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The Physical World – 2

V V Raman

Multiple Uses of the Word Energy: ***In scientific discourse terms need to be clearly defined***.

The word *energy* is familiar to us all. We speak of an energetic person, we say we are devoting a lot of time and energy for a task, we refuse to walk farther because we have no more energy left, etc. In recent decades the word has taken on an added significance. We frequently hear that our energy resources are being depleted. Environmentalists protest the damage wrought by technology, and plead for a slower pace in our exploitation of energy. Energy is something we need for our comfort and civilization, indeed even for our survival. The industrial revolution has energy at its base. Much applied science consists of a manifold use of energy to serve human needs and greed.

The concept of energy is implicit in many ancient writings. The Vedas, which date back to more than three thousand years, speak of the divine as cosmic energy: *Shakti*[1]. Ancient Greek thinkers used the term *energeia* to mean activity[2]. Many ancient thinkers felt that there was some aspect of motion that remained unaltered when changes occurred. Soon after the rise of modern science, thinkers tried to quantify this invariant feature of motion.

For two centuries the notion of energy was not clearly defined. By the beginning of the 19th century, Thomas Young introduced the term energy for the *vis viva.* Sadi Carnot made a penetrating analysis of steam engines and their work output, and began a study of relationships between heat and work, paving the way for the science of thermodynamics. But it was largely from the work of William Thomson (Lord Kelvin) and William Rankine that the word became current in scientific literature in its modern sense, in the later half of the 19th century[3].

Associated with *energy* are the ideas of *work, force, power* and *action*. A popular writer in the later half of the 19th century used the last three words in just two sentences in connotations that

[1] The term *Shakti* has several meanings in the Hindu contexts: metaphysical, mythological, prayerful, etc. Symbolically it refers to the female creative principle that rules the cosmos.

[2] Aristotle who coined the word derived it from the Greek word *ergon* which means work. Interestingly, work and energy are already related in that word.

[3] For more on the history of the development of these concepts, see V V Raman, The Energy Conservation Principle, *The Physics Teacher*, Vol.2, pp.80–86, 1975.

have nothing to do with their technical meanings:

"It is *energy* – the central element of which is will – that produces the miracles of enthusiasm in all ages. Everywhere it is the main-spring of what is called *force* of character, and the sustaining *power* of all great *action*"[4].

This is a major distinguishing factor between science and non-science. In science, every term is precisely defined. Hazy or unambiguous use of words (like the italicized ones above) is neither encouraged nor permitted. But in poetry and literature, extended and metaphorical use of words is permitted and encouraged, for the goal here is not precision but enjoyment. It is not to give information but to provoke reflection and imagination. The price one pays for this is that one cannot do much with poetically descriptive words; but a great deal can be accomplished, and needless debate can be avoided when clearly defined words are used in a discourse.

Work and Energy: ***Work and energy are related.***

In technical science *work* is not just something that you or I do, it is not a job for a paycheck, nor a task to be submitted to someone, but that which leads to energy. Work, for the physicist, involves a force that moves bodies. No work is involved in uniform motion. There is no work when the effects of forces cancel out. But when forces act and displacement occurs in the direction of the net force, then we say that work has been done by the force[5].

Who does the work? Not this man or that woman, not this animal or that machine: work is done *by* forces, and it is done *on* bodies. So we talk about the work done by weight or by friction, by the push of the hand or the tension of the string. When a body falls, work is done on it by the earth's pull (weight or gravity). When a speeding car screeches to a stop, work is done by the car against the frictional force. When the cable of the crane lifts a load up, work is done on the load by the tension in the cable. And so on.

Every time work is done on a body, the body acquires energy. Here then we have a technical definition of energy: as an entity that arises in a body when work is done on it. Likewise, if the body were to exert force and cause displacement, i.e., if a body were to do work, then it will lose energy. Work is the mode for transfer of energy. In other words, bodies gain or lose energy according as work is done on them (by an external force) or by them (by their own exertions).

