**What is energy?**

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Energy can be ‘defined’ in two ways: it is “the capacity to do work” and  
it is “that which is conserved”. There is yet a third ‘definition’, stemming from the Principle of Least Action – but we’ll come to that later. Let’s return to these two definitions and expand upon them.

(1) “**Energy is work-capacity**”  
This is the oldest and most intuitive definition of energy. From time immemorial, people have used tools, devices, machines, and ‘engines’ to do work – to crack open coconuts, irrigate hanging gardens, cross seas, lift hay-bales, transport produce, fire arrows, grind corn, plough fields, drain marshes, and so on. Gradually, it was understood that all such machines needed some fuel or agency to drive them. But what exactly was ‘work’ ?, and was there some underlying ‘essence’ common between all the different kinds of ‘fuel’ or ‘driving force’? The questions, let alone the answers, took years to formulate.

In the mid 17th century, Descartes (better known for “I think therefore I am”) brought in the first quantitative measure of work: a certain amount of work was equivalent to a certain number of weights raised to a given height. Then, in 1699, Amontons, while watching men polishing glass, observed that the work-capacity of a man is “about a sixth part of the labour of a horse” where the ‘labour of a horse’ is the “force exerted by the horse, multiplied by the speed of the horse at its point of application”. This was the first recognition of work as ‘force×distance’ (or ‘force×speed’ × duration). Five years later, the engineer Parent, in his treatise on water-wheels, made the connection between the ‘live force’ (essentially kinetic energy – see below) of a flowing stream and the ‘work’ that it could do. Also, he realized that the work of a flowing stream (using an undershot wheel) was ultimately the same as that done by still water in a mill-pond as that water fell (using an overshot wheel). So, perhaps ‘live  force’ and ‘falling weights’ were in some sense equivalent? At the end of the same century, the French statesman and revolutionary, Lazare Carnot, perfected these ideas, and finally, in 1829, Coriolis formally defined work as the integral (loosely speaking, a summation) of ‘force times distance’. (As it happens, every one of these investigators was French. We shall see in what follows that, for the first two hundred years or so, ‘energy’ was a *continental* European discovery.)

In the same period, there were other developments in other countries. Inspired by the Dutch natural philosopher and horologist, Huygens, the German *Universalgenie*, Leibniz, in the late 17th century, brought in the crucial idea of ‘live force’ or *vis viva* – what would later be known as kinetic energy, the energy of a body due to its motion. Leibniz proposed the formula *mv*2 , where *m* was the mass of the body, and *v* was its speed. The Swiss family of mathematical geniuses – the Bernoullis  (especially the father, Johann, and his son, Daniel) – made the important discovery that the total *vis viva* was always conserved (in a given isolated system). For example, in a collision between billiard balls, the total kinetic energy before the collision was the same as the total kinetic energy after the collision. (However, the argument appears circular, as this conservation rule is only true in ‘elastic’ collisions.)

Then slowly ideas about ‘potential energy’ evolved. It became understood (chiefly by Daniel Bernoulli, who coined the very term ‘potential’), that potential energy was stored kinetic energy or kinetic energy-in-waiting. For example, a body dropped onto a spring would come to rest but squash up the spring – it seemed that the kinetic energy had been stored. The ‘proof’ was that subsequently the squashed spring could stretch out and set the body in motion again. The Dutch natural philosopher, ’s Gravesande, (using apparatus that somewhat resembled a towel drying-rack), dropped weights into a tray filled with clay (the weight was stationary when it was released), and found that the depth of penetration into the clay was proportional to the fall-height. Repeating the experiments with different weights then, other things being equal, the depth of penetration into the clay was now proportional to the weight. Combining these two experiments, ’sGravesande finally concluded that the kinetic energy of a dropped body at the end of its fall is proportional to both factors, that is, to weight×(fall-height).

