RESOURCES FOR UNDERSTANDING ENERGY

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I. Introduction

One hundred and sixty years after its advent energy has become an indispensable concept for describing and explaining our world scientifically. Therefore it is now ubiquitous in school science curricula worldwide and regarded as of first importance universally by scientists and educators alike. Nonetheless, energy is not well understood by our students. Students graduating from secondary schools generally cannot use energy to describe or explain even basic, everyday phenomena like a stopping car. Students often cannot use energy to account for many of the prototypical phenomena that are staples of school science instruction about energy, like a burning candle, even if they can make a few calculations or repeat some standard phrases. Nor do they tend to think of energy as a useful tool for solving problems unless prompted.[1] Beyond that educators are not unanimous about how and when energy should be introduced to students.[2] Energy as presented in school science is not a single, coherent concept, and it is not always consistent with the scientific energy concept. Furthermore the energy concept in the professional science education literature is not even unitary.[3] As a result energy is not treated in consistent ways from year to year and from discipline to discipline in our schools. Today's school science energy concept has retained and acquired connotations that contradict the modern scientific energy concept and that hinder its comprehension by teachers and students alike.

In this paper I will describe why the typical school science energy concept is not very useful to students and how teachers and students can marshal native conceptual tools, analogies, and common representational resources in an effort to develop and to understand[4] the scientific energy concept better. The goal is for the school science energy concept to conform to the scientific energy concept in both structure and usefulness.

II. The mysterious school science energy concept

In order to be understood the energy concept must be understandable. The typical school science energy concept may not be understandable. Language used in textbooks and by experts belies a certain discomfort with energy that is unique among the concepts in school science. Energy is said to be "abstract," "invented," and in one of our national science standards energy is even said to be "mysterious."[5] Now all of these accusations may be true, but if so, then they would apply equally to other conserved quantities in science, mass and momentum, for example.

Why is energy alone among conserved quantities described this way? I will show that the ground for these exceptional assertions about energy is very likely that the typical school science energy concept is an incoherent patchwork of formulations that have acquired the patina of received truth. They are so widely used that it is unlikely to occur to us that they are not consistent with either the scientific energy concept or with human conceptual tools for thinking about causes and effects. In fact, the *scientific* energy concept, which is different from the school science energy concept, is incredibly useful precisely because of its accord with patterns in nature and with how we conceptualize causation.

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[1] Driver, R. and Warrington, L., "Students use of the principle of energy conservation in problem situations," *Physics Education*, **29**, pp. 171-176 (1985).

[2] "When should energy be taught?" Find it!

[3] Divergent viewpoints may be found in G.B.Schmidt and J. Warren

[4] "Understanding" entails the ability to account for some novel but basic phenomenon at some length in terms that an expert would deem to be valid.

[5] American Association for the Advancement of Science, *Project 2061 Benchmarks Online,* http://www.project2061.org/tools/benchol/bolframe.htm

A. Metaphors that blind

In school science energy is often presented merely as a quantity that we can calculate, only a number that always remains the same when determined for a closed system. It was invented, so it is sometimes said, only to help us do calculations; it has no status other than as a rule for bookkeeping. While there is *part* of the scientific energy concept in this view, if it is treated as though that is all there is to energy, then energy is seen to be just a numerological curiosity based on the values of other more real physical quantities. Energy seen this way seems abstract to us, because, being only a number, it has no physical status. Therefore, it lacks connection to the everyday conceptual resources that we use for other conserved, extensive quantities, like the concepts of mass and momentum. Being only a number that curiously turns out to be conserved, energy, then, is just a useful contrivance, a *fiction*.

Another problem with the school science energy concept is that energy has no consistent identity. Energy is said to change forms, whatever that can possibly mean. When we say that energy has different forms it usually is understood to mean that there are different *kinds* of energy. This is, in fact, the explicit claim of one set of national science education standards.[6] A difficulty arises, however, when we try to describe what we mean by different kinds of energy. When we describe the differences among kinetic energy, thermal energy, and elastic potential energy, for example, we invariably talk about differences in how energy is *stored*, not about differences among "kinds" of energy itself. This is because energy is always and everywhere only energy. Or, put in an equivalent way, there is only one kind of energy, but there are many ways in which it is stored. The concept "form of energy" is incomprehensible, since it is not physical. At best we could say that there are many ways (or forms) of *storing* energy, but we should assiduously avoid the misstatement that energy itself somehow changes in form.

Unfortunately, in saying that energy is changed from one form to another we unavoidably think that something about energy itself has changed. This creates two obstacles for understanding. First, in our classrooms we do not describe differences between energy in one form and energy in another (since there are none). Still we claim that there *are* differences. Whatever it supposedly is that makes one so-called kind of energy different from another cannot be put into words. Therefore, students and teachers alike may acquire the tacit understanding that energy is ineffable. Second, language about energy transformations diverts attention from the physically significant changes that really *do* occur when energy is transferred from one entity to another. For example, in melting ice it is commonly stated that thermal energy is changed to potential energy. If a student thinks that it is energy that has changed, then we have an instructional problem. What we *say* and what we *mean* should be explicitly brought into accord, because energy transformation language on its face implies that energy is a *physical system* in its own right that can change. Because of the idea that there are different forms of energy many physical changes are described only as energy transformations rather than as changes in physical systems that actually *can* be described and perceived or envisioned. This may be the reason that sometimes people erroneously claim that light is *pure energy*, rather than just a property of some proper physical system such as a photon or an electromagnetic wave.[7] No one ever would talk about light as *pure momentum*!

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[6] American Association for the Advancement of Science, *Benchmarks for Scientific Literacy: Project 2061*, (Oxford University Press, New York, 1993), p. 86.

[7] Herrmann, F, "Altlasten der Physik (9): Reine Energie," *Physik in der Schule* **33**, 206 (1995).

In his famous paper[8] of 1842 in which he asserted the energy conservation principle, Mayer stated that what we now call energy has different forms, because he found that work and heat, originally two quite independent concepts, were intimately related. Calling work and heat different forms of the same thing was a crucial step forward in the development of the energy conservation principle. Any cash value arising from the idea of forms of energy has long since been mined out, however. Nonetheless, the claim that energy exists in different forms is nearly universal in American school science texts and is simply assumed in the national science education standards. In summary, energy is not viewed in school science as a single concept but as many, and new forms of energy are spoken into existence as needed and at no cost. We get what we pay for.

Still one might argue that there are different forms of energy, since we calculate energy in different ways for different entities. But this is completely different from how we think about any other conserved quantity. For example, we calculate mass in an amazing variety of ways. Still, no one has ever suggested that mass has different forms because of this. Energy, unlike mass, simply is not viewed as the same thing all of the time, although it should be.

A school science energy that changes "form" in a way that has no physical interpretation shares common ground with shamanistic characters as well as occult features with the energy concept promoted by those selling "healing crystals,"[9] for example, since whatever it is that changes is hidden from us. Energy in school science can come to be seen as *metaphysical*.

School science energy suffers from yet another unusual and unscientific curse. At times it is clearly a property of objects as revealed by some identifiable feature like the stretch of a spring, but at other times it is apparently disembodied so that it cannot be thought of as being a property of *any* physical entity at all.

Gravitational potential energy in school science is an example of apparently disembodied energy. When a ball is thrown vertically upward it is apparent to students that it has kinetic energy. The ball's kinetic energy disappears as it rises. At the top of its trajectory the kinetic energy of the ball is gone. In an attempt to account for the lost energy it is commonly said still to belong to the ball ("The gravitational potential energy *of the ball* is…."), even though the energy is certainly not within the ball. Thinking that the ball itself has gained gravitational potential energy forces us to the unscientific conclusion that the change in the amount of energy belonging to something may not result in any change at all in the object!

A second and better attempt to help escape this awkward situation is to say that the energy is now the potential energy of the *system* consisting of the ball and the Earth. There is even a system variable that one can point to that changes along with the potential energy—the separation between the ball and the Earth. All this, of course, skirts the issue, because we are left with energy that cannot be attributed in whole or in part to either member of the system although it is still said to belong somehow to the system as a whole. But there is no place within this system for gravitational potential energy to *be*.[10] In order to do away with this problem one of the national science education standards simply postulates that the energy is in the system

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[8] Mayer, J.R., Bemerkungen über die Kräfte der unbelebten Natur, *Annalen der Chemie und Pharmacie,* **43**, 233 (1842); translation available at http://webserver.lemoyne.edu/faculty/giunta/mayer.html.

[9] "Energy is the force that comes with the power of Love and Light. Energy that helps provide happiness, health & hope along with peace and positive outlooks." http://www.energycrystals.com/index1024.html

[10] The missing component of the system is the gravitational field, or, from the point of view of relativity, spacetime. Gravitational potential energy is just a property of the gravitational field or spacetime. Just how one describes how gravitational energy is stored is not resolved. For one account of gravitational energy see, Misner, Thorne, and Wheeler, *Gravitation*, (Freeman, San Francisco, 1973), pp. 466 ff.

anyway.[11] Therefore, gravitational potential energy seems to exist by fiat and in name only. Yet it can reappear (from nowhere?) as the ball falls and gains kinetic energy.

