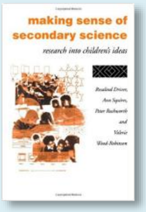
Best Evidence Science Teaching

Approaches
Teaching energy

Energy is hard to teach both because it is an abstract idea that is difficult to define, and because there are many contradictions between the everyday and scientific usage of the word energy.

What ideas do children have about energy?



> *An 'energy gets used up' view, in which things go until energy is used up or fuel is consumed, was found to appear frequently in children's understanding.*
>
> Rosalind Driver *et al*, Making sense of secondary science, 1994

Children generally think about energy in terms of:

- human activity – I'm tired because I have run out of energy or I can run very fast because I have a lot of energy
- health – as in 'exercise is good for you because it builds up your energy' and 'when we run out of energy we need medicine and vitamins'
- food and fuels – some objects and materials contain a lot of energy that can be used up to help us move about and to make other things happen.

Students often confuse ideas of energy with ideas of force, work or power. The most common misunderstanding students have about energy is that, like food or a fuel, it gets used up.

What is the scientific idea of energy?

Nobel Prize winning physicist Richard Feynman describes energy as 'a numerical quantity that does not change when something happens'. But he does not attempt to say what this numerical value measures. What can be said about energy is that:

- Energy is a quantitative property of a system (an object or group of objects).
- When a system changes in some way (e.g. in its motion, or position, or temperature), its energy changes and we can calculate the amount of change.
- Energy is always conserved during any event. So, if the energy of one of the systems involved in the event decreases, the energy of another system (or systems) increases <u>by the same amount</u>.

A good model, if used carefully, for thinking about energy is as a **quasi-material substance** that can be transferred from place to place. This is used by *The Institute of Physics* in their 'Supporting Physics Teaching' materials and made visual using orange liquid, poured from beaker to beaker to represent the transfer of energy.

> **Quasi-material substance:** energy is like a material substance in how it behaves

In considering a teaching approach I think one ought to focus on establishing manipulable models, with quite concrete representations to depict the essence of how one wants children to think about an idea.

Ian Lawrence, Physics Education, 2007

Energy is not concrete stuff, however. This is just a useful model for thinking about it and is the basis of the 'stores and pathways' model. It is helpful in developing understanding and many science education researchers have argued that it does not present barriers to future learning.

Energy can usefully be imagined as an invisible, intangible substance that is never created or used up, which can be stored in a number of different ways, and which can be transferred between different energy stores by several different mechanisms.

- Energy does not explain or predict what will happen

Energy is an accounting, or book-keeping, quantity. We can calculate amounts at the beginning and end of an event and they will always tally. But this does not help to explain the mechanism or process by which the event occurs. For that we need ideas such as force, or electric current.

- Energy does not 'make things happen'

~~'Energy makes things happen'~~

This 'definition' is not true

In every event energy is conserved, meaning that there will be the same amount of energy after an event as there was at the start. This means that if 'energy makes things happen', then every event would be just as likely to happen backwards – as energy would still be conserved.

From a scientific point of view the driver of a mechanism that 'makes things happen' is something called *entropy*. Entropy is a measure of how disordered a system is. The higher the entropy, the more disorder there is. The second law of thermodynamics states that *the total entropy of an isolated system can never decrease over time*. This means that in any event, entropy tends to increase, the system becomes more disordered, and there is a direction to what happens.

There are examples however, that appear to contradict this law. For example, living things create order in their structure and crystals can form from solutions as they cool. But in both of these examples, energy can be transferred to or from the external environment, which means the systems are not *isolated.* The localised order that is created is at the cost of a greater amount of disorder generated in the surroundings. In each case the *total* entropy increases.

Ideas of entropy are generally agreed to be too difficult to introduce at a school level, instead it can be helpful to talk about how energy tends to be transferred to more and more places and become more spread out.

For example, a hot cup of tea placed in a room contains particles which are generally moving faster than the far greater number of air particles around it. As particles collide at the surface of the tea, air particles mostly speed up and tea particles slow down. Air particles moving away from the tea collide into and speed up more air particles and so on. The result is that energy from the tea becomes more spread out because it has been transferred to, and shared between, many more particles throughout the room. The temperature of the tea reduces and the temperature of the whole room increases by a tiny amount.

Similarly, after a ball is thrown it moves through the air colliding with air particles and making them move faster. This slows the ball down as energy is transferred from the ball to many individual air particles. Another way to describe this, is to say the energy that the ball has *because it is moving* is being transferred to the air particles.

The energy the ball has *because it is moving* can be referred to as its **kinetic store of energy**. The ball also has energy because it has a temperature, which can be referred to as its **thermal store of energy**. The energy it has because of the materials it is made from is its **chemical store of energy**.

