# Preliminary Literature Review: Energy and Entropy in the teaching of science

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The study of the teaching and learning of energy/thermodynamics is different from (and more complex than) other physics topics in two key ways. First of all, instruction in this topic extends far beyond "physics" classes, as it is a core subject in biology and chemistry, as well as science classes from elementary school on up. Though most of the literature I have found is from the physics education and science education fields, some is from chemistry and biology education. There seems to be room for much more research into the interdisciplinary aspects of the topic, particularly at the high school and university levels (after the disciplinary boundaries have been drawn). Second of all, there is substantial debate about the physical concepts themselves and their interpretation. There is not one single "expert" consensus on the definition and nature of energy and related concepts. As a result, the discussions on student understanding of energy and on how energy concepts should be taught cannot be completely decoupled from the expert conversation on what energy is. Our research group talks about this debate as a disciplinary divide between physics and biology, but most of the published debate is **within** the physics community (and, to some extent, chemistry), so explicit interdisciplinary confrontation between physics and biology in this area may also be a new area of (formal) research.

## What is energy?

A classic textbook definition of energy is "the ability (or capacity) to do work". Even though this definition is now deprecated, it seems to have enduring power: when asked to define energy on a homework assignment, a substantial number (I haven't counted up the percentage yet) of Physics 121 students gave some version of this definition, often verbatim, suggesting that they are recalling what they were taught in previous science classes. [Lehrman 1973] argued that "Energy is the capacity to do work" is not only incomplete, but incorrect, because it ignores the 2nd Law of Thermodynamics, which states that not all energy has the ability to do work. The 1st Law says that energy is conserved, yet the 2nd Law says that the ability to do work is not conserved, so this definition of energy leads to a logical contradiction. [Hicks 1983] reiterates Lehrman's arguments, and shows that "the capacity to do work" makes sense for mechanical energy, but not for thermal and other forms of energy. Even though many physics classes do mechanical energy first and therefore this may seem like a reasonable way to start, Hicks advises against even starting with this definition.

Still, there is explanatory and intuitive power in "the capacity to do work" that is useful for students in understanding physical situations, but this doesn't happen to match up to the physical concept called "energy". [Viglietta 1990] recommends teaching "exergy", which **is** defined as the maximum work that can be provided by a system, and argues that this is a more intuitive way to quantify Second Law constraints than the usual approaches of entropy or efficiency. [Pinto 2004] recommends focusing on "energy degradation", the transformation of energy into less useful forms, explained at the microscopic level by energy dispersion. They claim that this corresponds better to students' experience of energy "conservation" in the sense of "not wasting energy" (rather than in the physics sense of conservation).

In place of "the ability to do work", the alternative that has become commonplace (from [Lehrman 1973] forward) is to avoid any direct definition of what energy is, but to define it simply as a conserved quantity. Many papers cite the approach in the *Feynman Lectures*: there are a number of different physical quantities whose sum is always constant (as a physical law), so we call that sum "energy". These various physical quantities are typically called "forms of energy".

However, there are debates about how to understand "forms of energy". [Kaper 2002a] shows that in thermodynamics, there is only energy, not different forms of energy, and in that context, the idea of transforming energy between forms is meaningless. They show that the "forms of energy" language is valid only under specific constraints, e.g. a system undergoing small changes; otherwise the change in "chemical energy", "thermal energy", etc., is a path function rather than a state function, and is not well-defined for a particular system. [Swackhamer 2005] takes a harder line and rejects "forms of energy" entirely. Instead, he says that energy is just energy, stored in an object, and transferred from one object to another. He argues that gravitational/electric potential energy is stored in the field, and explains various phenomena this way. Citing Lakoff, he argues that a "stuff" model of energy, based on energy transfer (rather than energy transformation) is more consistent with how we conceptualize events, using the metaphor that change is movement of possession. [Papadouris 2008] takes the opposite position, that energy transformation is a better model than energy transfer, since there are many situations that cannot be accounted for with explanations based on energy transfer alone.

[Moore 1993] addresses different formulations of the First Law of Thermodynamics, and distinguishes between E (total energy) and U (internal energy). He argues that the correct form includes E, and the restricted form only works when E=U, i.e., quasi-static processes. He advocates for including some non-equilibrium thermodynamics in introductory physics, using some examples of situations in which the internal energy interacts with macroscopic energies.