4 Samuel Smiles, *Character,* Echo Library, p.81, 2006.

5 This definition goes back to the work of Sadi Carnot in 1824. In the current international system, if a force of one *Newton* causes a displacement of one meter along its line of action, it is said to do one *joule* of work.

When a spring is compressed, work is done on it; so it gains energy. When a compressed spring bounces back, it does work, and loses energy.

Since forces and displacements pervade the world, work is done all the time. Never a workless moment for the tireless universe. This means gain in energy or loss for various bodies. Creatures may work by day and rest by night, but the world keeps working forever.

Kinetic Energy: ***Motion is a form of energy.***

Ordinarily we look upon motion only in terms of change in location. When a runner runs, an eagle flies, when the pendulum swings, the wheel turns, the rocket zooms, and the planet moves, they all display a burst of energy. We call this their *kinetic energy*[6]. When Descartes spoke of matter in motion, unbeknownst to him, he was talking about the universality of kinetic energy. From microcosmic minuteness to grand galaxies, every bit of matter is endowed with kinetic energy with respect to some reference frame or another, for there is nothing that we know of that is at absolute rest.

Kinetic energy has also been quantitatively defined in terms of the mass of a moving body and its speed of motion. If a mini car and a huge truck are both moving with the same speed, the more massive truck has far more kinetic energy than the tiny one. On the other hand, the faster any car goes, the greater will be its kinetic energy.

During the 19th century it was thought by quite a few thinkers that the energy of motion (kinetic energy) was the only form of energy there is: or at least the only form in terms of which all energy modes can be expressed. Heat and light and electricity could all be reduced to some kind of motion or another. This was the kinetic view of nature: a natural outgrowth of the Cartesian sweep of matter in motion.

Dissipation: ***Kinetic energy is often dissipated away.***

We give a kick to a ball, it flies and falls, rolls on the ground and comes to a stop. We give a push to the child's swing, the oscillations gradually attenuate and bring the swing to a halt. We spin the wheel on its axle, and it too slows down and loses its rotational motion. Even a furious

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[6] The formula for KE as (1/2)(mv^2) is due to Josephe Louis Lagrange (1788). Thomas Young introduced the term energy, and William Thomson (Lord Kelvin) popularized the term kinetic energy in the second half of the 19th century.

meteor that comes zooming into our atmosphere loses speed. Every moving thing here on earth, if left to itself, slows down and stops, sooner or later. Put differently, its kinetic energy diminishes and disappears.

What happened to the kinetic energy the ball received from the kick, the swing got from the push, and so on? Where did it all go? The answer is that the kinetic energy in these cases was dissipated by friction. It was lost as kinetic energy and became frictional heat. Only in the case of the meteor is this glowingly visible, for the intruding stone burns spectacularly as a falling star. The ball and the swing lose their energy to friction too, but the heat generated is so slight it is barely perceptible.

So there is frictional dissipation going on all around, for all motion on earth is on surfaces: solid land, liquid water, or gaseous air. We can minimize, but we cannot eliminate friction altogether. A little grease perhaps at the point of contact from where the swing hangs, and an ice floor for the skating rink will help reduce friction, but not do away with it altogether.

Up there beyond the blue skies where no air pervades, the kinetic energy of a moving body does not get dissipated. So the moon revolves and planets orbit, never losing their kinetic energy. If they did, much havoc would follow. It is good that space is really vacuous.

But near our earth, even at great heights where air is thin, there is enough friction to slow down a lowly satellite and spiral it down to a splash. Like some devouring pit, friction is always there to gobble up all kinetic energy. There is no escaping this.

Potential Energy: ***Energy may be stored.***

Though kinetic energy is often dissipated as frictional heat, this is not always the case. When I kick a ball upwards and it lands on the roof of a house, the energy I imparted to it has ceased to be kinetic, but neither is it all lost as frictional heat. Rather, it is stored in the body, and can become kinetic again when it has a chance to roll off from the terrace. In its silent static form the ball does not show the energy stored in it. We say it has *potential* energy.

