Thermodynamics and We, the Humans

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1. Celestial affairs have always captivated the human minds. Even after the Copernican revolution great scientists as well as prominent philosophers have not ceased to be interested mainly in what happens "up there" - as did Tycho Brahe, Kepler, Galileo and, above all, Newton. As late as the turn of the twentieth century Pierre Simon de Laplace, then the towering mind in physical sciences, was praised even by Napoleon for his *Mécanique Céleste* expounded in five thick volumes! (1799-1825). But while on the Continent most scholars continued to plow the same furrow as their forerunners, in Britain scholars, skeptical empiricists as British have usually been, became interested in some pedestrian problems they considered to be far more important for the human welfare than the celestial affairs. Prodded by a practical issue, they began to study the properties of a gas or a vapor enclosed in a vessel. As we shall see in due time, that issue pertained to the depletion of forests everywhere for a long time and at a growing rate so that by the end of the seventeenth century the availability of wood - at that time the only source of heating fire - was seriously menaced. The situation was so critical that not only in Great Britain but even in a country such as Norway cutting trees from the woods had to be restricted by legal decrees.

2. No one then and, as it seems, no one ever since, perceived the profound reason for what happened during that historical episode. Why do humans need fire so badly? All other living creatures, even the warm-blooded animals, survive without fire. This may seem a silly question, yet it is highly fit to guide us to a deeper understanding of our own nature.

So, to begin let us observe that while we are one of the species on this planet, we differ from all others in a fundamental way. All species, ours included, become fitter for life when some of the organs with which every individual is endowed by birth become more efficient for their proper roles. As these organs belong to the individual's soma they have been labelled *endosomatic*. It is by biological mutations that each species may become better (occasionally worse) fit for survival, with stronger muscles, sharper claws, better vision or hearing, more comprehensive brain, and so on down the line.

But this manner of becoming fitter for life is both fantastically slow and completely uncertain. Our species, however, at a moment in its long past transgressed the purely endosomatic adaptation. Instead of waiting for some favourable mutations to occur in the unpredictable haphazard sequence as mutations not provoked by some artificial excitation always come off, some of our biological ancestors initiated a highly valuable procedure of evolutionary advancement. They began using detachable organs, *exosomatic* organs: at first, a club picked up by chance from the woods with which those protohumans must

have felt, as we may safely surmise, their arms longer and more powerful; later, a sharp edged stone to cut animal skins and meat; nowadays, atom bombs and spaceships. By now we can run faster than a cheetah, fly higher and faster than any bird, and kill in one go more living creatures than a tiger, although we do not have the muscles of a cheetah, nor the wings of a swift, nor the claws and fangs of a tiger [16,17,19].

To be sure, many other creatures also use exosomatic organs. The beavers and the bees "manufacture" their exosomatic organs from elements found in their environment. A fascinating Galapagos woodpecker finch, *Cactospiza pallidus*, tailors a cactus spine just right to reach each worm inside its crack [26]. However, we are the only creatures on this planet to produce exosomatic organs by which to produce exosomatic organs in a progressive sequence. As Joseph Schumpeter used to put it wittily, we make machines to make machines, to make machines, ... which is the quintessence of the economic process.

3. The fact that I have contrasted the two modes of evolution and pointed out that the endosomatic evolution occurs in a haphazard way, as I have just done, should not be taken to suggest that the exosomatic evolution occurs with a stochastic frequency, that is, in the way which analytically is called random risk [16, 17]. Both endosomatic and exosomatic mutations are subject to true uncertainty. Therefore, the superiority of exosomatic evolution rests only in that it supplies living creatures with *new and more powerful* organs, not in that they are under some control by us. Yet some economists have sustained that innovations cannot only be predicted stochastically for the need of decisions, but can also be forced to sprout, so to speak. Apparently, they had never had any contact with biologists to learn of the latter's racking about the succession of endosomatic mutations.

Biological mutations and technological innovations are not only similar in that individually they are not predictable. Between them there is a deep dialectic analogy which has transpired in a historical event that has arrested the attention of no one. In a celebrated volume of 1912, a young economist, Joseph A. Schumpeter [43], set forth the theory according to which economic evolution consists of the sustained sequence of innovations, not of all but only of the palpable ones, that is, not of those so insignificant that they could be simply reversed - a new kind of window dressing, for example.

The point I can hardly overemphasize is that about thirty years later a prominent biologist, Richard Goldschmidt, startled his peers by arguing in a perfectly analogous way with Schumpeter that the biological evolution is not the result of imperceptible endosomatic changes as the Neo-Darwinism then preached. Schumpeter elucidated his theory by remarking that "Add successively as many mailcoaches as you please, you will never get a railway [engine] thereby". Goldschmidt in turn argued that since biological evolution is irreversible it is carried on by the emergence of a "successful monster" [19].

