Darshana Jolts

On the Nature of Heat – 1

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Introduction

In certain regions of the world, summer heat can often be unbearable. The fiery sun fiercely shoots its harsh rays. We perspire profusely and run for shade. But people do manage to live in such zones.

But where there is no warmth around, and the air is bitter cold in the open, we shiver and suffer frost bite and worse. That is why there are no human settlements in polar regions with their perennial ice and sheets of snow where all is bleak and no vegetation will grow.

We realize the importance of heat for our survival. We need heat to cook our foods too. Among the sensations we feel, warmth is most closely linked to comfort and coziness. We speak of a warm person and of warm hospitality. The poet speaks of love as "for ever warm and still to be enjoy'd." It is supremely satisfying to warm ourselves in front of the fireplace or under a thick wool blanket on a wintry night.

There is fire that burns and kills. There is also fire that cooks and heats. There is cold that causes blisters and lays its hands on corpses. Cold can also be refreshing as beverage or ice cream, and there is cold that is pleasant in an air-conditioned room.

The human body needs heat to carry on its normal activities. Heat is at the very basis of life. This fact has been recognized since ancient times. It gave rise to the notion of *innate heat* and *inborn fire* as the root of all life. Heat was seen as playing a role in eating and in breathing, and in reproduction too.

We are not content with the experience of heat and cold. We want to know what exactly is the source of these sensations. As with everything else, we wish to probe into the root of this perceived reality also.

Radiant Heat: *Heat rays and light rays are both of the same kind.*

The hot water from the shower does not give out light. The shining phosphorescent pail is cool when we touch it. The hot slab of rock on the road does not emit light. We feel no warmth from the full moon that shines brightly in the sky. All this might suggest that heat and light are intrinsically different. Yet, the same sun that gives us light, gives us heat also. The same fire that is so hot lights up the room too. The candle flame is both bright and burning. From these it is reasonable to conclude that heat and light are intimately related. So the heat-light relationship was not clear even to careful observers for a long time. In 1800, while working on light filters, the musician-astronomer Wilhelm Herschel discovered what he called calorific rays, now known as infrared (or heat) rays[1]. By the first decades of the 19th century physicists had come to understand that calorific radiation and light are essentially the same, They pictured them as vibrations propagating through an all-pervading medium they called the ether.

Only by the second half of 19th century did it become clear that the difference between radiant heat and visible light lies simply in their wavelengths. Radiant heat waves have longer wavelengths than light. What this means is that our sensory systems respond very differently to various electromagnetic waves, depending on their wavelengths[2].

The Temperature of the Sun: ***It is possible to measure the temperature of celestial bodies from earth.***

Textbooks will tell you that the surface temperature of the sun is of the order of 5500 degrees Celsius. But how did one determine this? This is just one of countless examples of how experimental, quantitative and theoretical understandings enable us to acquire knowledge that mere philosophical criticisms of modern science can never achieve.

From the quantitative and experimental studies of radiant heat during the closing decades of the 19th century it became clear that the intensity of heat radiated from a source depends in specific ways on the temperature of the surface which is emitting the radiation[3]. This is a finding of enormous import, for it furnishes a means of measuring the temperature of bodies we cannot touch and which are beyond our reach. With this knowledge one can know the temperature of a blast furnace without inserting a thermometer into it, by measuring the wavelength of the heat emitted.

In the late 1830s Claude Pouillet invented the *pyrheliometer*, an instrument for measuring the

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1 Herschel noticed that his red filter for observing sun spots was getting heated when sunlight passed through it; this led to the discovery of infra-red (heat) waves/radiation. Ironically, Herschel also believed that the sun was not very hot and that it had inhabitants.

2 This is an extraordinarily complex process, perhaps the most marvelous in the universe, for it translates physical vibrations into the experiential states of sight and feel.

3 The mathematical relationship between the (absolute) temperature of a (black) body and the total amount of energy of all wavelengths that it radiates from unit area of the surface per unit time is known as the Stefan–Boltzmann law, discovered in 1879 by Josef Stefan and in 1884 by Ludwig Boltzmann.

amount of radiation received on earth from the sun[4]. With his crude instrument, long before one had developed a theoretical framework for radiation, he estimated the solar surface temperature to be about 1800 °C. Other estimates using only the early data ranged from a few thousand to 10,000 °C by Francesco Rossetti[5]. Finally, it was Josef Stefan who, used the data from previous experimenters, and applied his own formula relating radiation intensity and source temperature, obtained the value of 6000 °C[6].