Many bodies and systems in the universe have potential energy: stored energy which may be released in different ways. For example, when a pendulum bob is hanging with the string in the vertical position, it has no potential energy, nor kinetic. When it is displaced away from this position, it acquires some potential energy. Now if it is let go, the potential energy is gradually transformed into kinetic energy until at the lowest level all of it is transformed into kinetic energy. As it swings towards the other extreme position, the bob slows down, i.e., it begins to lose its kinetic energy and gain potential energy until it comes to a stop. Thus we see that as the bob oscillates back and forth, its energy is being continually transformed from the potential to the kinetic and vice versa. We also note that the pendulum is most stable when the string is vertical, i.e., when the potential energy is least.

There are any number of other situations also where energy is stored. Chemical energy – the energy arising from molecular bonding – is stored in countless molecules. A matchstick has potential energy, and this can be released as heat (fire) when it is struck. Candle, gasoline and a log of wood also have energy hidden in them, energy which can be released as heat and light.

If kinetic energy is like cash, obvious and directly negotiable, potential energy is like money in the bank: safe and secure in the vault, retrievable under appropriate conditions.

Forms of Energy: *Energy appears in different forms.*

Like the soul of religions, energy has never been recognized in its unclad glory, but it manifests itself in countless garbs. So there is heat and light and motion, sound and electricity too. All these are active principles, energy in one form or another. As the Nature poet William Wordsworth wrote in his poem *The Excursion*:

"To every Form of being is assigned,"
Thus calmly spake the venerable Sage,
"An 'active' Principle:—howe'er removed
From sense and observation, it subsists
In all things, in all natures; in the stars
Of azure heaven, the unenduring clouds,
In flower and tree, in every pebbly stone
That paves the brooks, the stationary rocks,
The moving waters, and the invisible air".

What is significant is that the manifestations of energy affect us in ways that not only serve our basic needs for survival, but also add richness to our lives. Thus, for example, ordered motion or mechanical energy serves us in locomotion, whereas random molecular motion affects us as heat and warmth. Material waves include the ups and downs in water as well as the vibrations of strings and air columns which produce sound and music. On the other hand, there is a whole range of immaterial (electromagnetic) waves which strike us as light and radiant heat.

The world of perceived reality is thus made up of energy in various forms. These different forms of energy create different impressions. We go through the pains and pleasures of life without pausing to consider the energy aspects of the world around us. But they are there at every turn, sometimes blatantly obvious, sometimes not so apparent, and in other contexts stealthily hidden, as it were, waiting to be released when opportunities arise.

Music can only be experienced in one of its countless manifestations. There is no such thing as music *per se*. It is always this song or that melody, this *bhajan* or that *keertanam*. So too there is no such thing as energy *per se*. It is always in one of its several manifest-modes. We observe and experience the various manifestations of energy like we enjoy different pieces of music.

In this context it may be mentioned that Hindu seers referred to the unmanifest aspect of the universe as avyakta (or *akshara:* imperishable). The tangible physical universe is referred to as *khara* (ephemeral), its manifested aspect. In this terminology, energy per se is *avyakta* whereas its particular forms of energy are transient and may therefore be called *kshara*[7].

Energy Transformations: ***All phenomena are energy transformations.***

But there are important differences with the music analogy. Music cannot be measured in units, as energy can. Nor can one piece of music be changed into another as energy forms can. Heat can be converted to motion (kinetic energy), motion into electricity, electricity into light, light into sound, and so on. Indeed such transformations are at the root of perceived reality. This whole experience we call the phenomenal world turns out to be a complex of energy transformations.

Energy transformations are endless, and they are complex too. Even the most trivial episodes in cosmic history involve fairly complex energy transformations. It is a challenge to visualize the extraordinarily complicated ways in which energy changes occur in the universe, either partially or totally or along multiple channels, and give rise to phenomena. Consider snapping a finger which calls for muscular effort. The energy generated for that was from a series of biochemical reactions which were possible because of the ingestion of foods (chemical energy), which came from other molecules (proteins, fats, etc.) whose source is ultimately the green

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[7] In the *Bhagavad Gita* (II.) Lord Krishna says that all beings were unmanifest at the beginning become manifest, and then unmanifest again: *avyaktādīni bhūktāni, vyakta-madhyāni, avyakta-nidhanāny eva*. Some of these metaphysical worldviews can be meaningful in the scientific context, whether or not their originators thought in these terms..

kingdom which captured some energy from sunlight, which came from the core of the sun as a result of nuclear reactions which occurred, as per our calculations, some ten thousand years ago. And it goes on, for that mechanical energy became sound and got dissipated in the air, giving a slight boost to the kinetic energy of a few molecules. What a mind-boggling chain of transformations! This is but an insignificant fraction of the countless transformations ceaselessly occurring at all scales of perceived reality.