There were still conceptual difficulties, not always spelled out: was potential energy the same as ‘work done’ the same as summation of ‘force×distance’? Anyway what was ‘force’, and what was the connection between ‘force×distance’ and ‘weights raised’?  And what was ‘work’ when no weights *had* been raised (but, say, glass had been polished instead)? Clarification came through a slow merging of insights along three routes: potential energy as stored kinetic energy; special problems solved by  ‘geometers’ (the shape of the Earth, the vibrations of a cord fixed at both ends, the shape of a hanging rope, etc.); and the engineers’ need for a measure of ‘work done’ (in order to compare the ‘efficiency’ of different machines). There was even a fourth route (nascent in the 18th century, starting properly in the 19th century) – ‘potential function theory’, and then the crucial concept of a ‘field’. We’ll leave all this for a while.

(2) “Energy is that which is conserved”

As we have said in (1), from time immemorial, philosophers understood that machines needed a fuel to drive them – but there was also, at exactly the same time (and often coming from exactly the same philosophers), the contradictory hope that perhaps a machine could be made to run perpetually without need of a fuel or external agency. In fact, the search for ‘perpetual motion’ (a perpetually-acting self-driven machine or engine) became a frenzied quest. Machines of all different kinds were suggested: overbalancing wheels; attractions using sponges, capillary tubes, or magnets; gravity shields; a windmill that drives bellows that generate the wind to drive the said windmill… – but always the attempt ended in failure (and sometimes an outright fraud was exposed). The impossibility of ‘perpetual motion’ was seen to be underpinned by the old adage of ‘cause equals effect’ – but did this impossibility mean that ‘*something*’ was being conserved? The sheer variety of ways in which perpetual motion was sought but was not found argued that this ‘something’ was universal – but subtle, slippery to define. Then gradually, over roughly 150 years culminating in 1850, in one of the most amazing and gripping tales in all of human history (described in EtSC), the true physical concept of energy came through. It came through as not simply “that which is conserved” but as “that which is *defined* by this property of being conserved”.

No analogy captures this better than that given by Richard Feynman in his Lectures on Physics, Volume I, 1963. (Feynman was a supreme explainer of physics as well as a supreme discoverer of physics.) We are to imagine a child, Dennis, playing with a set of blocks. The mother, being a thinker, notes an interesting law: no matter what the child does with the blocks, at the end of the day there are always the same number of blocks (say, 28) to pack away. However, the mother has to be ingenious to check up on her law. One day, after searching in every nook and cranny, there are only 26 blocks – but then she notices that the bath water (so dirty that she can’t see through it!) has risen up by 1.2 cm (strange that she should know this detail but there it is). Determining that one submerged block displaces a height of exactly 0.6 cm water, she deduces that the raised bath-water has concealed the missing two blocks (the formula that captures this information is: number of hidden blocks = [height of water displaced]/0.6 cm ). Another time there are three blocks missing. Then the mother realizes that the toy treasure-chest is heavier than before. When empty it weighed 480 g but now it weighs 735 g. (Dennis, a bit of a menace, screams if she tries to prise open the locked chest and check for the blocks directly.) However, knowing that a single block weighs 85 g, she deduces that the three blocks are hidden inside (the formula this time is: number of blocks = [weight of chest – 480 g]/85 g ).

By continuing on with this process of theorizing, experimentation, and, above all, measuring, more and more complicated formulae arise. (For example, there could be one concerned with an analysis of a pile of ash if the mischievous Dennis decides to burn some blocks…) Adding these formulae together, the mother slowly traps every way in which Dennis could hide the blocks. A telling feature is that measurement – *quantification* – is crucial. Another telling feature is that the formulae are all utterly different one from the other (but, adding them all together, the number of blocks comes out constant).

What is the analogy to the concept of energy? Once again, different abstract formulae, each now representing a different form of energy, must be added together in order to arrive at the fixed total quantity. But there is one striking difference for the conservation law for energy – *there are no blocks*. That is, there is no ‘stuff’ that is actually being conserved, and all we are left with is the bare abstract bones of the mathematical formulae themselves. The project is also incredibly more nuanced and difficult than that just outlined for Dennis’s blocks. In order to check that something is conserved, we must make sure that none of ‘it’ is getting ‘in’ or escaping to ‘the outside’ (in technical jargon we say ‘the system must be closed’, or, ‘the system is isolated from its surroundings’). Feynman is careful to mention this detail in his analogy (the mother must check that Dennis hasn’t thrown any blocks out the window, and that his friend Bruce doesn’t introduce extra blocks from Bruce’s own collection). But, in the case of energy, how do we know what counts as ‘inside’ and ‘outside’ when we don’t yet know what ‘it’ is? Also, the missing energy may not present itself conveniently, one formula at a time (think of yet another analogy – taking your car to the mechanic, or your body to the doctor; is there just one thing wrong, or could there be two, three, or more simultaneously competing and intertwining factors?).