## Student understanding of energy

[Watts 1983] documents students' alternative frameworks about energy, and places them into seven categories: 1) human-centered, 2) depository (some objects "have" energy and others "need" energy), 3) ingredient (energy is in things, to be released), 4) activity, 5) product, 6) functional, and 7) flow-transfer model. [Trumper 1990] focuses on three of these as the most pervasive: anthropocentric, active deposit, and product.

A number of studies look at students' energy concepts in terms of a stage model. [Liu 2005] uses a neo-Piagetian model of development, and shows that students' acquisition of energy concepts correspond to the stages of their conceptual development. In order, these stages are: activity, capacity to do work, various sources/forms of energy, energy transfer, energy degradation, and energy conservation. Liu backs up this ordering with a statistical analysis of exam questions. (However, I am not convinced that these stages reflect inherent properties of students, rather than the order that energy concepts are taught in schools.) [Dawson-Tunik 2006] explains students' difficulties with energy in terms of stages: 9$^{th}$ graders are still at the stage of single abstractions (understanding potential energy as the potential for energy to happen), while understanding energy transfer or energy as the ability to do work requires the abstract mappings stage (understanding kinetic and potential energy as different energy states). Similar to Liu, [Lee 2009] proposes a learning progression, going from energy sources to transformation to conservation. They argue that the energy conservation concept requires a higher level of "knowledge integration": connecting ideas to explain a phenomenon.

[Solomon 1985] reports confusion between sources of energy (e.g. fuel) and energy itself. Similarly, [Goedhart 2002] cites earlier studies showing that students think matter (e.g. fuel) can be converted into energy, and [Papadouris 2008] shows that students identify energy with its "carrier" (e.g. current).

[Solomon 1985] shows that students' ability to recall the principle of conservation of energy was **negatively** correlated with giving correct answers to questions about energy dissipation and degradation: these students incorrectly applied the principle of conservation, and thought that the energy was still there and available to do work, while students who did not recall conservation gave the more intuitive (and in this case, correct) answer. [Goldring 1994] documented the same confusion, with students thinking that energy "lost to friction" is converted to potential energy. As part of an overall study showing that quantitative success in solving problems about energy (as we know from many other areas of physics) does not necessarily mean qualitative understanding, Goldring also showed that students confuse energy with power, and confused "conservation of energy" in the physics sense with "conservation of energy" in the sense of not wasting. [Papadouris 2008] shows that students have difficulty seeing energy as a transphenomenological construct, providing a single explanation for distinct phenomena. Papadouris also demonstrates an overreliance on mechanical models, and confusion between energy and force.

[Bryce 2009] shows that students do not have a strong qualitative understanding of the difference between momentum and kinetic energy, and that instruction generally does not provide this (for example, it is often emphasized that momentum is a vector, but not that kinetic energy is a scalar or the significance of that).

In the chemistry realm, [Boo 1998] documents the common student belief that breaking chemical bonds releases energy. Boo suggests that students see chemical bonds as a physical entity, and they are extrapolating a macroscopic idea (energy is needed to build things) to the microscopic conclusion that energy is needed to create chemical bonds. Furthermore, students pick up the idea from biology that "food contains chemical energy" (rather than the more correct view that the energy comes from the food/oxygen interaction). Boo also shows cases in which students think that making **and** breaking bonds both require energy, and suggests that students are superimposing school science (breaking bonds requires energy) with intuition (making bonds requires energy. (However, I would suggest that "making bonds requires energy" is an idea that students could get from school science too, since this is indeed the net effect of some biologically relevant reactions, such as the synthesis of ATP.)

## Teaching energy

Based on the research on the nature of energy and on student understanding of energy, many different approaches to teaching energy have been proposed. [Trumper 1990], having defined three frameworks by which students already understand energy, proposes a constructivist approach to build up these frameworks into the scientific energy concept. [Van Huis 1993] says that constructivism is too hard, because student ideas are all over the map. Instead, they use a systematic approach, having students define the system of interest and analyze its energy budget, and they found that this led to students asking productive questions (e.g., does the sun run out of fuel). [Arnold 1996] uses a water flow analogy for heat transfer, to tell the scientific "story". [Nordine 2010] uses a middle-school curriculum focusing on energy transformations in nonidealized phenomena (rather than the usual idealizations), and finds that this promotes preparation for future learning. [Solbes 2009] starts a high-school physics class with energy transfer (work, heat, conservation) rather than with mechanics. [Reif 1999] proposes a curriculum to teach thermodynamics in introductory algebra-based college physics based on atomic phenomena (i.e. statistical mechanics), rather than the usual macroscopic approach (though, unlike the other papers, this is only a proposal, rather than a report on a curriculum that has been tried).

