Understanding Energy

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Introduction

Traditional physics texts develop ideas and concepts in a hierarchical structure. Authors assume that the proper way to understand the subject is by working your way up through a web of ideas, from simple stuff at the bottom to higher concepts at the top. A serious defect in that approach to writing school-level physics is that by keeping it simple at the basic level we can also make it wrong. This article, which is intended to be provocative, is an updated version of one that I wrote for an earlier workshop (Sefton, 1998). I assume that you already know quite a lot about the concept of energy in physics and that you have gained a lot of that knowledge by reading the kind of text-book that is aimed at your students. I am going to challenge and criticise some of that text-book knowledge (Andriessen et al, 2001) as well as the New South Wales syllabus (Board of Studies, 2002) and I will try to demonstrate some more scientific conceptions. The discussion here will probe somewhat more deeply than the syllabus does into the scientific concept of energy.

Naive conceptions of energy

Before we consider the text books, let's have a look at what students may already know. Many of the ideas that children have about energy have been summarised in papers by various educational researchers. Joan Solomon (1982, 1983) has reported that children typically start with ideas of energy related to personal experiences of human activities, vitalism and activity - "jumping about" or "being lively". But objects such as machines, wind and waves can also have energy. Solomon (1983) sees children's out-of-school conceptions of energy as being messy, contradictory and obstinately persistent. In my view, very few of the ideas that kids are reported to hold are totally incompatible with scientific meanings. To the extent that they are unscientific, many are simply incomplete while a few are overstated. Many of those overstated incorrect ideas, such as the widely-taught notion that "all energy comes from the sun", can easily be made valid, in this example by removing "all" or substituting "some".

Some researchers including Watts (1983), Duit (1984) and Trumper (1990a, 1990b, 1991) have tried to get some order into the findings of educational research by developing categories and conceptual frameworks to describe ideas about energy. For example Trumper and Gorsky (1993) identified nine distinct conceptual frameworks for talking about energy. Characteristics of these broad conceptions are as follows.

1. Energy is associated with people.
2. Things possess and expend energy.
3. Energy causes things to happen.
4. Energy is an ingredient in things and can be released by a trigger.
5. Energy is associated with activity.
6. Energy is created by certain processes.
7. Energy is a generalised kind of fuel associated with making life comfortable.
8. Energy is a kind of fluid which is transferred in some processes.
9. A scientific conception in which energy is transferred from one system to another.

Although the last item on this list implies that the others are unscientific, I think it would be unwise to dismiss all the others as being entirely wrong or irrelevant. Rather than simply contradicting students' views, a better strategy is to build on what students know and try to help them to modify their knowledge in appropriate ways. Whatever you may think about the interpretation of this kind of research, it is very important that teachers should be aware of the ways that their students talk and think about energy. Good sources with specific examples of young people's ideas include papers by Watts (1983) who developed a classification of conceptual frameworks similar to that above, Solomon (1982, 1983), Duit (1984) and Trumper (1990).

Energy as the cause of things

Possibly the least scientific in Trumper's list of conceptual frameworks (above) is no. 3 - energy as the cause of things. Energy of itself does not cause anything. This kind of interpretation may be reinforced by teaching programs which, recognising the importance of energy as a universal concept, go overboard by using energy as a universal explanation. The reality about the theories of physics is that energy itself has little explanatory power in telling exactly how nature behaves; it tells more about what is impossible. The conservation principle and the laws of thermodynamics restrict or constrain what can happen but they don't determine it. Jon Ogborn (1990) has explored these ideas in some depth.

Background concepts

All learning builds on prior knowledge. To provide a solid foundation for the conceptions of energy that I will outline we need to establish a few other concepts, notably the ideas of a physical system and a frame of reference. We will also need to develop an understanding of the nature of scientific theory and of modelling.