Seen from this point of view energy is unlike any other conserved quantity in science, since it is at times clearly a property of something and at other times it is not "there," not a property of any entity at all. Therefore, in school science energy is seen as a *phantom*.

It should come as no surprise that students often think that energy is produced in certain situations and that it disappears in others. As a phantom, or something metaphysical, or a fiction it may be conjured or dismissed at will with no consequence for the physical world. The school science energy concept just described offers few constraints that force useful inferences. Therefore, it is of little use in thinking about everyday life.

Neither mass nor momentum is routinely described as "invented," "abstract," or "mysterious," even though they have no higher ontological status than energy. No one speaks of *forms* of mass or *forms* of momentum, even though they are involved in the same processes as energy and are conserved just like energy. Nor is mass or momentum more concrete than energy. Energy is *no more* invented or abstract or mysterious than mass or momentum. These pejorative descriptors will no longer be applied to energy either once it is understood in the same way that momentum and mass are understood, namely as a unitary and universal concept that connects with our everyday conceptual system like other conserved, extensive quantities.

B. Cognitive hobbling

At least part of the problem with the school science energy concept has roots extending back to when two nineteenth century concepts were discredited and discarded. The first was caloric, and the second was the aether. Educators have endeavored since then to sever energy from the invalid ideas associated with these two concepts, especially the claim that they were both material. But caloric and the aether were proposed in an attempt to explain things. They were productive ideas in some limited respects. In particular, each concept had a useful role to play in accounting for phenomena related to energy.

When they were discredited the intuitions associated with these concepts were discarded, too. As we will see, although some of these intuitions are properly associated with a 20th century conception of energy they have not yet found their way back into school science.

Caloric was originally conceived of as a material substance that would flow from a hotter object to a cooler one which would then warm up.[12] But a material caloric became untenable. So when the energy concept was developed it was important to distance it from any notion that it was material. In snuffing out the idea that energy is matter, the clear picture of energy transfer that caloric fostered was unnecessarily lost, too. We should be talking about energy (rather than caloric) flowing or being transferred from the warmer object to the cooler one. Instead we talk about heat. So, we end up struggling against our intuition that *something* is transferred from the warmer object to the cooler one. But it isn't heat, because heat doesn't originally exist in the warmer thing from which it flows. Nor does it exist in the cooler thing that finally receives it. It is only the amount of energy transferred because of a temperature difference. "Heat" is of little use to our students and is so pitched against their valid intuition that neither national science education standard has anything to do with it as a scientific concept.

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[11] "This energy cannot have been lost, so it is postulated to have been stored in the system consisting of the object being lifted and the earth." Aldridge, B. and Strassenburg, A., eds., *Scope, Sequence, and Coordination of National Science Education Content Standards*, (National Science Teachers Association, 1995), p. 32.

[12] It is often claimed that the caloric concept was a fatally flawed precursor of the proper energy concept. This claim is problematic, because caloric is better seen to be a precursor of entropy, not of energy. See Falk, G., "Entropy, a resurrection of caloric—a look at the history of thermodynamics," *Eur. J. Phys*, **6**, pp. 108-115 (1985).

The aether was conceived of as a material substance that pervaded all space. Gravitational and electromagnetic fields were thought to be particular states of the aether. Stress and strain in the aether caused by electromagnetic and gravitational fields provided an intuitive way to think of the aether as a storehouse of potential energy something like a spring.[13] When the aether was discarded, the nature of fields became problematic, too.[14] Were they now to be thought of as a property of…nothing at all? Fields came to be presented as convenient mathematical abstractions that are not quite real rather than as physical systems in their own right. Therefore, since the demise of the aether, gravitational and electromagnetic energy have been homeless, at least in school science.

Modern textbooks pay special attention to the material nature mistakenly claimed for caloric and the aether. They seem still to be fighting the good fight of the 19th century: Energy is not matter! (That war is over. We can go home now.) The reason caloric and aether were of help in thinking about energy is that they both cued powerful, basic, conceptual resources while accounting for at least some observations. The helpful role that they played in accounting for energy is seldom mentioned, so it is no surprise that it is not missed. An unfortunate and unnecessary side effect of the demise of caloric and the aether has been to separate energy from the very intuitions that we need to understand it, intuitions that made caloric and the aether of some value to begin with. Having thrown them out, we should provide new, better accounts for energy in order to fill the vacuum left behind.

And, as we will see, the school science energy concept does not fit well into human conceptualizations of causation, though the scientific energy concept fits beautifully. Next, I will suggest how we may take advantage of our students' native conceptual resources and standard analogies in order to help their energy concept to be more consistent with the scientific energy concept. And I will describe how we can give energy an unchanging identity and a home. This will help energy to be more understandable and useful in their thinking about the world, because it will conform better to the scientific energy concept.

III. Conceptual resources for a hale concept of energy

A. Everyday intuition

Scientific thinking is simply a special case of everyday thinking. Therefore, I will argue that energy can only be understood in terms of appropriate everyday intuitions in order for our thinking about it to conform to the scientific energy concept. Indeed, we simply have no means for understanding energy other than our everyday cognitive tools. Making sure that appropriate intuitions are connected to energy will then provide a sound foundation upon which to build a sensible, useful concept.

1. *Our first intuition: Energy as a cause of changes*

The term "energy" is firmly integrated into colloquial thought. Dictionary definitions for energy tell us how the term is commonly used. For example, energy is "the capacity for acting or being active;" it is a "natural power vigorously exerted;" it is "the capacity for doing work." "Energy" is hardly different from "power" or "force" in everyday language. "Power" is "possession of control, authority, or influence over others;" "ability to act or produce an effect." "Force" is "strength or energy exerted or brought to bear: cause of motion or change: active

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[13] Maxwell, J.C., *Matter and Motion*, (Dover, New York, 1991), p. 67.

[14] Herrmann, F., "Energy density and stress: A new approach to teaching electromagnetism," *Am. J. Phys.*, **57**, pp. 707-714 (Aug 1989).

power."[15] Therefore, the most basic intuition associated with energy is that it is *a general cause of change*.

Fortunately a considerable body of empirical data concerning how people think about events, including cause and effect, has been developed. Lakoff and Johnson have written a useful synthesis of this work.[16] They argue that the human conceptual system that processes events arises from our bodily experiences. Narayanan has found that the same neural mechanism that controls bodily movements can also perform logical inferences about the structure of actions in general.[17] This is perhaps the reason that the prototypical human conception of causation that underlies all thought about cause and effect is the *volitional manipulation of objects by force*. One manifestation of this understanding in our students is the persistent association of energy with living things, and especially with people.[18,19,20]

According to Lakoff and Johnson there are two ways that we conceptualize events in everyday life based on this prototype. Our first conceptualization of events uses the following metaphors:

1) States are locations.
2) Changes are movements to or from locations.
3) Causation is forced movement of an entity to a new location.

This first conceptualization produces statements like "The homerun threw the crowd into a frenzy." In this case the cause is the homerun, and the object of that cause is the crowd which changed its state to one of frenzy. Here the cause "moves" the object in a generalized way. In Newtonian physics, of course, the cause is a Newtonian force. The object is some particle. The state of motion of the particle is caused to change.

Our second conceptualization of events uses the following metaphors:

1) Attributes are possessions.
2) Changes are movements of possessions.
3) Causation is the transfer of a possessible object to or from an entity.

This conceptualization of events produces statements like "The noise gave me a headache." In this case the recipient changed upon receiving a headache due to the agent "noise." Here the cause of change "moves" to and from entities which change as a result. This conceptualization also underlies the scientific energy concept. In a physical interaction energy is an attribute or possession that is transferred or moved from one entity to another, and this transfer causes changes in both entities. The agent that causes the transfer of energy is a physical mechanism. For example: "The temperature of the water rose because of energy received due to particle collisions."

The range of utility of these two conceptualizations is vast. Indeed, Lakoff and Johnson attest that they are among the most used and most profound conceptualizations in the human conceptual system.[21] The scientific energy concept is in full accord with this way of thinking. And school science energy should be, too.

Three statements about energy can guide the development of the energy concept in our students:

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[15] Webster's New Collegiate Dictionary 1980.

[16] Lakoff, G. and Johnson, M., *Philosophy in the Flesh*, (Basic Books, New York, 1999).

[17] Lakoff and Johnson, p. 177.

[18] Kruger

[19] Trumper

[20] Solomon

[21] Lakoff and Johnson, p. 194.