[Kaper 2002b] considers whether "forms of energy" (though it is not the appropriate language for thermodynamics) can work as an intermediate language on the way to thermodynamics, and finds that it leads to difficulties even as an intermediate. They suggest using "exchange value" instead; for example, replacing "gravitational potential energy" with "exchange value of height". [Goedhart 2002] (the same authors) distinguishes between physics and chemistry education research: in physics there are intermediate steps between everyday language (in which heat, temperature, and energy are all conflated) and thermodynamic language; "forms of energy" is one such example. However, chemistry lacks these intermediates, and uses thermodynamic vocabulary from the beginning, leading to confusion (for example, confusing state with process quantities, and confusing a system with its surroundings).

[Teichert 2002] shows that chemistry students in intervention sections (similar to physics tutorials), who were forced to integrate and explain their ideas, were more equipped to critique statements from biology texts such as "Breaking a chemical bond in ATP releases energy", and were better able to reconcile these biology ideas with the idea that energy is required to break a chemical bond. [Barker 2000] shows that a "context-based" chemistry course, focusing on applications and including a unit on fuel, also fixed the breaking-bonds-releases-energy issue to some degree.

## Entropy

The research on entropy and the Second Law of Thermodynamics is far more limited (and this is noted in the few papers I found on these topics). [Duit 1988] investigated student understanding of the Second Law (particularly in regard to heat transfer), and found that students do not have a strong sense of irreversibility: they understand that temperatures equalize over time, but then think temperature differences can arise later. They think of cold as an entity (parallel to heat), and think heat and cold can depend on the properties of substance (i.e. some substances are inherently hotter and colder than others).

[Cochran 2006] developed UW research-based tutorials on heat engines and the Second Law. The version based on entropy was more successful the version based on Carnot's theorem, and more broadly generalizable. [Christensen 2009] built on this and showed that students (inappropriately) displayed conservation reasoning regarding entropy, at least when addressing situations in concrete contexts. They developed a tutorial to address this.

[Carson 2002] looks at entropy and Gibbs free energy in undergraduate chemistry education. They cite Chi, who identifies the categories of Matter, Processes, and Mental States, and claims that students encounter difficulties when they place scientific entities in the wrong category. Carson shows that students think of entropy and Gibbs free energy as "Matter" (i.e. students think of these as other "forms of energy", parallel to kinetic energy or potential energy), but should be thinking of them as "Processes". Furthermore, students have no real qualitative understanding of Gibbs free energy, and just plug and chug.

## Energy in biology

The research on energy in biology is also limited, and what I found was only at the high school level and below. A common theme is the failure to integrate biology with the physical sciences, and to integrate among the levels of biology. [Lin 2003] writes about three hierarchical levels of biology: phenomenal (e.g. ecology), mechanical (e.g. cellular mechanisms), and physical (e.g. molecular processes). They find that students show a weak relationship between the living world (phenomenal and mechanical levels) and non-living world (physical level), when looking at energy flow, and argue that biology education is too compartmentalized between these levels. [Jin 2010] proposes a four-stage learning progression for energy concepts in biology. In Level 1, energy is a naturalistic/psychological entity, and in Level 2, energy is vital power. At Level 3, students make statements like "glucose and ATP are energy". They also display concepts of matter-energy conversion: in photosynthesis, light turns into glucose. (Cf. [Solomon 1985] and [Goedhart 2002] discussed above.) Energy is cycled in the ecosystem without degradation, and energy of food turns directly into energy of motion (without reference to the chemical reactions that make this possible). Finally, in Level 4, students trace energy successfully. This paper also calls for linking the multiple scales of biology.

[Barak 1997] gave a survey to high school students and teachers to distinguish vitalistic reasoning (the living world is fundamentally different from the non-living world) from scientific reasoning (biology is based on chemistry and physics). They showed that those who understood energy were much more likely to display scientific reasoning. They suggest that misunderstanding of energy may prevent scientific understanding of biology, or the effect may be in the reverse direction. They suggest that some of the vocabulary in biology around energy may contribute to a vitalistic approach, e.g. "plants produce energy". They propose a curriculum based around the Second Law of Thermodynamics, in which energy is linked to order.

I propose extending this research on energy in biology to study student understanding of energy in biology at the university level, and in particular to look at the interface between energy in biology and energy in physics (for students studying both biology and physics); from what I can tell so far, nothing has been done yet in this particular area.

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