A physical system can be any collection of things that we want to study, such as a moving car and its contents. Usually we can mentally draw some kind of imaginary boundary around the system. Then everything outside the boundary can be considered as its environment. In the case of the car, the environment would include the road and the atmosphere. In a typical mechanics problem we would construct an abstract model of the system by ignoring some features which might be quite important in other contexts, such as the fact that a car sucks in air and emits exhaust gases. Depending on the problem, we might model the car as a solid object with four rotating wheels in contact with the road. The atmosphere might be modelled as a vague object which exerts a retarding force located at some point on the car. The connection between the ideas of energy and system is that it is often useful to think of the system as having energy and to study how the system may be exchanging energy with the rest of the universe (the environment).

A frame of reference (or frame for short) is provided by some object (or a collection of objects) onto which we can tie a fixed system of co-ordinate axes and a time scale. The idea of a frame will be important for understanding definitions of kinetic and potential energy. For more about frames find a chapter about relativity in your favourite text or see my article about *Understanding Relativity* in this volume .

Definitions of energy

Didactic teaching often seems to demand that ideas should be given precise definitions, but energy can be a slippery concept: just when you think you have grasped it some new example is likely to elude you. There is really no unique, absolute or universal concept of energy and it has no simple definition. Furthermore, even though it would be nice if the concept of energy were immutable, the history of physics shows that conceptions change. Ideas about energy are still developing and cropping up in new contexts. For example, physicists of half a century ago (as I was) would have a hard time understanding the modern, somewhat speculative, concept of a "dark energy" that drives the expansion of the cosmos.

One of the best elementary explanations of energy was given by Nobel laureate Richard Feynman (Feynman et al 1963, pp 4-1 to 4-80). Energy is not something perceptible but a quantity that has to be calculated using a comprehensive set of rules. Feynman used a metaphorical story about a mother counting a kid's toy blocks. An underlying principle, conservation of blocks, leads Mother to look in more and more places (do more experiments) and to find new ways to account for blocks (invent more theory) to make sure that the conservation principle works. That kind of explanation is nothing like a traditional schoolbook definition. Feynman's introductory statement is about a thousand words long even before he gets to specific examples. His "definition" differs from formal texts in another very important way: the concept remains open to future modification, even falsification. In effect, he says "I don't know what energy is but if you have plenty of time I can teach you how to calculate it".

Extending Feynman's approach with words rather than calculations, we could seek a comprehensive definition of energy by making a list of independent and valid statements about the nature of energy. Such a list could be very long, but consider this lot for starters (some of these will be developed further in this article and in the workshop session).

- Energy is an attribute of a system which may consist of one or more objects.
- Changes in the energy of a system can, in principle[*], be calculated (or measured indirectly), but it is usually not feasible to assign a value to the total energy of a system.
- Whenever the energy of a system increases (or decreases) there is a corresponding decrease (or increase) outside the system. (Conservation of energy - weak version)
- Changes in the energy of a system can be tracked across the system's boundary. (Conservation of energy - strong version - also called local conservation)
- There are only two basic kinds of energy: kinetic energy (KE) and potential energy (PE).
- Kinetic energy is associated with motion.
- Potential energy is associated with interactions between objects.
- Potential energy can be defined only for a system consisting of two or more parts (i.e. the system must have some structure – an isolated particle can't have potential energy).
- Electromagnetic PE can be described as being stored in and transmitted by the electric and magnetic fields.
- Chemical changes involve changes in electromagnetic PE (i.e. chemical interactions are entirely electromagnetic in nature).
- When a hot body and a cold body are in contact, the hot body loses energy and the cold body gains energy. Most physicists refer to the energy transferred in that way as "heat".
- When the internal energy of a system changes so does its mass: $\Delta E = \Delta m c^2$.

  .... etc.

Further understanding may come from a list of statements about what energy is not. These are easier to generate. We can, for example, go to the popular press and find references to "energy" which are clearly not the idea that we are talking about in science. Here are some starters.

- Energy is not given off by crystals.
- Energy is not a feeling of well-being.
- Energy does not cause things to happen.
- In spite of what it says on my gas bill, the gas company does not sell energy.

  .... etc.