1) As an attribute energy is viewed as a possession that can be "stored" or "contained" in a "container," namely, a physical system.
2) Energy can "flow" or be "transferred" from one container to another and so cause changes.
3) Energy maintains its identity after being transferred.

In essence, then, we can think of energy in terms of a substance *metaphor*. Among the conserved, extensive quantities commonly emphasized in school science energy alone has been divorced from this substance metaphor, perhaps because of the effort to avoid the caloric concept. This is why energy in school science seems weird.

We can hook up energy to this substance metaphor in our classrooms by changing the language that we use to talk and think about it. First, we will say that *energy is always stored or contained* in some physical system. Therefore, we will always have to think of energy as a property of some identifiable physical system. So, energy will always have a home. There can be no such thing as "pure energy." Similarly this will discourage saying that "energy is released" during some process without the identification of an entity that receives it. We will insist that energy remain only a property (technically, a "state function") of a physical system. It can have no independent standing at all. Having a storehouse for energy also helps to defeat the idea that energy is simply an inconsequential invention or fiction that has no role other than in bookkeeping, because the state of a system always depends on its energy. Finally, in these storehouses we also have a "location" for energy that is intuitively necessary for attributing existence to energy in the sense required by energy conservation.[22]

Second, we will say that *energy flows or is transferred* from one physical entity to another during interactions. This yields a big dividend: An essential part of the energy-related conceptualization of events is that an attribute of some entity is transferred *because of some agent*. Therefore, our intuition about an energy-related phenomenon is not satisfied without an account of this agent. In the case of energy transfer the agent is a physical mechanism. So, a physical mechanism for the transfer of energy has a natural and necessary place in our energy-related conceptualization of events as well as in the scientific energy concept that is based on it. Our intuitive need for mechanism can be satisfied in some appropriate way in any given science class.

It should be noted here that the claim that an event involves an energy *transformation* often constitutes an end-run around mechanism, since the so-called transformation itself is sometimes presented and perceived as the change of interest. So, while energy transformations help us to avoid the effort of conceiving of a mechanism, the effort avoided happens to be the work that our conceptual systems are built for! As diSessa has stated, "Perhaps the most devastating implication of ignoring the sense of mechanism in instruction is that building an unwarranted wall between prior knowledge and scientific understanding may alienate students."[23]

Third, we will say that *regardless of where energy is, it remains always and only energy*. The substance metaphor entails an invariant identity and so avoids the transformation trap. Regardless of where a substance is, it remains the same substance. The concepts of mass, momentum, and electric charge benefit from this substance metaphor, since they are always regarded as the same thing regardless of where they are "stored." Energy should benefit in the same way. So when energy is transferred we need to look for some changes not in the nature of energy, but rather in physical systems,.

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[22] Lakoff, Johnson, *Philosophy in the Flesh*, (Basic Books, New York, 1999).

[23] diSessa, A, "Toward an Epistemology of Physics," *Cognition and Instruction*, **10**, pp. 105-225 (Nos. 2, 3;1993).

This substance metaphor for energy is delimited by these phrases. Not only do these phrases hook up energy to the substance metaphor, they bring us closer to a scientific conception of energy, because energy is always a function of the state of some physical system. And even though this change of language seems relatively simple, using these phrases consistently in place of misleading talk about forms of energy requires considerable effort and a significant change in thinking about energy for many teachers and students. The price is cheap, though, since this substance-like concept of energy can help to avoid the difficulties that teachers and students must confront in the school science energy concept .

When energy is transferred from one system to another, changes occur in both systems. It is already standard practice to associate energy transfers with temperature changes, changes in the speed of an object, changes in the shape of a rubber ball, and changes in the length of a spring. But unfortunately energy transfers are not always associated with the resulting changes. For example, although students recognize that a braking car is losing energy because its speed is decreasing, many are hard-pressed to identify any other change that would suggest that the energy is being transferred *to* anything. Indeed, many textbooks mistakenly use the work-energy theorem here in a fallacious attempt to determine how much work is done on the car (very little indeed!) instead of pointing out the central physical change—missed by a large fraction of our students—the brakes get hot as the car slows.[24] So the car (which includes the brakes) loses its energy through heating primarily.

Similarly, when students boil water while observing its steady temperature in spite of the heat (or should I just say energy) transferred to it, it is generally claimed that thermal energy is converted to potential energy. The dissatisfaction and difficulty that students have with this is that they cannot identify any physical change that satisfies their intuition. A change in the "form" of energy doesn't have much currency with them. Nor should it. Looking for the salient and satisfying physical change will lead us to some good physics. A change in "form" of energy will not.

Identifying the salient changes produced by energy transfers that are demanded by the energy concept and our intuition not only will help students and teachers to understand energy better, it will lead us to consider physical systems and mechanisms that are often ignored. And by making explicit the changes at each end of the energy transfers of interest, instruction may also support the energy conservation principle better.

One of the most common student difficulties with energy concerns its conservation. Although students nearly always can state that energy can neither be created nor destroyed, a large fraction simultaneously maintain that energy can be *produced* by certain reactions like combustion or that it can *disappear* without a trace as with a flashlight's beam. The substance metaphor for energy can help address both of these difficulties. Phantoms and mere numbers cost nothing to produce and can disappear without a trace, but a substance-like thing is more substantial. It has to be somewhere, just like energy has to be somewhere, *i.e.* as a property of some physical entity.

We already think of the other extensive quantities in science as being in some ways *substance-like*.[25] Mass is a primary example of a physical quantity that we think of in terms of a substance metaphor, and it provides an example from which we can learn. Children learn to

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[24] Therefore, very little "work" is done at all!

[25] For a thorough development of the validity and usefulness of a substance metaphor for extensive properties in science see the Der Karlsruher Physikkurs,, Abteilung für Didaktik der Physik, Universität Karlsruhe, Karlsruhe, Germany (1997).

attribute permanence to material objects while very young. They associate a substance metaphor with material objects and eventually with their mass. Therefore, additional or missing mass in a system becomes a matter of consequence for science students even in the middle school years, since they believe that mass is conserved. No one believes that mass is lost when it flows from one place to another or when it becomes unobservable for some reason. Similarly, no one believes that mass is created when more matter appears in some container. The substance metaphor associated with mass forestalls such beliefs. Joule himself made a similar argument in his lecture about energy conservation at St. Ann's Church in 1847.[26]

It should be the same with energy, but all indications are that it is not. Additional or missing energy is often not seen to be anything that needs to be accounted for by students, no doubt in part because of the deliberate severance of energy from the substance metaphor. Without considering energy to *be* a substance, it too can be associated with a substance metaphor *as is mass* (*which is not a substance either*). So the substance metaphor can support conservation whether of mass or energy.

Finally, a substance-like view of energy allows it to be seen as much more than just a number. The closest concept to energy is mass. The energy stored in an object at rest has mass. Energy and mass differ by only a scalar factor, c^2. As with mass, one may often attribute a spatial density to energy as well. It is this close connection between energy and mass that most clearly legitimizes associating energy with a substance metaphor just as mass is.

Doesn't a substance-like view of energy attribute too much reality to the energy concept?

Some physics educators have expressed strong objections that such a substance metaphor is misleading when used for energy, because students may come to the conclusion that energy is "there" something like Mt. Rainier is there or that energy is stored in things like bread is stored in a breadbox.

These objections may arise from the ongoing war against caloric. Educators rightly do not want students to think of energy as a material substance. But we educators must not confuse the substance *metaphor* that is so useful to us as a basic cognitive tool with the substance *concept* which has a clearly specified domain. Besides that, thinking of energy as matter is apparently not the main battle that students confront in their effort to learn the energy concept. Their problems concern the utility of energy in analyzing phenomena, energy conservation, and metaphysical views of energy. Besides, since over 90% of the mass of the Mt. Rainier or bread, arises not from particles but from energy stored in the gluon fields holding the constituent quarks together, it is a pretty accurate statement in many instances to say that energy is there just like bread in a breadbox.

So, does energy exist? "Energy can neither be created nor destroyed." This statement implies some sort of existence for energy. There is no use or sense in talking about the conservation of something that does not exist. Besides, energy in systems at rest has mass. So we must think of energy as existing to the extent required by its conservation law and its property (or alter ego), mass. If we accept some kind of existence for energy, then we necessarily think of it as existing *somewhere*, since it is impossible to conceive of something existing without conceiving of it being somewhere.[27] This is one reason that disembodied potential energy is a cognitive failure and therefore, a pedagogic failure. Since it does not exist

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[26] Watson, E.C., "Joule's Only *General* Exposition of the Principle of Conservation of Energy," Am. J. Phys, **15**, 383-390 (Sept-Oct, 1947).

[27] Lakoff and Johnson, p. 205.

in any identifiable entity, it cannot be thought of as existing at all. Mysterious, indeed. A postulate by necessity.