We will not tell all the wonderfully intricate story of how the various forms of energy were arrived at by this algorithm – “energy is that which is conserved”- except to pick out one twist, the most intriguing of all. This concerns the form of energy known as ‘heat’. By the first half of the 19th century, it was known what kinetic and potential energy were (kinds of ‘mechanical energy’), and that  only *together* were they conserved, but it was not appreciated that heat was also a form of energy. So, even while the countryside was becoming more and more criss-crossed by railway lines, and the Steam Age was well underway, still it wasn’t understood that the steam engine was driven by *energy* (although Watt, discoverer of the steam engine, and his financial backer, Boulton, had prescient inklings – they called it ‘power’). Today we are so familiar with facts like ‘the calorific value of coal determines the amount of heat it can yield’, and countless other examples, that we can barely un-know that heat is a form of energy. Heat was, instead, thought to be an indestructible fluid that was weightless and invisible and without smell or any other sensory signature (hence, ‘subtle’). Above all, ‘Heat’ and ‘Mechanical Energy’ lay in completely different worlds, like PSA (Pleasant Sunday Afternoon) and psi (pounds per square inch).

The impasse was eventually crossed, beginning (back in 1738) with Daniel Bernoulli’s kinetic theory of gases (compare with Dalton’s *static* ‘air atoms’ !); Count Rumford’s cannon-boring at the Munich Arsenal, and his weighing of heat; Mayer’s epiphany after seeing the redness of blood in the Tropics; and all of Joule’s outstanding experiments (to mention only a select few investigators). Mayer and Joule independently realized that heat and mechanical energy could be converted one into the other, and were ‘equivalent’ (and thus heat *was* a form of energy). Finally, the theoretical underpinning was given first by the German, Clausius, (in 1850) and then by the Scot, Thomson (Lord Kelvin), (in 1852). This led to the First Law of Thermodynamics: the total energy of any isolated system is conserved.

In summary, this conservation-property (definition (2)) enabled the identification of the various forms of energy (the ‘blocks’) but also showed that energy was convertible between these forms. However, one very curious feature was realized by Clausius – the conversions were more likely in some directions than others. In detail, ‘work-energy’ could be totally converted into ‘heat-energy’ (for example, for a carriage with the brakes full on, the work done by the turning carriage wheels would be completely converted into heat at the brakes and axles), but heat-energy could never be 100% converted into work-energy. This led to the Second Law of Thermodynamics, and later to Clausius’s idea of entropy (the reader is referred to EtSC or Atkins’s book). Realizing they had discovered something monumental, and had founded a new discipline – Thermodynamics, Thomson and Clausius put the capstone on in a novel way: they issued cosmic proclamations that everyone could understand (in ordinary language and containing no mathematics),

“There is a universal tendency to the dissipation of mechanical energy…[therefore the earth will eventually become] unfit for the habitation of man” Thomson 1852

First Law of Thermodynamics “The energy of the universe is a constant” Clausius 1865

Second Law of Thermodynamics “The entropy of the universe tends to a maximum” Clausius 1865

Despite being in ordinary language, it was half a century later before the general public began to absorb this knowledge, a process that is still going on – the ideas are just too big (cf. Global Warming today).