It is important to fully appreciate this in the context of the history of science: Standing here on planet earth, humans could measure the temperature of the unapproachably hot sun millions of miles away only in the 19th century.

Heat, Temperature, and Direction of Heat Flow: ***Heat energy always flows from hotter to less hot.***

The temperature of the fire in an oven is high, that of the ice cream is quite low. The nurse takes the patient's temperature, and the weatherman reports the day's high and low temperatures. It is common to speak of temperatures, even if one may not be clear about what exactly this means. A common misconception: temperature is a measure of "how much heat" a body contains.

The world of physics took a long time before it clarified this notion. It was only in the second half of the 17th century that thermometers came to be constructed, assigning to the freezing and boiling points of water standard values. Air, alcohol and mercury have also served as materials for temperature-measuring devices[7].

The temperature of a body refers to its thermal condition: a condition which determines the direction of flow of (heat) energy to or away from the body. Thus, temperature is a state relative to others. It is not unlike water pressure which determines the direction of water flow: always from regions of higher to regions of lower pressure.

When we touch a body and it feels hot, heat energy has flowed into our body. We say that the body's temperature is higher than our own. When the body feels cold, heat flows away from our body: the body's temperature is lower than ours. It is this flow of energy that constitutes heat.

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[4] René Taton, Claude–Servais–Mathias Pouillet', *Dictionary of Scientific Biography*, N Y Charles Scribner's Sons, Vol.XI, pp.110–11, 1975.

[5] 'The effective temperature of the Sun', *Monthly Notices of the Royal Astronomical Society*, Vol.55, pp.242–242, 1878.

[6] The result was first published by Josef Stefan in 1880. It is one of the greatest jolts given to human understanding by theoretical and experimental science, but is seldom recognized as such.

[7] See in this context, W E K Middleton, *A history of the thermometer and its use in meteorology*. Baltimore: Johns Hopkins Press. Reprinted ed. 2002.

Heat always flows from hotter to colder bodies. We call this the zeroth law of thermodynamics[8]. This need not have been so. Why should not heat energy flow from colder to hotter bodies? Consider wealth, for example. Does it always flow from the richer to the poorer classes?

Heat and Work: First Law of Thermodynamic: ***Heat energy and mechanical work are precisely inter-converted.***

Heat is a form of energy, and so is motion. We measure heat energy in calories and mechanical (kinetic plus potential) energy in joules, even as French currency is in francs and Indian is in rupees. That you can generate heat by rubbing your palms is ancient knowledge. But that there is always an equivalence between heat and mechanical energy is new. In other words, as we saw earlier, in any energy transformation, the total amount of energy does not disappear. It is like a person's worth, as it were: some of it may be in money, others in goods. One may use the money to buy more things, or sell things and acquire more cash. Except that in the realm of energy, the intrinsic value of the cash and materials do not change with time.

This precise equivalence and preservation of the net amount of energy when transformations occur without input from or output to the outside is known as the *principle of conservation of energy*[9]. When the transformations are between heat and mechanical work, we refer to it as the *first law of thermodynamics*[10].

This seems like a simple idea, but it was a long time before one appreciated its full significance. Like the laws of motion, energy conservation comes into play in every phenomenon in nature. It governs the operation of all the appliances devised by human beings. So much electricity becomes so much heat and light, so much chemical energy from gas is converted into so much energy of motion in the car, and so on.

Kinetic Theory of Heat: ***Heat energy reflects the random kinetic energy of atoms and molecules.***

Once heat was thought to be a subtle fluid (*calorific fluid*) flowing from body to body. Some did experiments to weigh this fluid. It was believed that bodies expand on heating because the fluid needed more volume.

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[8] This name was given by Ralph Fowler; see, Peter Atkins, *Four Laws That Drive the Universe*, Oxford University Press, New York, 2007.

[9] See V V Raman, Energy Conservation Principle, *Physics Teacher*, Vol.13, No.2, pp.80–86, Feb 1975.

[10] loc.cit. 8.