The substance metaphor I advocate does not seem to foster the notion that the substance-like quantity to which it refers (here it is energy) actually is a *material* quantity. For example, this substance metaphor is just the one we use for information. We *store* information in hard drives. A CD-ROM can *contain* 250 MB of information. Information *flows* at a rate of so many bits per second through our connections to the Internet. We *transfer* information files. Yet no one is accused of fostering the idea that information is a material substance. Energy is no more or less real than information. They are both "free creations of the human mind."

2. *Our second intuition: More energy transferred means more change*.

A second primitive cognitive tool that we can associate with energy is "Ohm's p-prim."[28] According to diSessa, p-prims are basic, more or less stable units of cognition that we use unconsciously in thinking about phenomena. He describes Ohm's p-prim this way: "An agent or causal impetus acts through a resistance or interference to produce a result. It cues and justifies a set of proportionalities, such as 'increased effort or intensity of impetus leads to more result'…." It costs us energy to stretch a rubber band a bit. If we stretch it more, it costs us more energy. The change associated with this energy transfer is apparent in the rubber band and in the person who stretches it. If we wind up a music box, we get sound. If we wind it up more, we get sound for a longer time. The more energy we add to a pot of water on the stove, the greater its change in temperature. When more energy is transferred intuition leads us to expect a bigger effect. Fortunately, so does the scientific energy concept.

Unfortunately, the school science energy concept does not accord with either intuition or science in the case of potential energy. When energy is stored gravitationally, electrically, or magnetically we cannot sense the changes that occur in the storehouses, which from a classical point of view are the corresponding fields. With no apparent effect, the status of energy itself becomes a problem. One way that we avoid this difficulty temporarily in schools is to pronounce the separation of the interacting objects to be the variable of interest with respect to energy. And to an extent this serves well as a proxy; it is the variable that we need in order to do valid calculations. For solving problems sometimes that is sufficient. Intuitively it is not sufficient, however.

The *pedagogical* failure of separation as the variable to associate with gravitational potential energy is its lack of accord with Ohm's p-prim. For example, when we lift a 20 kg bucket of water to a height h, we have no difficulty understanding that it costs us energy. The problem is to figure out what we have gotten for our money. Usually it is said that the height of the bucket h is what we have gained. There is a problem here that our brains do not miss. If we lift a 40 kg bucket of water to the same height h it costs us a lot more energy, but we haven't gotten any more height for our extra expenditure. This is counterintuitive. We expect more effect for more energy expended, but in the height h we do not get what our intuition expects.

The *scientific* failure of separation as the significant variable is that physics tells us that there is more involved. The field through which two objects interact is altered. Instructively, from the early days of the field concept, the field (or rather the aether modified by the field) was seen to be the locus for potential energy. Energy would be stored within the aether through stress created by the objects within it. The aether served as a "springy" storehouse for potential energy and permitted our innate sense of mechanism to be associated with its storage and transfer. The

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[28] diSessa, A., "Toward an Epistemology of Physics," *Cognition and Instruction*, **10**, pp. 105-225 (Nos. 2, 3;1993).

greater the amount of energy stored, the greater the presumed distortion of the aether.[29] When the aether was discarded, the physical status of the field was diminished for those who saw it as a property of the aether. In its place we now think of electric and magnetic fields as physical systems in their own right that can store and exchange energy, while spacetime is the modern locus of gravitational potential energy.

So then, what *are* the important changes associated with field potential energy? For electromagnetic potential energy the intensity and volume of the electromagnetic field are the real features of interest. This classical model has been worked out in some detail.[30] By taking advantage of animations of three dimensional electric and magnetic field lines of force as in the series *The Mechanical Universe and Beyond* and as in the video clips accompanying *Electric and Magnetic Interactions*[31] students can view representations of fields and see the lines of force or field vectors change as charged objects approach and recede from one another. When attractive charges approach one another, the intensity of the electric field dramatically diminishes over most of space. When they are separated, a stronger electric field fills more and more of space. You can't get a field for nothing. You pay for it with energy. Nor does it disappear without a trace. When the field disappears, the energy it stored is transferred to other things.

In the case of gravitational potential energy the structure of spacetime is the important thing. There is no way in general relativity to describe where in spacetime gravitational potential energy is stored, however. A problem confronting the storage of gravitational potential energy is that spacetime is imperceptible. In lieu of a complete description (which is not necessary for school science in any case), the visualizations permitted by embedding diagrams and the rubber sheet metaphor for spacetime bring us closer both to our intuition and to a scientific understanding of energy and gravitation. A stretchy rubber sheet and embedding diagrams are common bridging analogies for spacetime that allow students to associate energy storage with distortion. There are real limitations to the validity of these analogies (no location can be specified for energy stored in spacetime but it can be located in a rubber sheet), but they also have enough validity to be ubiquitous in introductory texts and popular books about gravitation. More massive objects lead to more distortion of both the rubber sheet and the structure of spacetime. So Ohm's p-prim would be triggered, and our everyday intuition would be useful.

One might wonder about how to design instruction in which fields become significant physical systems. At first it seems daunting and too abstract, too invisible for our students. Part of the problem is that this concept often is new even for teachers. We need time to reconceptualize the role of energy with respect to fields. But this is not a recent innovation. Robert Karplus's text from a generation ago, *Introductory Physics: A Model Approach*,[32] shows how to do this in a qualitative and highly useful way that is appropriate even for secondary school science. Fields are needed for two functions in school science: 1) to exert forces in order to avoid action-at-a-distance, and 2) to store energy in order to avoid disembodied potential energy. We should heed the need.

By using the substance metaphor for energy and reinstating fields (at least qualitatively) to their role as energy storehouses, we can retain the energy-related conceptual benefits once provided by caloric and the aether in a twenty-first century universe filled with particles and fields.

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[29] Maxwell, J.C., *Force and Motion*, Dover

[30] Herrmann, F., "Energy density and stress: A new approach to teaching electromagnetism," *Am. J. Phys.*, **57**, pp. 707-714 (Aug 1989).

[31] Chabay, R. and Sherwood, B., *Electric and Magnetic Interactions*, (Wiley, New York, 1995)

[32] Karplus, R, *Introductory Physics: A Model Approach*, (W.A. Benjamin, New York, 1969)

C. Analogies

Metaphors are tools that we use to relate intuition to phenomena. Analogies arise from metaphors made explicit, and two common analogies for energy are widely used in physics education.

The first analogy for energy is money. It is so commonly used that it hardly needs to be elaborated. Put simply, money is exchanged between people and between accounts. This exchange is similar to energy transfers (or exchanges) between physical systems. It is presumed in the analogy that some hoodlum with a printing press cannot create new money, nor can some disaffected militiaman destroy it. Therefore, in this analogy money shares three crucial characteristics with energy. It can be stored in some recognizable entity, it can be transferred from one entity to another, and it is conserved. One could push the analogy a little farther, but limitations arise pretty quickly. There is, for example, no inexorable dispersion of money to more and more entities as there is with energy. Otherwise, poverty would naturally be eliminated in the natural course of events. But every exchange involves some sort of mechanism, many of which are known by state and federal bank examiners.

Feynman wrote the second common analogy in his Lectures on Physics.[33] The analog for energy here is blocks. The Feynman blocks have the same characteristics as money: they can be stored in some identifiable place, they can be transferred, and their number and nature remain the same. The two analogies are really equivalent.

One characteristic of these two analogies that should be exploited is the fact that neither blocks nor money changes form. They are only transferred from one place to another. Since this is consistent with the scientific energy concept but not with the school science energy concept (which includes the misleading claim that energy changes *forms*) these analogies are tools that we can use to improve instruction about school science energy. We need only use them well.

Underlying both the money and the block analogies is the same conceptual system for understanding events that underlies the scientific energy concept (in which attributes are thought of as possessions, changes are movements of possessions, and causation is the transfer of a possessible object to or from an entity). Both analogies also are examples of how the substance metaphor really does help us to think about energy, since these analogies entail the substance metaphor and more. They *are* material. Their well-earned place in energy instruction is due to their fine conceptual lineage arising from the interaction between phenomena and thought that spawned the energy concept to begin with.

In addition to analogs for energy itself, analogs for physical systems help us to understand their relationship to energy. For example, the deep conceptual connection between “the volitional manipulation of objects by force” and physical change fosters a conceptual connection between living things, especially people, and energy. Vitalism still widely influences people by the claim that *anima*, elan vital, prana, pneuma, chi, ki, life force, etc. constitute important causal attributes of living things. As early as 1854 Hermann von Helmholtz used mechanical musicians as analogs of people in order to credit energy with explanatory power in living beings.[34] Robot

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[33] Feynman, R., *The Feynman Lectures on Physics, Volume I*, (Addison Wesley, Reading, 1963).

