinctness" makes it "not possible to refine or develop intuitive knowledge to the point that

it becomes the veridical physics knowledge" [3]. Recent studies counter that both experts and novices make productive use of matter-like ontologies for concepts such as heat, light, and electric current and that in both populations, multiple and overlapping metaphors for physics quantities (including energy) complement one another in complex representations of physical phenomena [5]. The data presented here adds to the evidence supporting the latter claim.

DATA

For this brief paper we illustrate our analysis methodology and results with excerpts from (1) video records of an eighth-grade classroom in a public middle school in the Pacific Northwest and (2) introductory physics textbooks.

The video data was collected for the Energy Project, a teacher professional development and physics education research project to understand effective teaching and learning of energy [13,14], as part of an activity in which participating teachers videotape their own classrooms for discussion with peer teachers and Energy Project researchers. The presented episode was selected because of the high visibility of students' science ideas. (The correctness or incorrectness of their ideas was not part of the selection process.) Students in the presented episode have just begun their study of energy by watching a movie showing various phenomena: a bus driving, a bicyclist pedaling, leaves blowing in the street, and so on. After the movie, students work in small groups on a worksheet that asks them to decide how energy is involved in each of the phenomena in the movie. Five students participate in the following discussion.

Tamara: All right. Leaves in street. I don't think so. Cause it's just the wind.
Laila: Yeah. I don't think I don't think the leaves in the street have energy. They have a type of energy, but-
Kelsey: But is wind energy?
Laila: Wind is energy.
Tamara: Oh, should we write it down?
Kelsey: Well they're getting wind energy.
Pierre: But it's not talking about the wind.
Laila: -about the wind, it's just talking about the leaves in the street. Leaves - leaves in the street, do they have energy.
Tamara: No.
Pierre: They are pushed by energy
Laila: They have energy, but they do not have the energy, like, to move.
…
Laila: But wind - I don't think wind has energy. Well it has energy
Kelsey: You can use wind to like power stuff
Laila: Is it - to create energy. Wind-
Kelsey: It can be a source of energy.
Laila: Yeah, your wind is like your foot on the pedals.
Kelsey: Yeah. It's a source of energy.
Laila: I don't really think-
Kelsey: I mean the leaves have a source of energy.
Laila: The leaves have a source of energy but they don't have like energy to move they're talking about its motion. Is motion energy there and I don't think the leaves have motion energy.
…
Kelsey: But the leaves were moving.
Laila: But they're moving because of the wind. I'm saying if you could have-
Kelsey: That is their source of energy.
Laila: -leaves in the street without, without, if we had leaves without the wind, it wouldn't move then. I'm just thinking of both cases.
Kelsey: True but I mean but like a bus without gasoline wouldn't move either.
Laila: No, true.
Kelsey: And like a bicycle without pedals, a pedaler, wouldn't move either. So.
Laila: I don't know I just feel like a leaf wouldn't
Stephanie: It seems like it is but
Laila: But I feel like in my mind I feel like it's energy! It's involved in a type of energy. I'm going to put yes-slash-no, because it's involved in a type of energy.

The textbook data is from two standard introductory physics textbooks [11,12] in the chapters referring to atomic physics. Key discourse markers are highlighted below.

OBSERVED ONTOLOGIES FOR ENERGY

We observe three main ontologies for energy in learner and expert physics discourse: (1) a quasi-material substance, (2) a stimulus to action, and (3) a vertical location.

Substance

Certain student statements in the above episode pose energy as being a substance-like quantity – a kind of "stuff" – and objects as being containers that can have such stuff in them:

Leaves in the street *have* energy.
They're *getting* wind energy.

The substance metaphor for energy is a powerful conceptualization that supports features valued in physics, specifically conservation, presence in objects, transfer, and flow [5,7-9,14]. The substance metaphor is explicitly promoted by instruction in the Energy Project [14] and other energy-focused instructional approaches [7]. Evidence suggests that potential difficulties of the substance metaphor (such as that energy has mass or occupies space) are not problematic in instructional practice [5,7,8]. In an Energy Project teacher professional development course, participants offered a refinement of the substance metaphor in which energy is infused into objects the way tea flavor is infused into water. This image retains the sense of energy as a kind of stuff that can be in objects, but is distinctive in that energy is understood as permeating solid objects and changing their quality without adding significant mass or volume, similar to an expert model of electric charge.

Some other student statements characterize energy as being something like fuel, and of certain kinds of objects as possessing fuel-energy:

Leaves wouldn't move without *wind* as a bus wouldn't move without *gasoline*.
Wind can be a *source of* energy.
You can *use* wind to *power* stuff.