To recap, we have the ‘definitions’ (1), energy is “work-capacity”, and (2), energy is “that which is conserved” – which is better? In definition (1) we still have the questions: what is work?, and must work always have an anthropic tinge? (the answer is “no”, work is any macroscopic rearrangement of interacting parts). And what about when the work is held back, perhaps indefinitely? (The example that tormented Galileo was that of a ‘dead weight’ that sits atop a post, forever. Consider also the case of hypothetical universes dying a ‘heat-death’ at different final temperatures; the amount of heat-energy is different in each case, yet the work-capacity is the same, zero). On the other hand, definition (2) is more abstract – but it did enable the discovery of the different forms energy can take: kinetic, heat, light, electrical, chemical, magnetic, nuclear, restmass, the existence of the neutrino, and so on. (Note that there are other quantities in physics that have a conservation-property – momentum, electric charge, etc. – but none are *defined* by this property (for example, momentum is defined as mass×velocity). Actually, there are some quantum properties – strangeness, baryon number, etc. – whose chief attribute is to be conserved. However, these are all tallies that are enumerated, for example, …-2, -1, 0, 1, 2, …, rather than a quantity with extension and needing to be measured. See Feynman’s “The Character of Physical Law”.)

Now both definitions (1) and (2) have a crucial property that we haven’t emphasized enough till now – they both relate to a *system*. A system in physics is any enclosed scenario with boundaries and ingredients specified in advance, and isolated from its surroundings. It’s essential to know what these boundaries and starting ingredients are if we’re going to be able to home-in on energy. How can we ascertain the work-capacity if the system-capacity has surreptitiously changed half-way through? How can we know that energy is indeed conserved if we don’t notice that some is leaking in or out? However, surprising to say, in Newtonian Mechanics the system has not been properly specified: there can be ‘fictitious’ forces (for example, centrifugal forces) that interfere with our tally of ‘work-done’; and the kinetic energy can disappear between reference frames (the Japanese bullet train has huge motional energy if we watch it whoosh by from the platform, but on board we can forget all about this motional energy). But there is a way to totally remove all these seeming ‘paradoxes’.

(3) Energy from the Principle of Least Action

This sets the scene for our third – and deepest – ‘definition’ of energy. It’s all to do with the Principle of Least Action, the systems-view *par excellence*. With this Principle, there’s no longer a ‘paradox’ of kinetic energy vanishing. This is because the train’s speed is set ‘honestly’, for the first time in physics – it is always *relative to something within the system* (instead of sometimes being relative to ‘absolute space’). For example, the train could have speed *v* relative to the said platform. Then if *v* is 300 km/h we see it whizzing by, or if *v* is 0 km/h we see the train stopped at the station; and if we’re on board the train then we’re talking of a totally different system anyway. As regards the so-called ‘fictitious forces’, these are also, for the first time, ‘honestly’ incorporated into the system (in the method known as d’Alembert’s Principle).

You will have to read my blog, “The Principle of Least Action – why it works”, in order to learn more about this Principle, but we are confident in using it for our founding definition of energy as this Principle is outstandingly successful across almost the whole of physics, and is the closest physics has ever come to a T.O.E (Theory Of Everything). In very brief, the Principle divides energy up into two kinds – kinetic energy and potential energy – and says that the evolution of the given physical process (a swing swinging, planets in orbit, and so on) is such that the *difference* between the total kinetic energy and the total potential energy is as small as it can possibly be, at each instant of time, and over the whole time-window of the given process. ‘Action’ is defined as ‘energy×time’. Time is a featureless ‘running coordinate’, whereas ‘energy’ has all the extension (mass and bulk) and structure (detailed information about what’s out there, what interacts with what, how they interact, what the architecture looks like, and so on). So we could tentatively define ‘energy’ as,

“energy is that which brings extension and structure into physics, and is subservient to the Principle of Least Action”.

Let’s explain a bit more about kinetic and potential energy: what are they? why are there just these two kinds of energy? is one more fundamental than the other? and why must kinetic and potential energy counteract each other? (‘counteracting’ is the same as ‘minimizing the difference’). Kinetic energy, we said earlier, is the motional energy of a body. It has the elemental form *mv*2 (more strictly, 1/2 *mv*2 ) because this is the simplest form that will ensure compliance with the conservation of momentum and the conservation of energy (this is explained in EtSC using the references, Maimon, and Ehlers et al. Also, a more abstract mathematical explanation is that kinetic energy has the speed *squared* because it relates to *two* ‘vector spaces’).