The elaboration of the close relationships between the mechanical energy of atoms and molecules on the one hand and the thermal properties of bodies formed by those atoms and molecules is a rich chapter of physics, known as the *kinetic theory of heat* [11]. The basic ideas of the theory are simple: Because of their incessant motion, the atoms and molecules possess kinetic energy, the *internal energy* of the body. Thus, the hotter a body, the greater is the *average kinetic energy* of its atoms and molecules which may be vibrating (as in solids and liquids), rotating (as in liquids and gases), and/or moving from place to place (as in gases). Any transfer of this random kinetic energy is what we call heat. It is important to recognize here that these understandings would be impossible without the modern knowledge of atomic – molecular constitution of matter (their masses, speeds, etc.), and precise quantitative measurements of the associated parameters[12]. Interestingly, this picture was erected long before anyone had seen atoms and molecules. It was mathematical investigations that unveiled this root of physical reality[13].

Heat Engines: ***The ratio of what we invest to what we get is a measure of efficiency.***

Much of our industrial – technological civilization depends on the conversion of energy from one form into another. Of these, turning heat energy into mechanical energy is of primary importance. Since ancient times, human ingenuity has constructed gadgets and appliances for a variety of reasons. From the pulley and the lever to the windmill and the plough, such gadgets have served all civilizations. But it was only during the 19th century, in the context of the industrial revolution and steam engines, that arrangements of this kind were studied from theoretical perspectives.

The model of all these is the conceptual heat engine: a device whose goal is to transform heat energy into mechanical energy. The steam locomotive is its prime practical example. The idea is simple: take in a certain amount of heat energy and convert as much of it as possible into mechanical energy (for locomotion, for example). The fraction of the input energy that is successfully transformed into mechanical energy (the goal) is a measure of the efficiency of the device. Thus a 30 per cent efficient engine means that three-tenth of the energy absorbed by the

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[11] As early as in 1738 Daniel Bernoulli proposed in his book on hydrodynamics the idea that the pressure of a gas may be due to the bumping of its constituents on the walls of the container – one of the first (qualitative) inklings of the kinetic theory of gases.

[12] These parameters are pressure, volume, temperature, and speed of molecules.

[13] Indeed, by the close of the 19th century there was wide disagreement among scientists (physicists and chemists) as to the very existence of atoms and molecules. The battle was especially virulent between Wilhelm Ostwald and Ludvwig Boltzman. Some have attributed the latter's suicide to his feeling of rejection by the scientific community for his commitment to molecules.

engine in a given cycle becomes mechanical work. The rest is usually dissipated [14].

Conceptually, then, a *heat engine* has a *source* from which it absorbs heat energy, and a *sink* into which the unused part is cast away. We note right away that whenever heat engines function there is always a certain amount of heat energy that is lost beyond recovery. The less the fraction that goes into the sink, the more efficient the engine.

Second Law of Thermodynamics (SLT): *One hundred percent efficiency in an engine is impossible.*

Some people strive for hundred percent efficiency. It is difficult to say what one means by this expression in common language, but with heat engines the idea is clearly defined. A hundred percent efficient engine is one which takes in a certain amount of heat from a source and converts all of it into mechanical work in a cycle. That is the kind of engine we would all like to have, for who wants to waste energy? But then, this would be like wanting to pay for a car what the manufacturer spent in putting it together. This is impossible because the car has to be transported, the dealer has to be compensated, taxes have to be paid, and so on. So, only part of what we pay is converted into the car proper.

Likewise, in heat engines, of the total heat energy gobbled up by the engine, only a part becomes mechanical work. In other words, the efficiency of the engine is less than hundred percent. Theoretical analysis shows that it is impossible to construct a one hundred percent heat engine. This is a limitation imposed by nature on what we can achieve realistically, and what we cannot. This built-in restriction in the transformation of heat into mechanical energy is referred to as the *second law of thermodynamics*[15]. One reason for this is friction: the inevitable consumer of mechanical energy that is unavoidable when motions of complex systems are involved.

The second law of thermodynamics is one of the fundamental laws of nature. It says, in effect, that the happenings in nature transform usable into unusable energy. The disorder in a system is a measure of the unusable energy in it.

Randomness and Entropy: *Levels of molecular disorder make a huge difference.*

We are often struck by the order in the world, impressed by its harmony and beauty. Yet, just as underneath all the civility and polite exchanges there reign the raw passions of basic instincts,

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[14] The first theoretical analysis of the heat engine was done by the 28-year-old Sadi Carnot who published his work as a book in 1824, entitled *On the Motive Power of Heat*, which is a classic in the history of science.