It is common knowledge in economics that long before Schumpeter it was Alfred Marshall who preached that "The Mecca of the economist lies in economic biology rather than in economic dynamics", but in contrast with Schumpeter he did not use the truth he intuited for an articulate vista of the economic process. So, it was from the great master, Joseph Schumpeter, that I got to my bioeconomic perspective which, I claim, is a recognition of the existence of that particular domain over which thermodynamics is significantly at work. This comes to the earlier suggestion that both economics and biology are life processes with which thermodynamics is uniquely involved.

4. Although exosomatic innovations cannot be controlled as we would like them to be, only exceptionally few people would deny that exosomatism is an extraordinary blessing, yet hardly anyone would think of it as a mixed one. First, since our specific production must be planned, controlled, and supervised, our society inevitably must include governors and governed. This is a division that cannot therefore be eliminated by any political regime, unless we revert to a primitive exosomatism like that of the australopythecines. The latent social conflict between the mandarins and the ricksha men which periodically becomes open is an unavoidable predicament brought about by our advanced exosomatism. No other exosomatic species is plagued by it. When in the fall the worker bees kill almost all drones, it is a natural biological incidence, not a civil war [19].

The calamities of the social conflict are further aggravated wars whose origin lies in the skew distribution of mineral resources on the Earth. And as I stated to The *New York Times Magazine* twelve years ago (29 December 1979), it is because of this distribution of vital resources for our exosomatic life, as almost every oil-well will become dry, warheads are likely to fly for the possession of the last drop of fossil oil. The Gulf War has been only a rehearsal, one in full dress, of what may be in the bag for the human species.

5. I submit on this occasion, too, that the fundamental reason for this view - pessimistic as it has been labelled by the legion of those who strive for applause by selling an optimist snake oil, e.g. Herman Daly in [14] - is the ineluctable working of the entropy law.

But what IS entropy and how DOES the entropy law work?

The extant literature can hardly help one arrive at some transparent answers, for the concept of entropy travels there from one definition to another. A concept of momentous importance not only for the understanding of physical reality, but especially for our survival on this planet, it is poorly understood even by many physicists [17]. At first a mysterious conception, entropy is now mentioned by many just for showing off.

Several incidents have contributed to this quandary. Because on the surface the verbal formulation of the entropy law is, as we shall see later, dangerously simple, the topic has attracted writers a legion who surprisingly have succeeded in getting published although they were not up to such a task. It is from that kind of literature that entropy emerges as an oblique and murky concept. Apparently for avoiding a clear exposition of the relation of entropy with some usual heat engine, it has been suggested that entropy represents what happens in the engineer's mind [17].

But what has made the problem of entropy truly exasperating has been a general fashion to extend the denotation of that term to problems other than the transformation of energy. Salient cases of such licenses are the association of entropy with the structure of vocabularies and with the layout of human settlements. That most of these essays have not been stained by absurd conclusions it is because the formula for statistical entropy $\Sigma f_i \log f_i$ can also serve as one measure of statistical dispersion [18], which was the true object of those analyses.

Both the concept and the law of entropy have also been increasingly beclouded by a swarm of senseless mathematical phantasies. The most guileful of these phantasies - not an innocent one - is the equating of low entropy (labelled amiss as "negentropy") with "information", an old term defined ad hoc as the measure of what a message - a telegram, a newspaper, a magazine, a book - can add to the reader's knowledge [18]. A funny corollary of that concoction (one can get a lot of fun with it) is that a Sears-Roebuck catalogue may contain as much knowledge as that which may be necessary for a Ph.D.

6. Struggling with the divergent and vacillating literature has helped me to arrive at a realistic yet pellucid (I claim) viewpoint of thermodynamics as a comprehensible and inclusive physical discipline intended from its inception. For we should not forget that thermodynamics grew out of the 1824 memorable memoir of Sadi Carnot, a young officer of the French Engineering Corps [10].

Although surrounded by the dominant preoccupation with celestial mechanics, Carnot became aware of the importance of the achievements of the British scholars struggling with the crisis of wood. As those results converged on the steam engine recently invented, Carnot set out to study that engine with the view to determine the conditions that would make it work most efficiently. Obviously that was a physical problem. But Carnot is known to have an appreciable interest also in economic problems, but it was because of the problems treated in his memoir that I saluted him as the first genuine econometrician [16,17].

7. Viewed as a science of natural phenomena, classical thermodynamics deals with energy but only with energy *in bulk*. No thermodynamic concept makes any sense if applied to a microscopic element. An electron, for instance, has no heat, no temperature, no pressure, and no entropy.

The simple idea that I have found most helpful for framing a clear and realistic description of the entire edifice of thermodynamics is that the energy in bulk exists in two distinct qualities or states. There is available and unavailable energy, the admirable terms proposed hundred years ago by Lord Kelvin [47] and used exclusively by another founder of thermodynamics, H. W. Nernst. As Lord Kelvin justified that proposal, *available* energy is that sort that we, humans, could ("can" would be the wrong term here) use for our own purposes. But as illustrated by the sun's plasma, available energy is not necessarily also *accessible* to us. *Unavailable* energy then is that which we, humans, could not possibly use in any way. Lord Kelvin's classic example is the heat energy contained in the sea water which, immense though is, cannot be used for sailing or for any other purpose. (It would not do to shun the ensuing conundrums - is the energy of lightnings available or unavailable? - yet only their existence can be noted here.)