Potential energy is more tricky to explain. It is a store of energy but there are so many ways this can be done. Consider the following ways of storing energy: in a boulder on top of a hill, in the still waters of Lake Nasser (that feeds the Aswan Dam), a wound-up watch spring, a Roman Arch, a strong bow, or an electric battery. What is the common feature between all of these? The cord of the bow must be stretched back through a certain distance before it can be fired. Likewise, the boulder wants to move through a certain distance to try and reach the centre of the Earth (but is stuck fast at height, *h*). The dam’s water also wants to fall down through a height (also aiming for the centre of the Earth). An ordinary (linear) spring stores energy when it is stretched or squashed – when its end is displaced. We may be tempted to think that the common feature in all these instances is *displaced distance* (especially if we remember that work is force×displaced distance). However in the case of the watch spring, it’s a question of *displaced angle* rather than displaced distance. For the Roman Arch, energy is stored because of the special *shapes* and *configuration* of the component blocks (as well as their heights). When it comes to electricity, it’s even more interesting. Energy is stored in the battery because the negative charges, all squashed together, want to get further apart (in distance), but how much the potential energy drops in going around the circuit depends also on configuration (the *curved shape* of wires in an electromagnet, the *shapes* of capacitors, the *length* of wires and the overall *layout* of the circuit); but there’s also a brand new feature, *speed* (the *rate* at which the charge flows determines the strength of the induced magnetic fields and eddy currents, the rate at which we open or close a switch, or move a magnet, determines the strength of the induced currents, and so on).

There are two important generalizations that we haven’t explained yet. The first huge step (taken by Lagrange in 1788) concerns a new understanding of how to model the physical reality. We have assumed that kinetic energy has to do with a particle (a mass and the speed at which it is travelling) but from Lagrange we learn that we can as well take as primitive the motional energy of  ‘a whole lever-arm’, ‘the swing of the pendulum-bob’, ‘the spinning of a spinning top’, ‘the motions of the Sun, Earth, and Moon’, ‘the vibrations and rotations of a diatomic molecule’, and so on, each choice depending on the given system.

The second huge step is again to do with modelling. Physics involves the making of measurements (the height of a door is 2.10 m, the speed of the car is 98 km/h, etc.) and in this process we could say that ‘numbers have been mapped onto physical things’. However, in many cases a more complicated mathematical object than ‘number’ is needed. For example, the potential energy of a boulder (of given mass) can be labelled by just one number – the height of that boulder – but it is sometimes useful to imagine a whole landscape marked out by contour-lines whether there’s a boulder present or not. If the hill has a very regular shape (say, it’s a perfect cone) then these height-contours are curves of a definite *mathematical function*. It was in this way that Laplace and later Green developed ‘potential function theory’ wherein a function of potential energy exists, even in empty space (so, in the case of gravity, first the boulder drops out of the picture, and then the whole hillside drops out of the picture). Finally, an even more radical idea arrived – the idea of the ‘field’. Once again we have empty space (or in relativity theory, empty spacetime) but now instead of a function generating potential-energy contours we have ‘some appropriate mathematical procedure’ for labelling every point in the space. To recap, we have gone from a definite thing (a boulder, particle, electric charge, etc.) at *one point*, to *no thing* but an *infinity of points* in field-space, and where each point is labelled as needs must (it could be by a number, an arrow, a sum of numbers and arrows, a differential, a tensor, …, or any other especially crafted mathematical operator – as required by the given physical scenario).