[34] “The heat generated in the animal body corresponds to the amount which would be generated by the chemical process. The animal body therefore does not differ from the steam engine.” In Kline, M., *Popular Scientific Lectures by Hermann von Helmholtz*, (New York, Dover, 1979), p. 79.

toys may help us even in the twenty-first century to help students separate the scientific energy concept from metaphysical concepts.

III. Representational resources

The quality of our understanding of energy depends on the quality of our representational tools. Many aspects of the scientific energy concept are drawn from the various ways we represent it. Effective representations offer students new ways to think about concepts. They will think differently about a concept that is well represented in many different ways than they will if it is representationally impoverished. In this section I will describe 1) some of the tools that we have available for representing what we mean by energy, 2) what they can be used for, 3) why they aid understanding, and 4) when to introduce them.

A. System schema

The purpose of this section is to introduce *system schema* to represent some systems commonly included in school science curricula. These schema help to make explicit what the system of interest is and what interactions it may experience with other systems. Used in conjunction with other representations for energy related phenomena, system schema serve to define just what it is that energy is a property of. so that energy transfers and the changes they cause will not be missed.

System Schema

A system schema is a way to represent physical systems and their interactions. They open the door for further elaboration about the nature of the system and its interactions, as we will see. A simple electrical circuit consisting of a battery, wire, and a bulb is a system that is probably used in all science curricula.

How do we represent it with a system schema? First, we identify the objects that are important for this system. When energy transfers are the interactions of interest the criterion that marks an object as important is whether it experiences some sort of change as a result of the phenomenon. In the case of the simple circuit that we are considering, the battery and the bulb are definitely of interest. But that is not all we can consider. For example, the surroundings will receive some energy from the bulb (and a negligible amount from the wires and also from the battery if it is fresh). So we can represent the circuit with a schema like this:

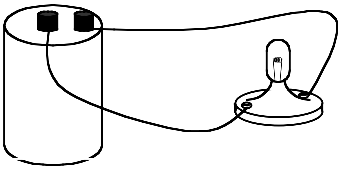


Figure 1: A simple circuit

Figure 2: A system schema for the circuit

Each object in the schema is represented as a box. If two objects interact with each other, draw a line to connect them. This line does not specify the nature of the interaction. It could be a force (*i.e.* an exchange of momentum) and/or an exchange of energy, for example due to collisions among microscopic particles. In this paper we are concerned with exchanges of energy.

Each object represented as a box in a system schema actually may be considered a physical system in its own right. Therefore the system of choice may include everything represented in the schema, or it may include only one of the objects. So, if we designate the all three objects, the battery, the bulb, and the surroundings, as the system, then each object is considered to be a subsystem.

If the all three objects are considered our system of interest, we can indicate that by surrounding them with a dashed line:

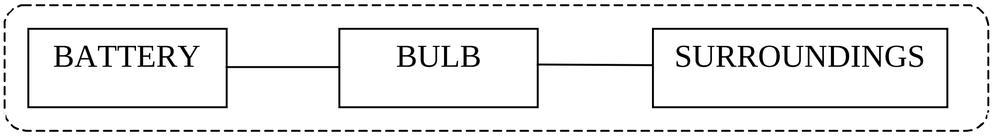


Figure 3: All three objects are the system of interest.

Note that this system is a *closed system*. No significant transfer of energy occurs with anything else. The total energy in this system will stay the same. But we could be interested in just the battery and the bulb. In this case the system would be *open*; energy would transfer from the system to the surroundings.

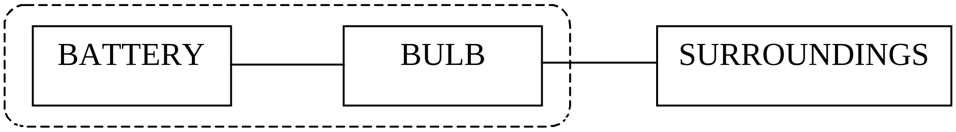


Figure 4: The battery and the bulb constitute an open system.

Another system that is ubiquitous in school science is the sun-earth system. In one respect it is simple to represent—there are only two objects in the system. In another respect it is ambiguous—the interaction between them could be either a force (*i.e.* a transfer of momentum) or a transfer of energy. Both interactions occur and are of signal import. System schemas by themselves are insufficient to describe the interaction in the way that we might want, but still they do serve to delineate the system that we are concerned with. In order to specify the interaction we would use either a force diagram for the earth and another for the sun to show the force each exerts on the other, or we would use an energy flow diagram to show the direction of energy transfer from one object to the other. Energy flow diagrams for several systems commonly used in school science will be illustrated later.

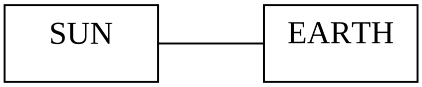


Figure 5: The sun-earth system

It is not always easy to describe a system. If we consider a pot of water warming up on an electric stove we will find that students will have some difficulty in describing a useful system. It is not so simple to decide what to include and what to exclude. Students will wonder if we should include wires, the kitchen floor that holds up the stove, etc. A teacher will need to know how to guide the ensuing discussion to the desired conclusion, but when energy is the interaction of interest, a guiding principle is to include only things that are changed as a result of heating the pot of water.

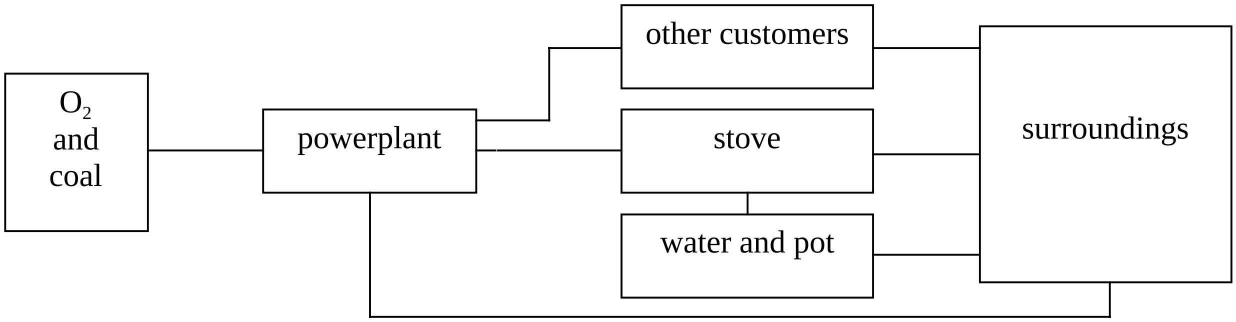


Figure 6: Schema for heating water on a stove

From a schema like the one above a student or teacher can decide what is of interest and what would make a useful system.

Energy always is going to be a property of something in the schema. It can never exist on its own. Therefore, we should carefully avoid making a schema like the following one:

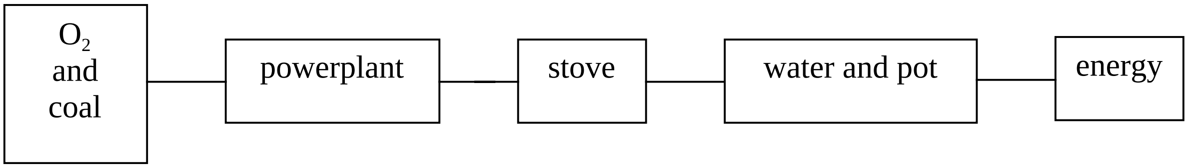


Figure 7: What is wrong with this schema?

Energy can never have an independent, disembodied existence. Energy is not just released; it is always released *to* some other object in which it is stored. Energy is never a system in its own right. Energy can never have its own box, because boxes are reserved for proper physical systems. So one major benefit of a schema is that the things that *store* energy will be made explicit. We will look to these storehouses for changes resulting from transfers of energy.

Once a useful schema has been drawn, we know what we are talking about. Then we can take another step: describe the interaction. In this paper we will consider only interactions that are energy transfers.

Energy flow diagrams

Once we have drawn a useful schema for an energy-related phenomenon, we have identified all the important things that interact as a result of the particular phenomenon at hand. In this analysis the interactions are exchanges of energy. We then need to face two important questions: How will we know which objects gain energy and which ones lose it? What changes about each of these objects as a result of these energy transfers? If our students can answer these questions for the phenomena that we include in school science, we will have gone a long way toward cashing in the educational value added to science because of energy. Perhaps then energy will be more meaningful and more useful to them for describing, explaining, predicting, and designing things in the world and also for solving problems on their high stakes tests.

Energy flow diagrams are augmented system schema. The lines, or "connections," are replaced by block arrows that represent the transfer of energy from one member of a schema to another. The fatter the block arrow, the bigger the transfer. So they illustrate how a system changes from one state to another, *i.e.* through some transfer of energy. And a transfer of energy implies some mechanism.