[15] For a history of this see, V V Raman, The Evolution of the Second Law of Thermodynamics, *Jour. Chem Educ*, Vol.47, No.5, pp.331–337, May 70.

behind all the law and regulation governing the phenomenal world, there is an irrepressible tendency towards disorder, to go amuck as it were. Every change that spontaneously occurs in the universe moves the world closer to a state of total mix-up. It is as if the goal of the universe is supreme chaos.

What does one mean by chaos in this context? (The term has acquired a totally different meaning in the field of *chaos theory*.) Here the notion refers to the level of inhomogeneity in a system with many component parts. When we shuffle an ordered sequence of cards we create greater chaos. When we stir the coffee into which sugar has been added, we are increasing the disorder. When dust spreads out more uniformly in the room, there is an increase in chaos too.

The world of physics has ways to measure the degree of disorder in a system. The term used for this is *entropy*[16]. When a physicist says that the entropy of a system has increased, all it means is that there is now a greater degree of disorder among the components of the system. A fundamental law of the physical world is that no matter what happens in the natural world, the net effect will always be to increase the entropy of the system, as long as heat is involved.

Though heat and mechanical energy are equivalent, there is this intrinsic difference between the two. Mechanical energy arises from ordered motion. Heat energy arises from the random motion of the molecules. If a thousand soldiers are marching in perfect order, that would correspond to mechanical energy. If there is an explosion and the soldiers run helter-skelter that would be disordered motion. It is easier to convert ordered motion into disordered motion than vice versa, especially when we are dealing with zillions of molecules: the reason we can't convert 100% of heat into mechanical energy.

The randomness of the kinetic energy distinguishes heat from mechanical energy. If a million molecules traveled all in a straight line with the same speed, their combined energy would not constitute heat. This never happens. The molecules of a gas move every which way, they collide and rebound, they are like a swarm of brainless bees, keep bouncing off one another thoroughly mixing up all the time. That is why not all the oxygen molecules in a room accumulate in one corner, and the nitrogen in another, not all the diamonds in a pack of a billion cards come to the top during a random shuffling.

A most revealing insight we have obtained from the notion of entropy is that what we experience as the direction of time is intimately related to the fact that the entropy of the whole universe is steadily increasing, never decreasing. The impression of the flow of time along one direction,

[16] Rudolf Clausius coined the term *entropy* in 1865 from Greek words *en* (in) and *tropi* (turn). The term has grown in meaning, significance, and application considerably since then.

and its irreversibility is essentially an experiential reflection of cosmic entropy-increase[17].

Closed Systems and Interconnections: ***The universe as a whole may be closed, but systems within it are interconnected*.**

Keep all the doors and windows of a building closed. No one can come in. Nobody can go out. We have a closed system with respect to human beings. But it is still an open system with respect to air which can creep in through the crevices, and to light which can come in or go out through the glass windows. A system is said to be closed with respect to an entity if there is no way by which that entity can come in or go out of the system. It is said to be open when this is possible.

Hot coffee kept within a tightly sealed perfect thermos flask would be a close system with respect to energy, and matter also. On the other hand, our planet is an open system: matter and energy are constantly pouring into and out of it.

A myriad things are happening in the world, and it is difficult to keep track of the multiplicity. There are changes all the time, motions and transformations never-ending. Are there any things at all that remain unchanging in the midst of all this? Consider, for example, people in a building. They may move from floor to floor, from room to room, change places and positions. They may interact in various ways: exchange gifts and words, share thoughts and ideas, foods and drinks, amongst themselves. But is there anything at all that remains unaffected by all this? What is unchanging amidst all this? If the building is closed, we may say that the number of people will remain the same (assuming no one dies in the meanwhile, and there is no birth either). When we consider closed systems, it is often to detect what aspects of physical reality remain unaffected in it even when all sorts of changes are occurring all the time[18].

When the system is open, there is free exchange with whatever is outside. Then it is difficult to speak of things conserved. In actual fact, practically all systems are open one way or another for it is difficult to isolate anything totally and completely. Indeed even apparently isolated systems are in subtle ways connected with whatever is outside. This leads to the notion of *interconnectedness*: that everything in the universe is connected either directly or indirectly to everything else.