The history helps explain the motivation for this development of the field idea. In England in the mid 19th century, the experimentalist, Faraday, and the theoretician, Maxwell, were wondering how to describe the effects of electric currents on tiny bar magnets (iron filings) in the empty space surrounding the current-carrying wires. The currents were influencing not only the motion of the magnets but their orientation – so each point in the “electromagnetic field” had to be labelled with an arrow (a vector). But, stranger than this, fluctuating currents at one place and time were influencing what happened *somewhere else* and at a *later time*. So the electromagnetic field had to be a sort of log, keeping track of everything that happened, and when, and also what should then happen, and all of this at each and every point. The connection with energy is that the field takes on a life of its own (distinct from any sources or test-particles) and *the field contains energy, and it transmits energy*. Consider: it’s a sunny day and you are relaxing outside in a deckchair when just then a cloud interposes itself between you and the Sun; suddenly you feel a chill. What this everyday example demonstrates is that the field contains energy, it transmits energy (and without need of a ‘medium’), and the cloud has intercepted this transmission of energy. (Of course, to say that the field contains energy is no woolly statement in everyday language. It means that quantities such as ‘the energy density at a point’, or ‘the flux of energy flowing through a surface’, are given precise mathematical meaning, and can be measured.)

How does the field-energy tie in with all the other forms of potential energy? It has been staring us in the face… potential energy is not just to do with an energy store, work-that-could-be-done, displaced distances, displaced angles, configuration-in-space, configuration-in-speed, the potential function, or energy-in-the-field – more fundamentally, potential energy is the *energy of interaction*. (The field tells what *would* happen *if* a test particle were brought up close; the boulder *interacts* gravitationally; the atoms in the watch spring *resist* being pushed closer together or stretched further apart; and other examples.)

Let us return to the Principle of Least Action. This was stated in terms of ‘kinetic energy’ and ‘potential energy’ (and the need to minimize the difference between the two, through time). Now if potential energy takes care of the interactions, does kinetic energy take care of all the non-interactions, that is to say, the ‘individual component parts’ of energy? Yes, this is exactly what kinetic energy is all about – but we must remember that the individual components are not necessarily (the energies of) simple particles, they could be molecules, planets, spinning tops, ions in solution, etc. In summary, potential energy describes an energy structure of interacting parts, and kinetic energy describes these very parts. However, we must also understand that there is no hard and fast distinction between kinetic and potential energies. For example, consider the case of an electrolytic cell. The negative ions (the individual components) rush away from the cathode and seek out the anode (the potential difference between the electrodes is the ‘energy structure’). When the negative ions arrive at the anode, they cluster around it, shielding its positive charge from the fresh batch of negative ions – thus the first batch have changed the potential difference and so changed the overall energy structure. In synopsis, the energy-structures dish out the ‘marching orders’ to the individual components, and these individual components respond, but in so doing the energy structure is slightly modified and so the ‘marching orders’ are now slightly different, and so on, and so on.

To explain this to-ing and fro-ing between kinetic and potential energies is the very *raison* *d’être* of the Principle of Least Action (see my forthcoming blog, “The Principle of Least Action for the layperson”). For present purposes it is sufficient to know that the Principle works across almost the whole of physics (everyday mechanics, all kinds of engineering, quantum mechanics, continuum mechanics, gravitation, electrodynamics, quantum electrodynamics, and so on) and its meat-and-potatoes is kinetic energy and potential energy. (Of course it also works in those extreme cases where there is only kinetic energy, or only potential energy – for example, the Principle explains the intuitive result that the potential energy is at a minimum (is ‘least’) in cases of static equilibrium.)

A curious question arises: is kinetic energy the only candidate to qualify for ‘individual component energy’? Answer: No – a mass, even a stationary mass, is an example of ‘individual component energy’. How so? First, mass *is* energy, via *E* = *mc*2 . Second, mass is ‘individual’ (don’t ask me what my mass is – that’s personal!). Third, the mass does indeed interact with an energy structure – it distorts the very spacetime that it rests in.

The most well-known equation in physics, *E* = *mc*2, needs explaining. In EtSC, I explain that even when the kinetic energy of a particle has gone to zero, there is still some energy ‘left over’. This sounds intriguing but makes it seem as if the rest mass-energy is a serendipitous extra. In fact (as Einstein realized), it is essential that energy has mass: this is because we need the laws of conservation of energy and conservation of momentum to apply to all phenomena in physics (light, electricity, and so on) and not just to ordinary mechanics, and the only way this can be guaranteed is if every kind of energy has a mass. (See the blog “*E* = *mc*2 , a simple demo” .) In summary: energy and mass are equivalent, all forms of energy have ‘inertia’, and all energy is subject to gravity.