In this section I will present and describe several energy flow diagrams that pertain to typical phenomena included in school science. They can help to make the explanatory role of energy explicit. They also can help us to think about phenomena according to rules based on energy conservation and the nature of energy as a function of the state of physical systems. As a function of the state of a system, something in the system must change when the amount of energy possessed or stored by the system changes. Students can use energy flow diagrams to make inferences. Thinking like this sometimes makes a phenomenon look much clearer (or stranger) than it did before bringing energy's role to the forefront. In any case, a clear account of energy's role is indispensable for a basic, scientific understanding of any phenomenon.

To begin with, let's make an energy flow diagram for the battery and bulb that we considered earlier.

Figure 8: Energy flow diagram for battery and bulb

This can illustrate the role of the battery, the bulb, and the surroundings. The arrows represent energy that is transferred from the battery to the bulb to the surroundings. The relative widths of the arrows represent the sizes of the energy transfers. In this case, the sizes of the transfers are the same, at least while the circuit is operating at equilibrium. This is the normal operation of the light and battery. As the battery runs out of energy and the bulb dims, the arrows would be drawn thinner.

The battery is the source of the energy that lights the bulb. It is not being replenished. We can conclude from this and energy conservation that it will run out of energy eventually. The bulb serves as an energy transfer agent. In essence its role is to transfer energy from the battery to the surroundings. It never possesses much energy, but it clearly is the transfer point.

This energy flow diagram could be introduced relatively early in elementary school, probably as soon as batteries and bulbs are introduced. Only the fact of energy flow need be dealt with at the earliest stages. In high school physics a distinction may be made among the different ways that energy can be transferred. The energy transfer between the battery and the bulb is because of electrical forces. If we designate the bulb as a system, then this energy transfer is called *work*, because work is the amount of energy transferred to or from a system because of a force. Of course, one need not call it work to have a complete physical understanding of the process. In fact, if we consider the bulb and the battery together to be a system, then the energy transferred from the battery to the bulb should *not* be called work. Energy is transferred from the bulb to the surroundings because of a difference in temperature. Again, if the bulb and the surroundings are considered to be in different systems, the amount of energy transferred is called *heat*, because heat is the amount of energy transferred from one system to another because of a temperature difference. Of course, one need not call it heat to completely understand what is going on. “Work” and “heat” are relics from the 19th century and are still in common use. Therefore, in deference to convention, but not because of logic, high school students should learn these narrowly defined, often misused, archaic names for two different ways that energy can be transferred. Of course, energy stored in the battery, or in the bulb, or in the surroundings can be called, very simply, energy.

What changes occur in each of the energy storehouses? In the *battery* reactants are attracted to each other, and products are produced as a result. A fresh battery and a thoroughly exhausted one may be cut open and compared to see differences. In the *bulb* the change is apparent; it lights up, at least when the battery is fresh. It may only be slightly warm as the battery runs out of reactants. The *surroundings* simply warm up as a result of receiving energy from the bulb.

For our second energy flow diagram let’s consider the sun-earth system. Like the battery in the circuit just considered, the sun is the source of energy, but it receives no energy. Therefore students can conclude (and they do) that the sun will run out of energy. But not next week. When energy conservation is understood and applied, it becomes a constraint that forces inferences.

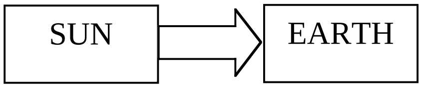


Figure 9: Energy flow for the sun-earth system

What else can we conclude from this flow diagram? Students need to wonder about how energy gets to the earth from the sun. It should be no stretch of their ability to determine that light has something to do with it. But there is more to light than meets the eye. Infrared radiation is also important, and other portions of the electromagnetic spectrum chip in their two bits as well. Certainly “light” alone would be a good enough mechanism for energy transfer from sun to earth in earlier elementary school. The other parts of the electromagnetic spectrum can be brought in to this flow diagram as they are needed in later grades.

Energy flow diagrams force inferences.

There is more work to be done with this flow diagram. The earth is only receiving energy, so far as we can see from this diagram. If that is the case, we should see some change. What would the change be? Global warming? Or something worse? If we take seriously the role of energy as a function of the state of an object, then something about the earth would change as it receives more and more energy from the sun. The main thing that we want students to think of is the temperature of the earth. Since it is not apparent that the earth's temperature is steadily climbing, we need to infer that something is missing from our schema (which now has been augmented to be a flow diagram). In fact, we need to include the surroundings of the earth, namely, space.

Figure 10: Energy flow for sun-earth-space system

Students ought to wonder how energy goes from earth to space. Like a warm (but not glowing) light bulb filament, it emits infrared radiation.

What would happen to the earth if the energy flow diagram looked like this?

Figure 11: A proposed energy flow diagram for sun-earth-space system

Or what would happen to the earth if the energy flow diagram looked like this?

Figure 12: Another proposed energy flow diagram for sun-earth-space system

In each case we can see what would happen to the relative sizes of the energy transfers if the earth is to experience global cooling and another ice age or global warming and nice winters in Chicago. The next question that naturally arises is what might cause the earth to experience a net gain of energy or a net loss of energy. The potential mechanisms for at least one of these two possibilities are very much in the press these days.

Energy flow diagrams are good for making inferences, so long as students are committed to a hardy energy conservation concept and the fact that energy must always be a function of the state of some system. Of course, that is what we purport to instill in them. In order to develop this commitment in our students, we need always to ask students about the changes that energy transfers may cause in the interacting systems. No energy transfer can occur without at least two changes, at least one in the giver and at least one in the receiver.

With system schema and energy flow diagrams in our box of resources, we will now use them to analyze phenomena that are often included in school science.

Sea breezes and land breezes are energy-related phenomena that often appear when children are learning about weather. The energy flow for these two phenomena can be represented as shown below:

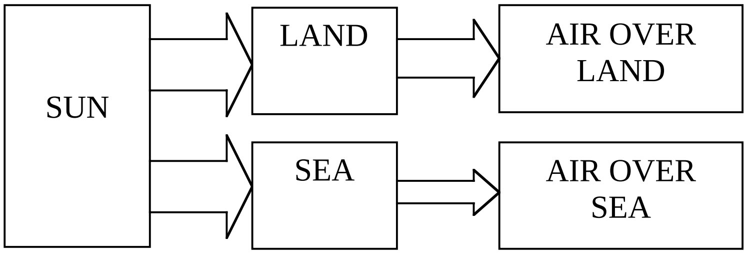


Figure 13: Energy flow for a sea breeze

The flow of energy from the sun into equal areas of land and adjacent sea is about the same. The land becomes much warmer than the sea does, however, as many children find from experience. Therefore, more energy is transferred to the air that interacts with the land than to the air that interacts with the sea. This causes the uneven heating during the day. During the night, the story is different.

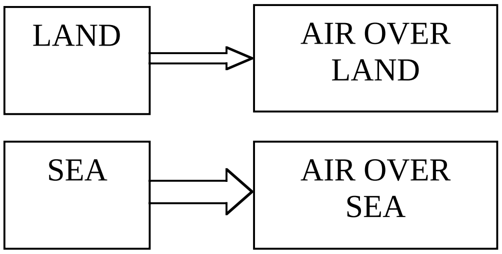


Figure 14: Energy flow for a land breeze

The land cools more and so transfers less energy to the air during the night than the sea does. Now the air over the water is warmer, and so it rises and is displaced by air streaming from over the land. A teacher might decide to use the fact of land and sea breezes to infer what must be happening to the energy flows. Or it the diagrams are made available, the need to account for why these diagrams must be something like this begs for an answer. The path to that answer leads through the idea of heat capacity and specific heat, should a teacher desire students to make arguments in those terms.

One driver of energy transfer is a temperature difference between two interacting systems. In the case of a cold-pack of the type used for sports injuries an energy flow diagram looks something like this:

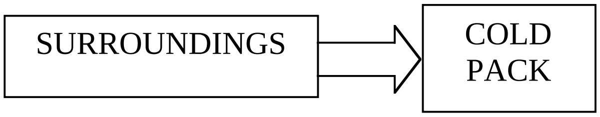


Figure 15: Energy flow for a cold pack

What must happen as a result of this transfer of energy? Specifically, we are looking for changes in some state variables. We know that the cold pack will eventually get warmer and the surroundings will certainly become cooler (that is the point of the cold pack, of course). But there are other things to think about. When a cold pack is first "broken" in order to get the reaction going so that it gets cold, what happens to the amount of energy in the cold pack? Since no energy escapes from the cold pack (What would happen to the surroundings if energy leaves the cold pack?), we must conclude that its energy does not decrease. On the contrary, the energy content of the cold pack increases, even as it gets colder…in fact, *because* it gets colder. The constraints of energy conservation and the requirement that energy must be a function of state can lead to this counter-intuitive but reasonable conclusion.

