Negative Energy: Why Interdisciplinary Physics Requires Multiple Ontologies

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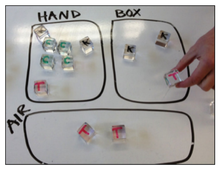
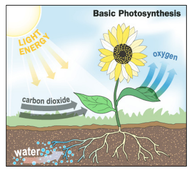
Ontological metaphors for energy

These are two (of many) metaphorical ways of thinking about what kind of thing energy is:

Energy as a substance



Scherr et al. 2012 [1]



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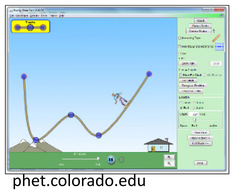
Energy is **in** objects
Objects **have** energy

Energy as a vertical location



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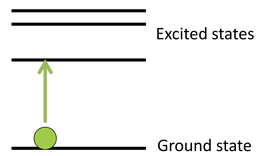


Objects are **at** energies
Objects **go** to **higher/lower** energy

Ontology can be implicitly conveyed based on the representations and discourse that we use to talk about scientific concepts.

The substance metaphor has attracted recent attention in PER

The substance ontology is metaphorical (i.e. energy isn't "really" a substance), but the case has been made that this metaphor has pedagogical affordances in several contexts.

"[T]he vast majority of discourse about energy implies that it is a substance. Although widely accepted that energy is not actually a substance, it is virtually impossible to discuss energy without referring to it as a tangible quantity. These metaphors are not only common, but also provide a fruitful framework for helping students conceptualize the abstract notion of energy." –Lancor 2012 [2]

"Treating energy as a substancelike quantity unlocks a wealth of conceptual resources for reasoning about energy conservation, storage, transfer, and agency." –Brewe 2011 [3]

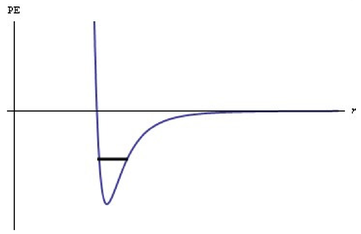
"Conceptualizing energy as a substance is especially powerful—perhaps inevitable, and perhaps even cognitively necessary—for understanding energy as a conserved quantity." –Scherr et al. 2012 [4]

Interdisciplinary physics for biologists requires negative energy

We have been developing an introductory physics course for life science majors (NEXUS/Physics) [5] that builds interdisciplinary coherence between physics, biology, and chemistry.

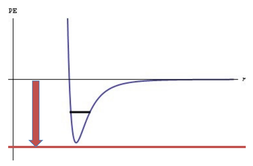
The energy most relevant in biological systems is "chemical energy," associated with chemical bonds and chemical reactions, which is usually treated as a black box in introductory physics courses (**and** in introductory biology courses!).

To open up this black box, the NEXUS/Physics course introduces electric forces and electric potential energy in the first semester, and models chemical bonds in terms of potential energy.



If the potential energy of unbound atoms is zero, then the energy of bound molecules is **negative**.

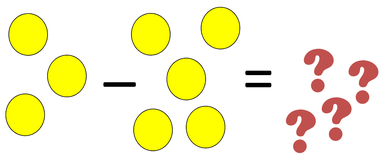
Why can't we just move the zero, to make all the energies positive?

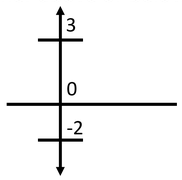


Ordinarily the "zero" of potential energy is not physically meaningful, and can be shifted by a constant. Here, the zero has a particular meaning: the atoms are far enough apart that they are not interacting. If we shifted the zero to a point below the strongest bond in the system, we would need to keep shifting it again as new molecules are added to the system.

Neither the substance nor the location metaphor is sufficient on its own

While the amount of a substance cannot be negative (without introducing another "antimatter" substance), a vertical location can be either above or below zero.





On the other hand, the substance metaphor captures some important aspects of energy that the location metaphor cannot:

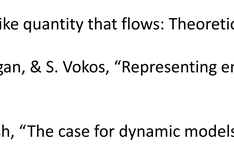
- Conservation of energy
- Interactions and energy transfer among objects

Incorporating negative energy requires mixing both the substance and location ontologies.

Expert physicists combine the substance and location ontologies

In this classroom excerpt (2/6/13), the physics professor teaching the NEXUS/Physics course fluidly mixes the *substance* and **vertical location** ontologies for energy:

One way to think about this is the potential energy between the two atoms. That if the two atoms are apart and form a bond, they **drop down to here** and *release that much energy*. And because that's **where they are, at that negative energy**, that's equal to *the energy you have to put in* to get them back apart. So it's just about **where you're going**, that when you're forming a bond, you're **dropping down**, and if you come in **at this energy** you *gotta get rid of this much*. But if **you're down here** and you want to **get back up to here**, you *gotta put in this much*.

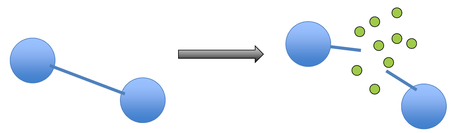


The combination is consistent: the energy of the system of atoms is described as a **vertical location**, while changes in the energy of the system are described as a *substance* (that enters or leaves the system).

This explanation, which switches between substance and location metaphors, is also consistent with other work showing that experts' and students' ontologies are dynamic. [6]

Combining the substance and location metaphors can be productive for students

Anita started out using a substance ontology for energy, which contributed to the problematic idea that breaking bonds releases energy:



Whenever chemistry taught us like exothermic, endothermic, … I always imagined like the breaking of the bonds has like *these little molecules that float out*.

…until I drew … the potential energy diagram, and that's when I realized, to break it you have to *put in energy*. (Classroom, 2/6/13)

Switching to a mixed substance/location ontology helped Anita make sense of bond breaking and bond formation:

What I imagine it is, to get it to break, you need to *put in energy*. So **to get up the hill**, you need to *input energy*… Say that **you're bicycling up the hill**. You *need energy to put it in*, that's what breaks the bond, but to bring them back together, it's *released*. So I just think of-- when you're **falling down**, if you're **going down a hill with a bike**, you're *not putting in energy* to the pedals, but yet your pedals keep going so *there's energy that's released*.
(Interview, 5/7/13)

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Acknowledgments

This work is supported by the NSF Graduate Research Fellowship (DGE 0750616), NSF-TUES DUE 11-22818, and the HHMI NEXUS grant. Many thanks to Ayush Gupta, Jessica Clark, Abigail Daane, and Ben Van Dusen for their helpful comments on an earlier version of this work, and to the University of Maryland Physics Education Research Group (PERG) and Biology Education Research Group (BERG).