As we just said, *E* = *mc*2 means that every kind of mass, even stationary mass, has energy – the rest-energy. Now it so happens that rest-energy  and kinetic energy are always positive. In relativistic kinematics (high-speed particle collisions, including creation and annihilation events), this brings in an interesting existential property for energy: whether or not the reference frame is moving, *any system with energy will always have energy; and any system with zero energy will always have zero energy*. (Note that the same cannot be said of the total momentum of a system.)  It seems that ‘energy’ truly is a tally, and the most physically-telling one of all.  (We are taking ‘system’ to mean ‘closed system’, ‘reference frame’ to mean ‘valid reference frame’, and ‘energy’ to mean ‘total energy’.)

One assumes that this existential property for energy extends from relativistic particle collisions to all physics, but this has never been shown (at least, not to the author’s knowledge). The arena of cosmology is especially challenging. For example, a quantum fluctuation followed immediately by an extremely rapid inflation could apparently lead to our long-lasting universe being created from nothing (see Alan Guth’s book, “The Inflationary Universe”). Such a fluctuation is extremely unlikely to occur but if an eternity precedes it then it will happen eventually…

Let us return to the questions posed earlier. Kinetic energy and potential energy: what are they? is one more fundamental than the other? are there just these two kinds of energy? and why must they counteract each other? We have already explained that kinetic energy is the energy-of-motion, and potential energy is the energy-of-interaction, but we have also counselled that it is necessary to understand them from the perspective of the whole system: kinetic energy is ‘individual component energy’ and potential energy is an ‘energy structure’ within the system. The great 19th century physicist, James-Clerk Maxwell, took the view that kinetic energy was the more fundamental as it has one elemental form (and a simple extension for rotations, vibrations, etc.) whereas potential energy comes in an infinite variety of possible forms. But the two kinds of energy are not so antithetical as is sometimes made out. Not only is there the continual morphing of one into the other (cf. the electrolytic cell), but the potential energy structure may sometimes be a structure-of-structures, or a structure-of-structure-of-structures, and so on – in other words, potential energy itself may have component parts; and ‘individual component energy’ may include ‘internal energy states’ (see Ehlers et al) – but then these internal energy states constitute a store of energy and so could be considered as a form of potential energy.

As regards the last question, it is essential that potential and kinetic energies counteract each other (as we said before, ‘minimizing the difference between’ is the same as ‘counteracting’). The potential energy structures issue the ‘marching orders’, and then the individual component energies respond (if kinetic, they respond by their very motion) – but it must be appreciated that this response is *reactive*. This must be so. Newton’s Third Law of Motion explains how there must be an ‘Action’ and an equal and opposite ‘Reaction’ when two particles interact. The interplay between kinetic energy and potential energy, as demanded in the Principle of Least Action, is an extension of Newton’s Third Law – an extension that works at the *whole-system* level: the individual kinetic energies are reactive but only when they are considered *in concert*. In this way a runaway growth in Total Action is avoided.

Finally, there is one form of energy that does not fit neatly into the categories kinetic or potential – this is ‘heat’. ‘Heat’ is quite different from all the other forms of energy discussed so far (too big a topic to discuss fully here, but see EtSC, Chapter 18). It has to do with kinetic energy inasmuch as it is a summation of the kinetic energies of microscopic components, but the summation is over such an enormous multitude (for example, around 1022 molecules in a litre of air under everyday conditions) that statistical methods are obligatory. Even worse, because the kinetic energies are distributed randomly then probabilistic methods are obligatory. We admitted earlier that the Principle of Least Action works across *almost* the whole of physics – well, the arena in which it doesn’t apply (in our present state of knowledge) is ‘heat’.

Bringing everything together, our third and deepest ‘definition’ of energy (a definition which in fact includes ‘definitions’ (1) and (2) as special cases) is,

(3) “ **Energy brings all the detail and specificity into physics, the extension and the structure, telling what there is, and how things interact, in accordance with the Principle of Least Action. There is in addition the form of transferred energy known as ‘heat’** ”,

or more compactly,

(3) “**Energy is that which enters into the Principle of Least Action; and heat**”.

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