Evaporation and condensation of water are universal components of school science, even in early elementary school. A series of energy flow diagrams follows that illustrate different levels of detail that one may include in flow diagrams and their accompanying description. Evaporation of a sample of water may be represented as follows:

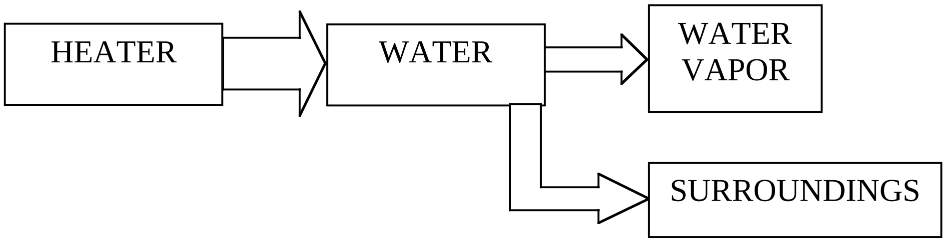


Figure 16: Energy flow for evaporating water

Water molecules are fairly well stuck to successive multiple neighbor molecules while in the liquid state. Water molecules are separated from each other in the vapor state, though they remain attractive to each other. It requires energy to separate them. That is just what the heater supplies.

But what about condensation? It may be represented as shown below:

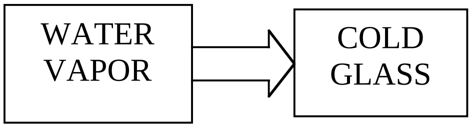


Figure 17: Energy flow for condensing water

Water vapor condenses when water molecules lose enough kinetic energy to some other physical system.

Figures 16 and 17 have a place in elementary school. But as a particle model for matter is developed in the years up to ninth grade, more detailed accounts may accompany energy flow diagrams. For example, in the case of a cold glass water vapor has an obvious recipient for the energy it sheds. But what about when fog develops? What, if anything, receives any energy then? If water vapor cannot give up energy to *something*, then there will be no change in the water vapor system. So what gets the energy and what are the changes that result?

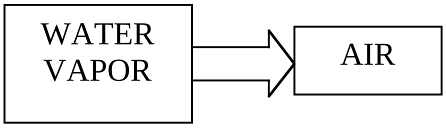


Figure 18: Energy flow for condensing water

Here is an account of how water vapor condenses in air. The water molecules attract each other. As they approach one another, they speed up. The kinetic energy they gain comes from the electric field through which they interact. As they approach each other they may collide with air molecules which, on the average, receive energy from the water molecules. Depleted of the energy lost in collisions with air molecules, the water molecules no longer have enough energy to escape each other. They remain bound to each other and then to even more water molecules, forming a droplet of liquid water. Air gains the energy lost by the water molecules in their collisions while in the vapor phase. The necessary change in the air is its temperature, at least locally. It is for this reason that nighttime temperatures seldom dip below the dewpoint. An energy flow diagram can help us here as well.

Figure 19: Energy flow for air cooling at night

In Figure 19 energy goes from air into space through radiation and the air cools, because the land does not provide as much energy to the air as it loses. When air does not contain much water vapor this process continues all night long without reaching the dewpoint. But things are different when there is a lot of water vapor in the air. The cooling process stops when the air becomes so cool that condensation begins. When the dewpoint is reached the air begins to receive energy from the condensing water vapor. From one point of view the change involved in the water vapor is the separation of the water molecules. For many purposes this may be adequate. From a more complete, microscopic point of view the change is the diminishing of the electric fields through which the water molecules interact with each other. The electric fields diminish as oppositely charges regions of polar water molecules approach each other. Electric fields around the water molecules contain less energy after being diminished. The change in the air is the acquisition of kinetic energy for air molecules where the fog forms. But the air temperature does not rise because the air loses just as much energy to space as it gains from the condensing water.

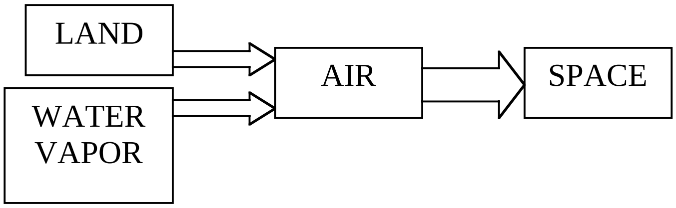


Figure 20: Energy flow for fog formation

Whatever the desired detail of the account, the energy flow diagrams can help students to understand the role and effects of energy transfers.

When huge amounts of water vapor condenses, huge amounts of energy are acquired by the air which therefore rises. Consider the energy flow diagram for a hurricane:

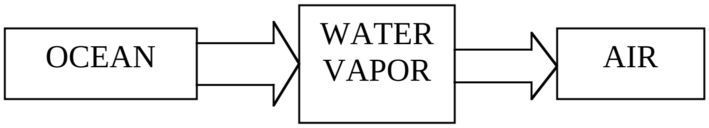


Figure 21: Energy flow for a hurricane

How much energy is stored in the ocean beneath a hurricane? Quite a lot. With such a large source of energy it is no wonder that hurricanes are often fearsome.

This diagram can be augmented even further to illustrate the range of information that may be included in such a diagram. In Figure 22 we show not only the energy flow, we also show the flow of matter by using thin arrows.

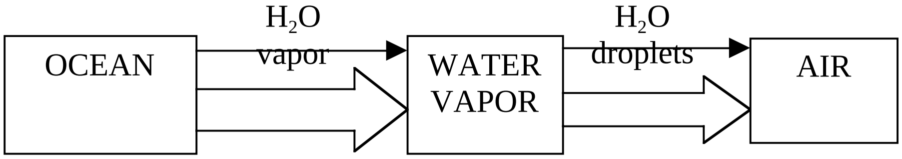


Figure 22: Energy and matter flow for a hurricane

Students could be asked to consider what may happen when a hurricane moves over land. Without the ocean for an energy source, the process of evaporation and condensation cannot continue to pump energy into the air.

Photosynthesis is fundamental in school science. Early in school students learn what the effect of sunlight on plants is. From an energy perspective we can represent the situation something like this:

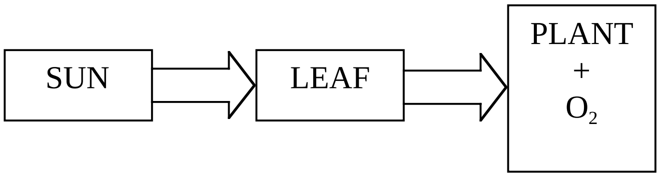


Figure 23: Energy flow for plants

The energy from the sun used in photosynthesis is not really stored in the plant alone. As biomolecules are built in the respiration of the plant, a separation of oxygen occurs. This separation takes energy. What you get for the energy input are enhanced electric fields through which these molecules interact. The fields are built up as regions of opposite charge in oxygen and the biomolecules are separated.

For biology students a matter and energy flow diagram can elaborate photosynthesis a little more.

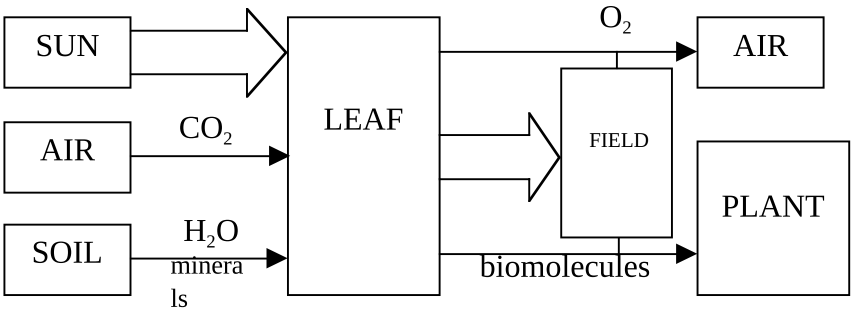


Figure 24: Matter and energy flow for a plant

Once again we have augmented the diagram so that the electric fields through which oxygen and the biomolecules of the plant attract each other are collectively represented as a physical system.

We see that the energy from the sun that is stored because of photosynthesis is not stored in the biomolecules. It is stored in the oxygen-biomolecule system as interaction energy, *i.e.* energy stored in the electric fields through which oxygen and these molecules interact. That is why oxygen *and* fuel are needed for combustion. The fuel alone doesn't have any energy available to tap.

We can get this energy back from the electric fields when oxygen recombines with the biomolecules. When the plant is dried out (necessary from an energy point of view so that a lot of energy isn't carried away by water vapor) a very complicated process can occur in which oxygen molecules in the air are attracted to and collide with biomolecules. If the kinetic energy of the oxygen molecules is sufficiently high (meaning a high temperature is needed) the oxygen may recombine with these biomolecules because of their mutual electrical attraction when they get close enough. The plant can burn, and the energy then is given mostly to the air through molecular collisions. Thinking about mechanisms in terms of particles and fields adds a level of detail that may not be necessary until a basic account of reactions at the atomic scale are of interest.