This is an incredibly fascinating revelation. Not even the most imaginative mind could have pictured: the conversion of energy from the sun's deep interior several thousand years ago to its climax in the snapping of my fingers. At every pause we take to reflect on the roots of perceived reality we never cease to wonder at the magnificence of it all, in scale and in variety, in complexity and in simplicity. It is this recognition that constitutes real science. This result is not culture, nation, or scripture bound. That is what makes it science.

Energy Conservation: ***There are invariant quantities in the phenomenal world: energy is one of them.***

Energy transformations may be random, but they don't occur in arbitrary measures. Like exchange rates in monetary currency, so much heat energy is equivalent to that much mechanical energy; so much electrical energy is equivalent to so much light energy, and so on. This was established by James Prescott Joule who published his result on this in 1842, but Julius Robert von Mayer had done very similar work a year earlier. There were controversies as to who should get the credit for this[8].

Be that as it may, when a certain amount of energy in one form becomes energy in another form, the resulting amount will be well-defined: except that the equivalence does not change with time. In other words, energy can change forms, but it cannot appear from nowhere, nor disappear into nowhere. We say that there is a principle of energy conservation. The total amount of energy in the transformations is unaffected.

Then why all this scare about running out of energy if the total amount of energy will be the same forever in the universe? The reason is that energy in one form may become less available than energy in another form. It is easy to switch on the light, converting electrical energy into light, but this light cannot as easily be transformed back into electrical energy. It is possible to

[8] See for more details, C Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain*, Chicago University Press, 1998.

exchange a hundred rupee note into an ice cream cone, but it is not as easy to change the ice cream back into the rupee note.

Aside from energy transformations that take place in the physical world, we humans bring about transformations for specific purposes. Primarily, depending on the context, we utilize only four forms of energy: heat, light, locomotion (kinetic energy), and sound. Technology consists in devising effective channels for bringing about appropriate energy transformations.

Matter and Energy: ***Matter and energy are precisely inter-convertible.***

We have seen that energy is the insubstantial dynamic dimension of the physical world: that which is manifest as light and sound, as heat and motion or is simply held trapped in positional constraints and in molecular configurations, ready to be released when provoked. Matter on the other hand is the static substantial feature of the world, concentrated and massive, localized in space, exerting nevertheless long-range forces on other pieces of matter in the universe.

So we have a world of matter and energy, of substance and action, one causing us to feel we are in a tangible substantial world, the other making us experience sensations like heat, sound, and light. Matter undergoes umpteen transformations, while retaining the total mass; and energy does a very similar thing, maintaining its quantitative integrity in the processes.

It turns out, and this was the great discovery of Einstein in the first decade of the twentieth century, that these two aspects of perceived reality, one so different from the other, are in fact two versions of one and the same entity, for which we have no simple name. Perhaps we may call it *mattergy*. We may regard matter as an extremely concentrated form of energy, and energy as a very diffuse and non-material manifestation of matter. Moreover, and this is crucial, matter may be converted into energy and energy into matter, violating the principles of conservation separately governing each.

Einstein's neat little formula[9] $E = mc^2$ says that there is a precise quantitative equivalence between the two, meaning that for a given amount of matter there is a precisely equivalent amount of energy and vice versa. In other words, if a certain amount of matter is transformed into energy, thereby disappearing from the material world, then a quantitatively calculable

[9] In this formula c stands for the speed of light. If m is expressed in kg, and c as approximately 300×10^6 m/s, then E will be given in joules as $m \times (9 \times 10^{16})$ J. This famous formula was given by Einstein in a paper published in *Annalen der Physik*, Vol.18, pp.639–643 in 1905. It was entitled, "*Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig*? ("Does the inertia of a body depend upon its energy-content?").

amount of energy will emerge. What this implies is that matter can be annihilated with the consequent production of energy. Equally amazing, subtle energy can materialize into gross matter: a flash of dazzling light can, in principle, become a little massive speck of matter.