Energy and work

Many texts give neat packaged definitions of energy such as: "energy is the capacity to do work". Taken literally, definitions like that are at best misleading. At worst they are just plain wrong. The main argument against such a definition comes from thermodynamics. In thermodynamics *work* takes on a meaning which is broader than the "force times distance" concept of classical mechanics. It refers either to a process of energy transfer or to the energy being transferred. Many

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[*] The phrase "in principle" means that we can do it if we have enough information, but we don't need the actual numbers to think about the process.

texts are not clear which of those two concepts they mean and often use them interchangeably, but when work appears in equations it always has the dimensions of energy. The catch is that not all energy can produce work; according to the second law of thermodynamics there is *always* some part of the energy of a system that cannot produce work. Such objections aside, there does not seem to be much information content in the statement that "energy is the capacity to be energy that is being transferred (by some process or other)" or "energy is the ability to do force times distance". For a good summary of this kind of argument see Lehrman (1973). Some other aspects of the debate about work and energy are covered in a paper by Sexl (1981) and a reply by Duit (1981).

Conservation of energy

To physicists the keystone of the vast energy concept is conservation. Without conservation energy would mean nothing. A severe problem for teachers is that the word conservation has two quite different meanings, even within science lessons. To a physicist, conservation of energy means that energy calculations, correctly performed, always balance to give a constant total. To most literate people, including many science teachers, conservation means saving energy or not wasting it. That meaning is continually reinforced by media reports. It must be a great puzzle for many school students to be told in some classes of the need to conserve energy and in others that it is always conserved, no matter what we do.

The common interpretation of conservation as husbandry fits well with naive conceptions of energy based on life experience and contradicts the notion of conservation as constancy. Think of nature conservation or the conservation of natural resources. In common experience energy, once used, is gone forever. That kind of understanding of energy is not only common but valid in a sense expressed by the second law of thermodynamics. Although the used energy has not been destroyed, it may not be accessible for re-use. Many of the untutored conceptions of energy can be related to an idea that we could call available energy, that is energy which can, in principle, be transferred between systems by the process called work. Such ideas do exist within the formal structure of thermodynamics but are not usually acknowledged in elementary treatments. A related idea, that should be compatible with people's life experiences, is that the energy-transfer process which most physicists call heat or heating is ubiquitous.

It seems to me that common experience involving energy is a good foundation for a teaching approach based on the two different meanings of conservation based on the second and first laws of thermodynamics. The second law matches the common meaning of conservation as avoiding degradation (you can't re-use the lost energy) and the first law matches the physicist's conception of conservation (the lost energy still exists). Such an approach is surely more intelligible than rigmaroles about capacity to do work. In an article worth reading for some good ideas about teaching energy to junior science classes Joan Solomon (1982) has outlined such an approach in which the second law is expressed by associating all energy changes with "a running down towards sameness".

Kinetic Energy

The idea of kinetic energy (KE) seems simple enough, but saying that it is $\frac{1}{2}mv^2$ is only part of the story. That formula applies, strictly, only to the abstract notion of a particle. In that case the meaning of v is quite straightforward: it is the particle's speed. On the other hand, real bodies have structure and different parts of that structure may have different motions and different speeds. Clearly, it could be a complicated business to calculate the total kinetic energy of a body. Think of a lump of jelly that has been thrown in the air. As well as its bulk motion along a trajectory it also shakes and rotates. What the syllabus and texts seem to be talking about when they refer to KE and $\frac{1}{2}mv^2$ is *translational kinetic energy* which is associated only with the motion of one point in the body called its centre of mass. You can think of the centre of mass of a body as being a point that represents an average position for all the body's mass. Whenever we model a real body as a particle, we put the particle at the centre of mass and concentrate all the mass there. Another thing to note about the translational KE of a body is that its value depends on the frame of reference that is used to specify or measure the speed.