A burning candle is a common system in school science for which we can make a basic energy flow diagram as follows:

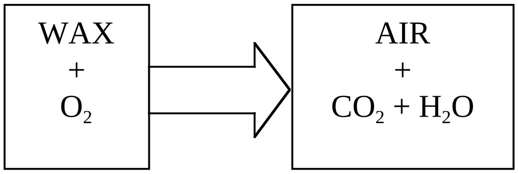


Figure 25: Energy flow diagram for a burning candle

Students often think that energy is produced by the flame when a candle burns. They do not believe that there is any energy there to begin with because it is not perceptible. (That's the way it is with energy stored in electric fields and gravitational fields.) They do not have a good understanding of energy and its conservation. If students make this claim, they should be challenged to draw an energy flow diagram for the situation. A student will then face interesting questions from within, from peers, or from the teacher in any attempt to justify the creation of energy.

A similar situation involves respiration in animals like humans, for example. Our energy flow diagram while resting might be drawn like this.

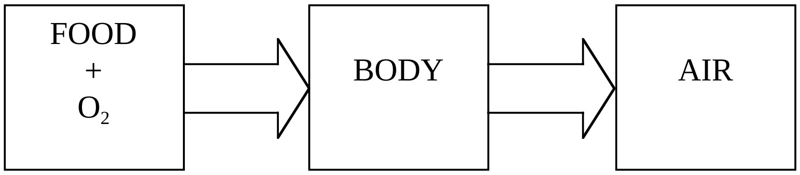
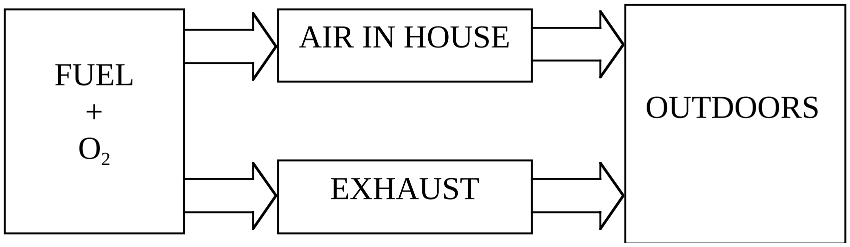


Figure 26: Energy flow diagram for a person at rest

Notice that energy is not stored in the food alone. It is not in the oxygen alone either. Technically it is stored in the electric fields involved in their mutual attraction. Therefore, we have to breathe in oxygen, or we will not have energy for life processes. This basic energy flow diagram also illustrates that energy must leave our bodies. Otherwise we would change; our temperatures would rise as we bring energy into our bodies through breathing and trap it there through the thermal motions of the products of respiration. Should a teacher so desire, Figure 26 could be augmented to show the flow of both matter and energy through our bodies.

Heating our homes is part and parcel of discussion throughout school science. Energy flow can make apparent what we may already know: Insulation reduces the use of fuel. Energy flow diagrams can make it clearer why this is so.



What will happen if we reduce the energy flow from the air in the house to the outside? If the energy coming into the house from the furnace ends up being greater than the energy flow to the outside, then the house will warm up. By reducing the flow of energy to the outside from our house we may reduce the energy supplied from the fuel and oxygen system. There are many ways to increase of decrease the flows of energy into and out of the house.

A refrigerator is an energy enigma for most people. An energy flow diagram for it may help to illustrate the role of energy in the cooling of the food inside.

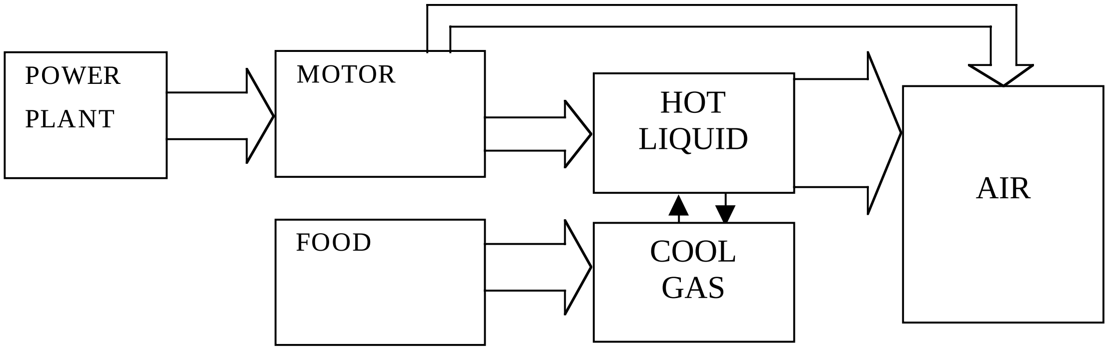


Figure 28: Energy flow diagram for a refrigerator

When a compressed gas is released, say, from a bicycle tire or an aerosol boat horn, it gets cold. The energy flow diagram for this process can be drawn as follows:

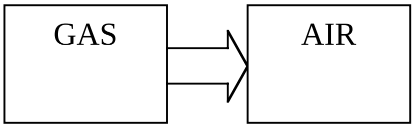


Figure 29: Energy flow diagram for an expanding gas

How does the gas give energy to the air? It pushes it back. What if the gas expands into a vacuum? What will happen to its temperature then? The energy flow diagram gives us a hint.

These energy flow diagrams simply give us a way to represent the transfers of energy explicitly. Whenever there is a difference between incoming and outgoing energy flows for a system, something in the system will change. Energy is not just a number, it is a function of the state of a system.

B. Pictures

In order to draw a picture useful for the analysis of some real or described situation students have to identify and abstract the salient objects and features. In this respect pictures have a function similar to that of energy flow diagrams. But they afford an additional opportunity for depicting an initial state, a final state, and a coordinate system that can be used to evaluate stored energy on a definite scale. Because *they are useful for describing the state of a system*, pictures will be most useful when the ideas of “system” and “state” become important. This is usually in high school.

C. “Before-and-after” energy bar graphs and pie charts

Energy bar graphs and pie charts enable students to create a qualitative analysis of phenomena based upon energy storage and transfers. Bar graphs in particular have been demonstrated to be a factor in increasing students’ problem solving success in conjunction with other representations. Since they are qualitative tools, they can be introduced in elementary school after such graphs become useful to the students for two interacting objects (a giver of energy and a receiver of that energy). One way to use bar graphs is in conjunction with a flow diagram for the situation of interest. The initial state bar graph is first sketched to describe the situation before the process occurs. The energy flow diagram can then be drawn to represent the transfer of energy that occurs during the process, and then the final state bar graph is drawn to describe the resulting final state of the system of interest. This combination of representations could be useful for seventh graders.

D. Graphical integral of force as a function of position

If students have already learned the Newtonian force concept, then the amount of energy transferred in some process may be quantified from the graphical integral of $F_x(x)$. In physics courses based on algebra this enables students to evaluate energy transfers for variable forces such as inverse-square forces without introducing equations strictly obtained using the methods of calculus. Furthermore, such graphical representations for energy transfers can coordinate with the other representations to give students yet another tool for thinking about energy. The appropriate time for introducing the graphical integral is in the introductory physics course.

E. Energy diagrams

Energy diagrams (or potential energy diagrams) are one of the richest representations for describing and explaining the behavior of two particle systems. These diagrams are plots of the energy stored in some field or some object such as a spring. Such plots make explicit the *functional* nature of energy; energy is not just a number. These diagrams can be used to account for binding and escape, and oscillations of bound systems. In typical use, energy diagrams for bound particles are used to deduce the amplitudes of oscillations and the cyclical exchange of energy between particle and field (or spring). For example, the kinetic energy of the particle may and the potential energy stored in the field may both be deduced if the total energy of the bound system is given. The forces experienced by the bound particles resulting from the field with which they interact may be obtained from the derivatives of these functions. Therefore such diagrams can account for attraction, repulsion, and equilibrium as well as amplitude.

F. Software

As rich as energy diagrams are, they cannot represent energy transfers that are involved in changing the energy of a bound system, in binding, and in escaping. In the microscopic realm these energy transfers occur in collisions with other particles. The educational computer program, *Atoms in Motion*, provides a virtual context for representing such interactions.

G. Equations

Ultimately mathematical expression provides the economy and flexibility to communicate. Seldom, if ever, do these expressions entail anywhere near all the various associations available to experts. These associations are provided by all the other possible representations and enable physicists to have a *visualizable* understanding of physical reality. This *Anshaulichkeit* has been highly esteemed over the years among physicists, except perhaps in various interpretations of quantum theory. It helps to provide meaning to the equations for those who know them best, those to whom the appellation *intuitive* is appropriate. In some small degree we hope that our students may gain such an understanding.

Chemical equations as currently written often include energy as a reactant or as a product on one of te sides. Are students to presume that it does not exist on the other side of the equation?