It is convenient to split up the total energy of the ball into separate **energy stores**, because the amount of energy in each energy store can be calculated from measureable properties of the ball. Changes in the amount of energy in a particular energy store can be calculated, and the effect on particular properties of the ball predicted.

If the ball did not have an energy store then it could not transfer energy to air particles and make them move more quickly. For students on an introductory course, aged 11 to 14, it is reasonable to say:

An energy store of some kind is necessary for something to happen.

When *anything* happens that transfers energy, energy is transferred between energy stores in a way that leads to a more disordered system. In other words, energy tends to spread out from objects or materials that have relatively larger stores of energy, which explains why things happen.

Why is 'energy as a quasi-material substance' a good model for teaching energy ideas?

In this model energy is an invisible, intangible substance that is the same wherever it is. It can be transferred from one energy store to another without ever being used up or any more created. This fits well with our understanding of energy as an abstract quantitative property of a system that is conserved.

As a visual aid when teaching the example of the moving ball, some orange liquid representing energy can be moved from a large beaker representing the kinetic store of energy of the ball to be shared between smaller beakers representing countless energy stores of the particles.

The energy in each energy store can be observed to increase or decrease, and importantly the amount of increase or decrease can also be calculated. This property of energy stores means that they can be used to be describe energy transfers qualitatively in an introductory course, for students aged 11 to 14, and later the amounts of energy they contain can be calculated quantitatively in more advanced courses. Clear explanations of how energy is transferred between energy stores remain consistent as students' understanding develops, although their explanations are likely to grow in sophistication.

Pragmatically, this model gives student the tools they need for thinking about energy, which they can use to think through new situations and to tackle exam questions with confidence.

What is the energy stores and pathways approach to teaching energy?

The energy stores and pathways approach formalises the model of energy as a quasi-material substance so that it can be applied and discussed in a consistent and helpful way. This approach is outlined below, and discussed more fully in the Association for Science Education (ASE) guide Teaching Secondary Physics (Millar, 2011) and the Institute of Physics Supporting Physics Teaching (SPT) 11-14 project materials (Lawrence, 2007), with only minor differences between them.

> *A framework based on energy sources and energy pathways is not perfect – but it is adequate and significantly better than those based on lists of 'forms of energy'*
>
> Robin Millar, School Science Review, 2014

Increasingly this approach is being adopted for teaching energy more effectively. For example, teaching energy using the energy stores and pathways approach is now strongly supported by the National Curriculum in England documents at key stage 3 (age 11-14) and key stage 4 (14-16). The 2016 science exam specifications in England for students at age 16 have also been changed to support this way of learning about energy.

Energy stores

We cannot observe energy or measure amounts of energy directly. But by making observations of how objects, or groups of objects, have changed it is possible to recognise when they have gained or lost energy. From these observations we can identify a set of energy stores:

- kinetic store of energy – an object speeds up or slows down
- chemical store of energy – reactants combine or separate to give products
- thermal store of energy – an object's temperature goes up or down
- gravitational store of energy – an object alters its distance from another mass
- elastic store of energy – an elastic object is stretched or compressed
- electromagnetic store of energy – magnets or electric charges are pulled apart or moved closer together
- vibration store of energy – the amplitude of a mechanical wave is increased or decreased
- nuclear store of energy – nuclear particles are rearranged.

It is helpful to talk about a kinetic store of energy and not a store of 'kinetic energy'

The first six of these are those most likely to be encountered by students aged 11 to 14 and later in their studies they will be introduced to equations that will enable them to calculate the amount of energy in each energy store.

During an event, one or more of these energy stores loses energy, whilst other stores gain energy, with the total amount of energy conserved.

As a good starting point for **energy analysis** students need to practise identifying each of these energy stores, and then to consider which have more energy or less energy at the end of an event, compared to at the start.

There is no mention here of electrical, light or sound stores of energy, because these are not energy stores, but ways of transferring energy from one energy store to another. They are all transient and there is no meaningful way to calculate the amount of energy stored in a system in any of these ways.

Energy pathways

An **energy analysis** of any event is usually concerned only with the amount of energy in each energy store at the **start point** and at the **end point**. A consideration of just these two points enables a clear description, and indeed calculation, of the energy that ends up where you want it to be and the energy that ends up somewhere else (is wasted), and hence of the efficiency of the process. Most often, between the start point and the end point, the details of how energy is distributed is irrelevant to the analysis, and usually the amounts of energy stored in different places (and in different ways) can only be calculated at the end points.

Instead of describing how energy is distributed it is much more useful to describe *how* energy is transferred from the energy store(s) at the start point to the energy store(s) at the end point. Doing this leads students to more insightful explanations of the mechanisms and processes involved in moving energy, which is the sort of understanding necessary for comprehending some of the more difficult topics of science, such as electric circuits.