Potential Energy

Potential energy (PE) is a strange term; it seems to mean energy that isn't energy yet but might become energy some time soon. That was probably the original meaning: PE can become what we now call KE. In modern usage potential energy means energy that is associated with the forces of interaction between objects. PE is always associated with a system of two or more objects, never with a single particle. Failure to understand that restriction is so serious that I have labelled it as a fallacy, on which I will say more later in this article. The value of PE can also be somewhat arbitrary because the formal definitions of PE always refer to changes in PE, rather than a value for PE itself. In situations where it is useful to think about a value for PE we need to specify or assume some configuration of the system which has PE = 0.

Internal Energy: KE and PE mingled

At a fundamental level of thinking, there are only two kinds of energy: KE and PE. In a classical (19th century) model of the structure of matter, everything consists of interacting molecules. All those molecules can have their own KE of translation, rotation and vibration and they also interact with each other, so that the system as a whole has PE. In this picture it is valid enough to think of the KE of an individual particle, but not the PE of an individual particle. Each particle interacts with all its neighbours. It just doesn't make sense to apportion the PE among individual particles. Furthermore there is a continual interchange between the KE of each particle and the PE of the system. At this level it is much easier to think about the total energy, KE + PE, of the whole system. In thermal physics that total energy is called the internal energy of the system. (Any KE associated with the motion of the system as a whole is usually left out of that definition of internal energy.)

At a smaller scale still we might consider the internal energy of an individual atom. Consider for simplicity an isolated atom that does not interact with any neighbours. Although the atom may be moving and therefore has a translational KE, we can also think of it as having an internal structure, a nucleus and a cloud of electrons, which also have energy. The appropriate theory here is quantum mechanics which can be used to describe the total energy of the system, nucleus and electrons, but there is really no sense any more in distinguishing between kinetic and potential energy for the individual components. The system simply has energy. This view contrasts with the discussion found in many texts which attribute energy to individual electrons. Again I think that view is mistaken - the energy belongs to the system. So when one talks, for example, about energy levels associated with the quantised states of an atom, those energies belong to the atom, not the individual electrons. Similarly with ionisation: to remove an electron from an atom requires that energy is given to the system, not just to the electron that is removed.

Forms of Energy

Many school text-books carry on a lot about “forms” of energy but many physicists consider that approach to be an unnecessary complication which contributes little to understanding. The labelling of the so-called forms of energy is often related to a context, which is fine if the label serves to identify the context but can be very misleading if the label is taken to mean that the character of energy is different in different situations.

Here is an example. Many texts say, reasonably, that light carries energy but it is also very common to see references to light energy, as though it were a new kind of beast. Worse still is the linguistic slide into saying that light is a form of energy. No, it's not. Light is light; it can be modelled as electromagnetic waves; it can be modelled as photons; but it is definitely not energy. To my mind, saying that light is a form of energy is like saying that grass is a form of greenness.

This idea that energy can take different forms seems to be analogous to the idea that matter can exist in different phases or states like solid, liquid or gas. If energy is substance-like then the concept of forms of energy probably makes sense, but what does it mean if we accept the abstract nature of energy as being something that we calculate according to a set of rules? In that case it seems that the "forms" must be defined by the rules and the names given to the forms are nothing more than names for the rules.

Several authors with teaching experience have suggested that teaching about forms of energy is at best unnecessary and at worst misleading. See, for example, Ellse (1988) who argues that in school it is more important to teach about energy transfer than energy transformation. Others, such as Falk, Herrmann and Schmid (1983), or Schmid (1983, 1984), while adopting a substance-like view of energy, nevertheless argue against the notion of energy forms. They prefer the notion of "energy carriers" which is based on the premise that whenever energy flows, so does at least one other physical quantity.

In summary: teaching about forms of energy other than KE and PE, while not exactly wrong, is not very helpful or illuminating either.

Energy as substance - can it be stored?

In some contexts many people conceptualise energy to be like a fluid which you can trade or keep in some kind of "container" such as a litre of petrol or a battery. On the face of it, this view seems to be rational enough. Given that energy is a conserved quantity, then thinking of energy in the same way that we think of substance, whose amount is also a conserved quantity, seems like a good idea. It is also compatible with the idea of energy transfer: energy can get from one system to another by "flowing" between them. That is the kind of mental modelling we use when we think thermodynamics: "heat cannot of itself pass from one body to a hotter..." (Flanders & Swann, 1964).