All through the ages people have known that the physical world is made up largely of matter. Many philosophers had proclaimed that there is only gross matter in the universe, and have been decried as materialists. Religiously inclined thinkers have often entertained disdain towards the material world, even though they can hardly exist without molecular matter. This was because matter stood for flesh and associated carnality, in opposition to spirit and its association with the divine. In any event, the world is not pure matter. It has energy too. As to spirit, it is beyond the purvey of science.

Besides being the most famous formula of modern physics, $E = mc^2$ has earned its legitimacy in countless ways, not the least of which was the Hiroshima horror of 1945. It is also lighting many towns and cities by electrical energy generated in nuclear reactors (which is derived from the annihilation of matter) [10]. More spectacular still, we have come to know that the decimation of matter with the consequent release of radiant energy has been going on for astronomical ages in the core of the twinkling stars that adorn the nocturnal sky, and right in the heart of our own effulgent sun. Every bit of sunshine comes at the sacrifice of minute masses in the body of the sun. Slowly but surely, the sun is depleting its massive abundance by turning it all into heat and light and other radiations that perennially escape away, abandoning their place of origin forever[11].

Zero-point Energy: ***Nothing can ever be brought to total rest.***

The atoms and molecules in a piece of solid are normally in a state of vibration because they have kinetic energy. If we give the body some more heat energy, its atoms vibrate faster. If we cool it, we are taking away energy from the atoms, and they vibrate more slowly now. Now suppose that we cool the solid more and more, going as low in temperature as we possibly can. The atoms become increasingly sluggish, like a long-distance marathon runner who is totally exhausted and collapses, coming to a standstill. It might seem that by reaching the lowest possible temperature, we can bring atoms to absolute rest.

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[10] In nuclear bombs matter (from uranium/plutonium nuclei) is converted into lethal radiation. In nuclear reactors nuclear matter is converted into electricity. According to a report published in 2010, some 440 nuclear reactors are generating commercial electricity in thirty countries.

[11] If current astrophysical calculations (and theories) are correct, the sun has been radiating for at least 4.57 billion years, and will continue to do so for at least that many years more before extinguishing itself for good.

Not really. Walther Nernst in 1905 showed that it is impossible even in principle to reach such a lowest possible temperature[12]. He showed that, contrary to what one might expect, at the so-called absolute zero temperature there is perfect orderly motion rather than perfect rest of the atoms. Later developments in quantum mechanics confirmed this result. As Matthew Arnold poetically put it,

For something in the depths doth glow
Too strange, too restless, too untamed[13].

In other words, energy, the life-breath of the physical universe, will never by annulled. There will always be a residual heartbeat even if the universe were to reach asymptotic chillness. Inactivity may be for the lazy, rest for the tired, and inertness for the lifeless. But a modicum of energy will always be associated with atoms and ultimate oscillators. Here is another root of perceived reality that has been unearthed by scientific inquiry: We live in a world that has been keyed to innate dynamism.

Vacuum Fluctuations: *There are palpitations in pure nothingness.*

The most powerful material microscopes do not suffice to fathom the smallest frontiers of perceived reality. For this we need the piercing power of mathematics. Equipped with this, theoretical physicists have explored the deepest roots of the material world and dug even further into the hidden recesses of nothingness. They have found, in complete contrast to what common sense might tell us, that there is activity galore in utter emptiness. In the insubstantial sea of pure vacuum there are ceaseless fluctuations: All sorts of energy-bundles are constantly appearing and disappearing in the void-core. This is the picture we get from what is known as *quantum field theory*: the language and framework of a dominant branch of current fundamental physics.