Fuel is not energy; rather, it is a (literal) material substance that stores energy and can transfer that energy to other objects at a selected time. In physics, any object can do that. Fuel is distinctive in that the stored energy is often chemical energy; the transfer often takes place by combustion; and the desired effect of the energy transfer is to do mechanical work, so that the energy of interest is the "useful" energy and the objects of interest are those we use as "power sources" (wind, gasoline, batteries, food). Fuel is also unlike energy in that it is used up (transformed into non-fuel substances). Nonetheless, the strong everyday association between energy and fuel may be a resource for instruction if learners can be persuaded to think of fuel as *having* (and giving) energy rather than *being* energy. The burning of fuel may also support understanding the second law of thermodynamics in that it is a compelling everyday example of an irreversible process.

Stimulus

Other student statements in the quoted episode pose energy as being a stimulus, whose primary property is that it has an effect on objects. In some cases, this stimulus is spoken of as being much like what experts would term a force:

Leaves in the street *are pushed by* energy.

In other cases, energy is seen as being an agent that exerts something like a force:

Wind *is* energy.

Other statements characterize energy (or an energy-associated entity) as a general trigger or impetus for action:

Wind is like your *foot on a pedal.*
Leaves wouldn't move without *wind* as a bicycle wouldn't move without *a pedaler*.

In other contexts, we have observed energy being spoken of as a stimulus whose effects are specific to the object being stimulated: magnetizable things become magnets, stretchy things get stretched, lights turn on, movable things get moving. Such objects may be described as being "energized," in the sense of being roused.

The stimulus metaphor for energy is distinct from the substance metaphor in that instead of energy being *in* objects (as a fluid is in a container), energy *acts on* objects (as a stick prods a goat). The stimulus metaphor is a conceptualization that supports features valued in sociopolitical discourse, specifically the necessity of energy for making things happen. It also supports the idea that energy is the "ability to do work," if such an ability is understood to be strongly associated with forces. However, the stimulus metaphor does not support conservation: forces (or more general trigger/impetus mechanisms) can appear and disappear without constraint and do not transfer from one object to another. For this reason, we do not emphasize it in instruction.

Vertical location

A third ontology for energy is in place when we speak of energy as being an ordered set of vertical locations, for example, "The kinetic energy of the cart gets *higher* as the cart speeds up." (Both *higher* and *up* as used here indicate common orientational metaphors, in this case "more is up" [4], but only *higher* refers to energy). Graphs with energy on the vertical axis are a diagrammatic representation using this same metaphor. In these examples, the set of vertical locations is implicitly understood to be continuous. In the study of quantum harmonic oscillators or atoms, discourse arises of discrete energy

levels. Physics textbooks commonly include statements such as:

> The electron makes a transition *from* the n=2 energy level *to* the ground level (n=1). [11]
> One way an electron makes a quantum jump *up to* a greater energy level is to absorb a photon. [12]

Most physics textbooks show a graphical version of the same metaphor with energy-level diagrams, in which energies are visualized as rungs on a ladder and transitions are represented as vertical arrows. In these textual and graphic (implicit) statements of the nature of energy, energy is not *in* an object (substance metaphor), nor does it *act on* an object (stimulus metaphor); rather, objects are *at* energies (location metaphor).

The vertical location metaphor is a conceptualization that supports the idea that effort must be exerted to increase the energy of an object, consistent with the first law of thermodynamics. It harnesses many of the same cognitive resources as the concept of gravitational potential energy, which increases with (literal) height.

IMPLICATIONS FOR INSTRUCTION

Instructors who appreciate the advantages and limitations of various metaphors are better prepared to hear them in student discourse and use them as a resource for helping students deepen their understanding. Specific implications for instruction depend on an instructor's theoretical commitments and learning goals.

One instructional approach is to harness the specific affordances of particular metaphors for progress toward key learning goals. Instruction focused on learning and applying ideas of energy conservation, for example, may rely on a substance metaphor. This is the approach taken in the Energy Project [9] and other energy-focused curricula [5].

The ontological incompatibility hypothesis implies that "teachers should not try to bridge the gap between students' misconceptions and the target instructional material, as there is no tenable pathway between distinct ontological conceptions" [3]. Rather, this perspective asserts, instructors need to facilitate the creation of proper ontological categories in learners' minds and carefully monitor that only the correct category is endorsed in classroom discourse.

Our observations support the model of dynamic intuitive ontologies [5] in that they document variability in novices' intuitive ontologies. This model suggests instruction that builds expert concepts from students' everyday resources and reinforces the beginnings of expert-like thinking skills as they appear in classroom discourse. This general instructional orientation underlies a variety of specific teaching approaches [15,16].

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