Thinking of energy as a kind of substance is anathema to many physicists such as J. W. Warren (1982, 1983, 1986) who has ridiculed much writing, teaching and proposed curriculum development about energy as being mystical and unscientific. Although Warren's critique is built on a somewhat rigid view of the structure of physics he has articulated many good arguments against sloppy and unscientific thinking about energy in school texts and syllabuses. For example energy is one measure of the state or condition of a system whereas work is not energy but a process that changes the energy of a system.

I too have some serious problems with the conception of energy as substance. One of these is related to frames of reference. The principle of conservation of energy apparently leads some people to think that the value of the total energy of a system is completely defined by the laws of nature, but that is not so. Conservation of energy depends on picking a suitable frame of reference and sticking to it. For example, the kinetic energy of a moving object depends on the frame of reference used to specify it. In a frame of reference that moves with the object, the object's KE is zero. But other choices of frames can give any value at all! As the relative speed of object and observer's frame approaches the speed of light you can get arbitrarily large values of KE for the object. In contrast to that idea, the amount of substance that you measure does not depend on the frame of reference; a mole of stuff is a mole of stuff however and wherever you look at it.

Just as an arbitrary choice of a reference frame can give any value of KE, you can also get any value of PE that you like within one frame because the definition ascribes values only to changes in PE. So absolute values of PE are in principle arbitrary. It is very difficult to reconcile these arbitrary aspects of energy with the notion that it is like a substance that can be stored.

There is also a problem in conceptualising the energy associated with electromagnetic fields. Although conservation of energy implies that you should find the total energy of a system by adding up all the bits of energy, that calculation principle works only up to a point. For example if you want to find the energy associated with the electric field in a system, you have to go about that calculation in the proper way. Consider the simple case of the energy associated with a charged conducting sphere. There is an electric field in the space surrounding the sphere and a certain amount of energy associated with that field which you can calculate using the appropriate formulas. Now suppose that you have another charged sphere nearby. The proper way to calculate the energy distribution associated with field in the system of the two charged spheres is to set up the system first and then do the calculations. If you add the field energies for two subsystems each consisting of one of the charged spheres on its own you will get the wrong answer. If you use field in your calculations of energy you must calculate the field before you calculate the energy.

This rule is illustrated in the way one calculates interference patterns in optics. Think, for example about Young's double slit experiment. To calculate where the energy goes in the interference pattern, you must first calculate electric fields ("wave disturbances"); you add up (or integrate) the contributions to the total field from different sources. Only when you know enough about the field can you calculate where energy goes – essentially by squaring the total field. If you try to calculate the energy contributions from the different sources first and then add all those energy contributions you get the wrong answer altogether. In technical terms, field obeys the principle of superposition, which means that you can (vectorially) add up its contributions to a whole, but field energy does not obey the superposition principle. This example suggests strongly that it is misleading to think of electromagnetic energy as a substance-like thing.

So although conceiving or modelling energy as substance may work well enough in some situations, there are others where that view can be misleading – sometimes dangerously so. If, on the other hand, you accept that energy is a way of describing the state of a system, then it is difficult to see how it can be stored.

In spite of physicists' objections to the view of energy as substance, some educational researchers continue to see some merit in that approach because it is easier to learn. On the other hand, defenders of rigorous thinking, such as Warren (1982), acknowledge that energy is a difficult concept, requiring some kind of abstract thinking. Warren has argued that if the concept cannot be taught properly, then it should not be taught at all – it should be "eliminated entirely from elementary teaching". Unlike Feynman (1963), Warren asserts that energy can be defined as capacity for doing work and that therefore students must have a good understanding of work and its precursor concepts before they can understand energy. Given that the use of energy and daily media reports about energy are parts of modern life, teachers and researchers such as Duit (1987) conclude that energy must be included in school syllabuses and are willing to be at least a little bit wrong in order to be intelligible. My view is that, by being aware of the common fallacies about energy, we should be able to invent ways of making our teaching both scientifically respectable and intelligible to school students.