If the mechanisms and processes of how energy is transferred are not clearly explained, then students will not have all the tools they need to make coherent sense of new situations and nor will they be able to tackle exam questions with confidence.

The different ways that energy is transferred can be distilled into five distinct **pathways**:

- mechanically (by a force acting over a distance)
- heating (because of a temperature difference)
- electrically (electric current)
- by radiation (electromagnetic waves)
- by chemical reaction.

The first four of these pathways are described in detail in the Association for Science Education (ASE) guide Teaching Secondary Physics (Millar, 2011) and the Institute of Physics Supporting Physics Teaching (SPT) 11-14 project materials (Lawrence, 2007). In the BEST resources an extra energy pathway is used to describe energy transferred by chemical reaction, as this is helpful in extending the energy stores and transfers approach to examples from biology and chemistry.

Energy analysis

A three stage approach to thinking about an event can be used to separate explanations from energy analysis, and prepare students for calculations at a later stage of their learning:

1. Observation – a description of what happens in everyday language
2. An explanation – that uses mechanisms and processes to explain what happened
3. An energy analysis – using a start and end point to compare how full different energy stores are before and after the event.

Examples of using energy stores and pathways to explain processes

It is helpful to remember that the explanations and energy analyses provided here are suitable for an introductory course for students aged 11 to 14. In more advanced courses the explanations often need to be more sophisticated and the energy analyses more quantitative.

A simple electric circuit lighting a bulb

Observation – when the bulb is connected to the battery, it lights up.

Explanation – the bulb's temperature rises as energy is being transferred electrically through the wires (as the current passes through the resistance of the filament). As the temperature of the bulb increases it gives out light and heats the surroundings.

Energy analysis – some energy is transferred electrically from the chemical store of the battery to the thermal store of the bulb and the thermal store of the surroundings.

Burning magnesium

Observation – when it is heated a piece of magnesium starts to burn with an intense white light. It keeps burning by itself until there is just a white powder left.

Explanation – heating the magnesium makes its particles move more quickly which allows it to react with the oxygen in the air. The exothermic reaction increases the temperature of the magnesium high enough to keep the reaction going.

Energy analysis – some energy is transferred by chemical reaction from the chemical store of the magnesium and the oxygen in the air to the thermal store of the surroundings and the chemical store of the magnesium oxide that was made.

Photosynthesis

Observation – plants need light to survive.

Explanation – plants make their own food, in the form of glucose, using the process of photosynthesis. This process only happens in the light, and uses up carbon dioxide and water to make glucose and oxygen.

Energy analysis – some energy from the chemical store of carbon dioxide and water and the energy arriving at the leaf from the thermal store of the sun is transferred by chemical reaction to the chemical store of glucose and oxygen.

How important is it to use the language of energy stores with accuracy?

The language of energy stores may seem cumbersome, but it describes accurately the model of energy as a quasi-material substance. Insisting that students use the phrases 'thermal store of energy' and 'kinetic store of energy' rather than 'thermal energy' and 'kinetic energy' can reinforce the understanding that energy is the same everywhere and is not magically transformed into a variety of types.

It is anticipated that each time a student's language is corrected, the scientific understanding of energy will also need to be briefly clarified, as in: *"you need to say a 'thermal store of energy' - the object has the energy **because** it is hotter; there are not different types of energy"*.

Where does the conservation and dissipation of energy fit in?

The conservation of energy is not something that can be conclusively demonstrated to students, but as it is *the* essential feature of our understanding of energy it must be strongly asserted.

It will make it easier for students to accept the idea of the conservation of energy if it is taught at the same time as the idea of dissipation of energy. Drawing students' attention to examples of dissipation of energy and encouraging them to identify unintended transfers of energy by heating can help them to reconcile conservation with their everyday experience of energy being 'lost'. Essentially dissipation identifies what has happened to the 'missing' energy.

Where does the energy stores and pathways approach to teaching energy fit into the BEST resources?

The BEST resources broadly follow the development of ideas about energy described in the Association for Science Education (ASE) guide Teaching Secondary Physics (Millar, 2011) and in the Institute of Physics Supporting Physics Teaching (SPT) materials, except that in the BEST resources an extra energy pathway has been added to describe energy transferred by chemical reaction.

The ideas of energy stores and energy pathways are first developed in topic: *PFM1 Forces*. In this topic heating by friction is introduced to prepare students for thinking about conservation and dissipation of energy, which are introduced more thoroughly in another early topic: *PMA1 Heating and cooling*.

Other topics that involve energy appear later on the subject map for all three subjects. As they arise the energy stores and energy pathways approach is used and consolidated each time.

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