Interconnectedness is a profoundly insightful idea,. It is one of the key notions to have emerged in the course of our century. It runs contrary to the physics of earlier eras wherein the emphasis

[17] The term *arrow of time* was coined by Arthur Eddington in his popular book *The Nature of the Physical World* (1928) where he discussed this thermodynamic interpretation. But it has expanded to include a variety of contextual meanings, as in radiative arrow of time, particle physics arrow of time, causal arrow of time, etc.

[18] For more on this idea, see, Perrot, Pierre, *A to Z of Thermodynamics*. Oxford University Press, 1998.

was one separateness, on closed systems, if only because, in order to understand the complex world in its multitudinous manifestations one has to analyze it first into separate and non-interfering components. This approach certainly proved to be most effective in the recognition of several roots of perceived reality.

But now we have come to realize that the pictures resulting from such piece-meal analysis, insightful and useful as they are, do not provide the complete picture. We need to explore the world in its interconnected totally. More than in the physical world, interconnectedness is crucial in the biological world. This understanding enables us to manage and manipulate the world better and more to our advantage.

Eventual Fate of the World: *The world would eventually have a heat death.*

This then is the fate of the world: To get thoroughly mixed up. The goal of the universe is to reach the state of maximum entropy. This may be described as a cosmic uniformizing principle, infinitely more drastic than what the most ardent communist could hope for on the economic plane. It has been working silently since the dawn of time. It is as if a giant clock is slowly winding down.

Reflecting seriously on the second law of thermodynamics of Rudolf Clausius, Hermann Helmholtz came upon an ominous conclusion: That eventually, the whole universe would run down to a state of ultimate chaos in which all bodies would have attained the same temperature, and there would be no further dynamism. This would constitute the ultimate Heat-Death of the universe. What a terrible thing to say! This is much more serious than any earthquake or volcanic eruption or plague or *pralaya* (global deluge). This is death to all, including mighty stars and the sun. This is cold scientific pessimism of the rational kind. As Erasmus Darwin wrote in his *Botanic Garden*[19]:

Star after star from heaven's high arch shall rush,
Suns sink on suns, and systems crush,
Headlong, extinct, in one dark centre fall,
And death, and night, and chaos, mingle all!

Is this the sort of conclusion we want to hear after two and odd centuries of penetrating physics? To have removed all the mystery from the planets and the stars was bad enough. To say that

[19] Interestingly, this poem was written in the last decade of the 18th century, inspired by William Herschel's projection that the whole cosmos would crunch back into one dark center. It had nothing to do with the thermodynamic heat-death of Wilhelm Helmholtz and Rudolf Clausius.

rainbows are mere consequences of the laws of refraction is prosaic enough. To speak of comets as minor masses following very elongated elliptical orbits was okay, perhaps, since that at least it rids us of the ominous fears some experience whenever one was spotted in the skies. But to be told that some day the sun would fade and the stars cease shining, and all would be degraded to lifeless uniformity: well, this was, as Shakespeare would say, the most unkindest cut of all. Poets and philosophers have surmised similar endings. But that was poetry, not to be taken literally. This is science, frighteningly closer to the truth, or so some felt. It may be of some consolation that there is so much matter and space in our grand universe that thermal dissipation can be going on for very long periods of time without affecting our daily plans of work and fun. If ours were a much smaller universe functioning under these laws, there might not have been time for our emergence. The whole lot of gross matter might have degenerated long ago. But now, the way things are, this threat of cosmic heat-death, even if it were to come about, is not within sight.

But still, even if this were to happen long, long after our most distant descendants come and go, there is something unpleasant in this whole idea of cosmic mortality. For one thing, this is not the sort of conclusion to which a merciful God would bring His creation. There must be ways of avoiding such an eventuality conceptually too.

Philosophers and physicists have written extensively on this theme[20]. Quite a few have argued for less drastic visions of the second law of thermodynamics. Now a new surge of interpretations is emerging from cosmologists and physicists to assure the general public that the so-called heat-death is by no means a logical consequence of serious physics.

[20] Frank J Tipler, *The physics of Immortality*: *Modern Cosmology, God and the Resurrection of the Dead*. Doubleday, New York, 1994 is a brave new attempt along this direction, .

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