Even if you decide, in spite of the arguments above, that there are cases where you find it useful to conceptualise energy as having form or substance, you should be aware that such conceptualisations are not required by the mathematical structure of physics. There is nothing in the equations or laws which says that energy has either form or substance. It is nothing more than an abstract entity which can be calculated according to rules which it is the business of physics to discover. The rest is arbitrary human invention which may either help or hinder the understanding of the physics.

Four fallacies about energy

Fallacy 1: A particle can have potential energy

Search any elementary physics text for its first example of potential energy and it's a fair bet that you will find that a body such as a brick gains PE of mgh when it is lifted through a height h. The serious error lies not in the concept of PE or the formula but in the subtle statement of ownership. The proper view is that the change in PE belongs to the system of the brick and the Earth. The reason for that is that the PE arises from the gravitational interaction between the brick and the Earth. If it were not for the Earth there would be no PE. The mental shift required to get this right may look like mere pedantry, but the concept is crucial. All potential energy arises from interactions between parts of a system.

Fallacy 2: Energy is stored in fuel and food

Even scientists who should know better fall for this one. It seems to be commonly taught in schools that energy can be conceived as something that we get from fuel – the energy-as-substance view. That approach accords with the sensible constructivist principle of building on common experience or knowledge but it deserves serious questioning from a rigorous scientific point of view.

First note that there is no way that you can get energy out of fuel alone. In order to release the energy the fuel has to be burned or combined with oxygen. It makes little sense, therefore, to say that the released energy comes only from the fuel; why don't we say that energy is stored in oxygen? The fact is that you don't get the energy until you bring the oxygen and fuel together and let them combine, so it seems strange to say that the energy is stored in either the fuel or the oxygen. The released energy comes from the system of fuel and oxygen together. This example provides a powerful argument against the conception of energy as substance, because it is not possible to identify exactly where the energy is until the system of fuel plus oxygen has been assembled.

Consider a simple example. Suppose that you collect some hydrogen and oxygen by electrolysing water. You put some energy in to the system, so you now feel that you can say that the energy that you supplied is stored in that system. Now suppose that somebody steals your bottle of oxygen. Have you lost the energy in your system? Have you lost part of the energy in your system? The only sensible answer is that such questions are ill-posed. In other words, it does not make sense to talk about stored energy in cases like that.

An equivalent fallacy is that we get energy out of food. That idea is reinforced by information on food packets which implies that the food contains "kilojoules". The rebuttal is the same as that for fuel. Getting useful energy out of food also requires chemical reactions with oxygen. (It may be noted, however, that there are some biochemical processes which do release energy from the breakdown of single molecules.)

There is another linguistic trap concerned with fuels and food: they are often called sources of energy. That is not strictly accurate either, because the true source of the energy is the combination of fuel and oxygen. I think that oxygen and coal have equal rights to be called a source of energy. Although it makes no sense to talk about energy stored in fuel or food or oxygen it is OK to talk about energy released when fuel is burned or food is metabolised.

Other potential misconceptions include the idea that energy is created (rather than released) by burning fuel. It is interesting to note the views of some children reported by Joan Solomon (1982). They rejected the idea that energy is stored in food or petrol but felt that those things have energy when they are used. For a thoughtful article about the differences and connections between energy and fuel see Ogborn (1986).

Fallacy 3: Energy is stored in chemical bonds

This fallacy is often put forward by people who try to defend fallacy 2 about fuel and food. The claim that chemical bonds store energy is exactly the reverse of reality and may arise from a misunderstanding of the technical term, *binding energy*. Binding energy is actually the energy that has to be added to a system in order to break the bonds and completely separate the constituent particles. Physics texts seem to shy away from discussing chemical bonds but we often find correct discussions of binding energy in the context of nuclear structure. Those discussions often cite the empirical evidence that the mass of a bound set of protons and neutrons is less than the total mass of the individual nucleons. The argument is completed using Einstein's relation for the equivalence of mass and energy: $\Delta E = (\Delta m)c^2$. The Δ symbols here are a reminder that, in a strict sense, we detect only changes in the internal energy of a system. To follow up on the refutation of fallacy 3: a system of fuel plus oxygen before combustion has less binding energy than the products of combustion – think about that.