All this is not fantasy, not the magical concoction of mythology where the strangest episodes are permitted, where beings may come and go by the whiff of a thought. The sort of thing physicists are talking about has grown from the solid soil of serious physics. The ideas rest on esoteric concepts like the electron's intractable *self-energy* which can swell to incalculable proportions,

[12] In technical terms, "As a system approaches absolute zero, all processes cease and the entropy of the system approaches a minimum value," but absolute zero cannot be reached. It is interesting that in the same year 1905, two impossibilities were established: Impossibility for a body of attaining the speed of light, and that of reaching absolute zero.

[13] Matthew Arnold, *A Farewell*, Poems by Matthew Arnold, Stanza 5. Macmillan, p.179, 1859.

and on technical analyses which involve terms like the *renormalization of infinities*[14]. From it all emerges a picture that is fantastic and fascinating. Some have even suggested that the universe itself may be one cosmic vacuum fluctuation[15]. These notions account for a whole range of experimentally measured data to an impressive degree of decimal places.

The essence of these investigations is that energy simply does not vanish even in absolute nothingness. Like writings on a blank blackboard, these *virtual* (ephemeral) *particles* appear and are promptly erased, as if strewn from perpetual cosmic fountains and sucked back into ubiquitous cosmic pumps. This is possible because at the underlying levels there are inherent latitudes as to the strictness with which matter and energy are conserved. For very short time intervals, as we shall see later, minor violations are permitted in microcosmic processes.

To repeat: This kind of dynamic vacuum is no quirky behavior in some remote corner of the universe. It is not a stray event like a comet or a supernova: interesting but not regular features of the observed world. Rather, if current cosmological models have any merit, virtual particles in the nether world are the ultimate agents responsible for the emergence of the universe. They are what gave rise to this material world of ours, and in quite unexpected ways too.

The Universe from Nothing: *There occurred a Big Bang from total silence in an unimaginable Void.*

It all happened, there is reason to believe, some ten to fifteen billion years ago when all of a sudden a pre-universe of nothingness where neither space nor time, neither matter nor physical law existed, burst forth all of a sudden as the famous Big Bang, trumpeting as it were the birth of a universe, and initiating the chain of events that have led to you and me, and to a zillion other more interesting things with the slow passage of time. Though not formulated in mathematical terms the *Násadiya Sukta*[16] speaks of an emergence from nothingness:

> *Not even nothing existed then*
> *No air yet, and no heaven.*
> *Who encased and kept it where?*
> *Was water in the darkness there?*
> *Neither deathlessness nor decay*

[14] See in this context, Richard P Feynman, *QED, The Strange Theory of Light and Matter*, Penguin, 1990. This is a remarkable book which reveals the strengths and limitations of quantum electrodynamics.

[15] Edward P Tryon, Is the Universe a Vacuum Fluctuation, in *Nature*, Vol.246, pp.396–397,1973.

[16] *Rig Veda*: X.129, Nasadiya Sukta.

Nor the rhythm of night and day:
The self-existent, with breath sans air:
That, and that alone was there.

What a burst it was! In an unimaginably brief interval of time that lasted for 10–30 seconds, a tiny, tiny bit of this violent vacuum exploded to 1050 times its size, its stupendous energy stored in what has come to be called the Higgs field. It is this Higgs field that blew space into a sphere of enormous radius. When the expansion became a little steady, there was a *symmetry breaking* at which instant particles and antiparticles materialized in abundance. Thus was born our physical universe. This is the sketch of the grand Genesis, as suspected by current cosmologists. They go on to say that ours may be just one of many universes thus formed, like bubbles in unconnected islands of space[17].

Now, one may ask with a touch of skepticism, is this what really happened? Is this how the universe came to be, and not in seven short days by a fiat from the Creator or by the routine of Brahmic creation at the dawn of every kalpa? As the Vedic sage-poet exclaimed[16],

How creation arose, when or where!
Even gods came after creation's day,
Who really knows, who can truly say
When and how did creation start?

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[17] For details, John D Barrow, *The Origin of the Universe: To the Edge of Space and Time*, Phoenix, New York, 1994.

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