Fallacy 4: Electric currents carry energy

I have discussed this fallacy in detail in the proceedings of a previous workshop (Sefton, 2002) so I will give only a short explanation here. The idea that an electric current, or the electrons which constitute the current in a wire, pick up energy from a source and carry it along wires to some load such a light globe is an attractive one but it is clearly wrong. It's wrong because the electrons don't actually get far enough fast enough. In an alternating current the electrons don't go anywhere at all, they just jiggle about and in a direct current they just drift along very slowly indeed. In view of these well-known ideas, it is a surprise to me that writers of school-level texts can still get away with perpetuating this fallacy.

The origin of the fallacy may be traced to a common but spurious derivation about the power (VI) delivered by a battery. The argument involves following a charged particle from one terminal of a battery to the other and calculating the change in PE of that particle. That is fallacy 1 (above)! The particle does not own the PE – the whole system does. The derivation is also spurious because, as already pointed out, charges in circuits don't behave like that. (Nevertheless, $P = VI$ is a valid equation; it's just the common derivation that is a fudge.)

Work and Kinetic Energy

The standard hierarchical approach to physics teaching introduces energy via the concept of work. The simplest possible case has a constant force acting on a body that moves in the direction of the force. Work is then defined as the product of the force and the distance moved (the displacement). Later on students may learn how to generalise to cases in which there are many forces, the forces vary and the body's path is a curve. In all cases the central principle seems to be a connection between work and kinetic energy that is called the work-energy theorem. In my view that theorem is probably the most useless idea in elementary texts on mechanics – useless because the way it is usually presented applies only to a system of one particle. And for a single particle, the theorem amounts to something close to a tautology – it doesn't tell you anything new. I think that the problem here comes from trying relate a big-picture idea, energy, to trivial, oversimplified models designed to teach about more restricted concepts such as force.

Work and kinetic energy for a particle

Elementary texts consider the simplest possible case: a single particle acted on by a single constant force moving along a straight line in the same direction as the force. That's an example of "uniformly accelerated motion" and that set of three or four rather useless equations that we all used to memorise. The one that is relevant here relates final speed (v), initial speed (u), acceleration (a) and displacement (s):

$$v^2 - u^2 = 2as \qquad \text{... (1)}$$

Manipulate this and multiply by the particle's mass, m, to get

$$mas = \tfrac{1}{2}mv^2 - \tfrac{1}{2}mu^2 \qquad \text{... (2)}$$

The dicey bit comes when ma is identified as force (F), the equation transforms into

$$Fs = \tfrac{1}{2}mv^2 - \tfrac{1}{2}mu^2 \qquad \text{... (3)}$$

and the term Fs is identified as work. Translating the equation into words, the books say that "work done by the resultant force is equal to the increase in kinetic energy". The derivation can be generalised to include examples in which (a) there is more than one force, (b) the forces vary, and (c) the particle's path is a curve rather than a straight line. F now means the magnitude of the total force and s is the length of the particle's curved path.

What the books often neglect to tell you is that the argument breaks down if the moving object is a real thing such a brick or a car or anything else that can't always be modelled as a particle. In those cases equation 3 makes no sense because the term *Fs* no longer has any useful physical meaning. In general, different parts of the moving body move along quite different paths and the external forces act on different parts of the body. (Think of a lump of jelly or a spinning hammer or a car.) The upshot is that the meaning of *s* in the equations (1, 2 & 3) is undefined. One might try to rescue the situation by defining *s* as the length of the path followed by the total force, but the usual definition of total force (the vector sum) does not include a location at which it acts. So the term *Fs* in equation 3 is now completely meaningless. Furthermore, most real objects (such as cars) have lots of KE associated with their vibrational and rotational motions, but that KE is entirely missing from the simple equations above.

A rigorous generalisation of the work-KE argument is to model any body as a collection of particles (usually a humungous number) and to apply equation 3 to every particle separately. Then add up all the single-particle equations. Out of that derivation comes the statement that the sum of all the works of all the forces on all the particles is equal to sum of all the kinetic energies of all the particles. (Wow!) That is a true statement which is totally lacking in profundity and is of no practical use whatever for solving problems about real examples in school physics.

The argument that I have given here contradicts some statements in the syllabus for the preliminary course (Board of Studies 2002, page 30) as well as a text written to support that syllabus (Andriessen et al, 2001), so what can we do about that? Apart from agitating for changes to the syllabus, I suggest following an approach in which we acknowledge that the definition of work implied by the syllabus is not the usual scientific definition and to try to adapt to that. Here is one kind of compromise.

Pseudowork and translational kinetic energy for real body

It appears that by "kinetic energy" the syllabus writers mean "translational kinetic energy" and by "work" they mean what might be called "pseudowork" (see, for example Sherwood, 1983). Pseudowork is then defined in terms of the total force and the displacement of the body's centre of mass. In the unlikely case of a total or resultant force (*R)* which remains constant in both magnitude and direction and in which that direction is fortuitously the same as the direction of motion, we can adapt equation (3) to read:

$$R.s_{\mathrm{cm}} = \tfrac{1}{2}mv_{\mathrm{cm}}{}^{2} - \tfrac{1}{2}mu_{\mathrm{cm}}{}^{2} \qquad \text{... (4)}$$

That is still a very special case. To adapt the pseudowork concept to the general case in which (a) the total force is not in the same direction as the motion, (b) the forces vary and (c) the path is curved, we need an integral instead of the simple product on the left-hand side of equation 4. That is clearly beyond the scope of the stage 6 syllabus, but for the record, the correct versions of equations 1 and 2 should look something like this:

$$\int_{\mathrm{A}}^{\mathrm{B}} a_{\mathrm{cm},s}\mathrm{d}s_{\mathrm{cm}} = \tfrac{1}{2}v^{2}_{\mathrm{cm,B}} - \tfrac{1}{2}v^{2}_{\mathrm{cm,A}} \qquad \text{... (1a)}$$

$$\int_{\mathrm{A}}^{\mathrm{B}} ma_{\mathrm{cm},s}\mathrm{d}s_{\mathrm{cm}} = \tfrac{1}{2}mv^{2}_{\mathrm{cm,B}} - \tfrac{1}{2}mv^{2}_{\mathrm{cm,A}} \qquad \text{... (2a)}$$

The meanings of the subscripts are critical: $a_{\mathrm{cm},s}$ means the component of the acceleration of the centre of mass taken in a direction tangential to the path of the centre of mass and $v_{\mathrm{cm,A}}$ is the speed of the centre of mass at point A on the path. The expression $\tfrac{1}{2}mv^{2}_{\mathrm{cm,B}}$ can be interpreted as the body's translational KE at point B (which excludes internal motions, vibrations and rotations).

My conclusion from all this argument is that we should seek to abolish the concept of work and the "work-energy theorem" from the school syllabus and texts. For more discussion of work and kinetic energy see the papers by Bernard (1984) and Sherwood (1983). A final thought from my colleague Brian McInnes: "It seems much more profitable and sensible to introduce the concept of kinetic energy in its own right. There is a strong argument for introducing it prior to the discussion of force and of Newton's laws."

Further Reading

For an interesting perspective on how the teaching of energy in English schools has evolved over the last 40 years or so, look for the recent article in *Physics Education* by McIldowie (2004). (Free plug: that journal would be a great resource for every high school library.) For some discussion of some more fallacies that often appear in text-books try the article by Bauman (1992) in *The Physics Teacher*, another journal which would be worth having in your library.

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Feedback

I would like to know whether you found this article useful. Please email any comments or questions to I.Sefton@physics.usyd.edu.au.

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