With the aid of the Kelvinian concepts, the real meaning of the entropy law can now be enunciated in a clear and realistic way (it is my preferred formulation):

In an isolated thermodynamic system the available energy continuously and irrevocably degrades into an equal quantity of unavailable energy, so that the total energy remains constant while the unavailable energy keeps increasing up to a maximum.

If now, as is quite natural, we associate the concept of entropy with a quantum index of the unavailable energy in proportion to the temperature of the system - as the analytical definition of entropy suggests - we reach the famous stanza of Rudolf Clausius [12]:

The energy of the universe is constant.
The entropy of the universe tends to a maximum.

It was also Clausius who set forth the most faithful and transparent expression of the entropy law:

Heat always passes **by itself** *from the warmer to the colder body, never* **by itself** *from the colder to the warmer.*

In connection with the above or with any other formulation of the entropy law we should be aware of a frequent confusion which slides in and causes dreadful misunderstanding, at times quite harmful in controversies. To avoid it, let us make it sure that by an *isolated* system we understand one that can exchange neither energy nor matter with its environment (which, although a troublesome conception, does not invite discussion in this place). The entropy law cannot therefore be applied to a *closed* system that can exchange only energy with the environment (often times confused with the isolated one, as in Isaac Asimov's *Biographical Encyclopedia*). The least fit to serve for an application of the entropy obviously is the *open* system that can exchange both energy and matter with its outside. (A system that would exchange only matter with its environment, although it fits a logical slot, is not physically possible.)

8. I am fully aware of the fact that my view of thermodynamics sorely displeases purists since they do not even want to envision the possibility of accepting thermodynamics as a legitimate branch of physics. As they protest, it all smacks badly of anthropomorphism. I am at a loss however to think of a scientific concept completely detached from human nature. Are we not instructed nowadays that an atom is just an equation devised by the human mind? Is there any "later" or "earlier" that has not ultimately been established by the stream of human consciousness? Within my own epistemology there is nothing wrong therefore with the anthropomorphism of thermodynamics.

A salient illustration of the anthropomorphism of thermodynamics is the fact that the entropy law is the root of the basic economic scarcity, that is, not the scarcity resulting from the simple finitude, as that of the limited but *constant* Ricardian land (mere terrestrial space), but as finite stocks of available valuable energy (and, as we shall see presently, matter as well) that according to the Entropy law continually and irrevocably degrade into unavailable states. That is why I have claimed earlier that thermodynamics is a *physics* of economic value. And if we observe now that all living creatures strive to obtain the available energy and materials necessary for supporting their lives *by their entropic degradation*, we see why the life processes cannot be fully accounted by any mechanical system [17] and why thermodynamics may be regarded as a physics of living systems.

A great mystery of life (of which not even a hint could come from mechanics) we have not yet been able to unravel is how the entropic degradation of a flow of energy-matter is metamorphosed into a flux that we, the humans, call the enjoyment of life. I suspect that this entropic flux must be associated with absolutely all living structures. Even the amoeba must feel that flux in its highly particular way [17]. Economists have long manipulated with the utility function by which they relate the real income flow of a person to his or her level of enjoyment. Yet none seems to have ever thought that there ought to be a basic reason for that paper-and-pencil formula to have any realistic significance.

9. The drastic separation of our phenomenological view of the world into mechanics and thermodynamics is just a perspective adapted to our human consciousness. Actually, the present campaign for a unified science in a way attests that there are no conspicuous objective reasons for that methodological split. But as many a great physicist, Lord Kelvin above all, remarked, humans understand better a phenomenon when it is represented by a mechanical model, even truly well only when it is so represented. Of course, this is the consequence of the fact that for humans it is most natural to act by pushing or pulling, purely mechanical actions. But the feelings of warmth and pressure which are even closer to the vital processes remained for long without much attention precisely because they could not be explained by mechanical considerations. Given this limitation of mechanics and the deep-seated separation between the stress of throwing a stone for killing a bird, for instance, and the feeling of warmth at the mother's chest, that entropy had to emerge to help our minds bring within the perspective of reality those peculiar and momentous feelings.

In view of that innate split of our nature, the epistemological clash that has been constantly active does not seem to be eventually mended. There is nothing in any mechanics - Newtonian, relativistic, or quantum - to correspond to the elemental phenomenon of temperature, heat, or pressure. Carnot's memoir was the first rebellion against the doctrine of Galileo-Laplace-Newton that everything in the world is completely accounted by the laws of classical mechanics, a doctrine that is still going very strong among physicists.

10. The conflict between thermodynamics and mechanics is phenomenological and hinges primarily upon the fact that mechanical phenomena ignore all change of quality. In mechanical purview there is only change of place, for all consists of locomotion. There is another, more palpable, reason why mechanics and thermodynamics could not merge into a superdiscipline, although some of the recent triers, statistical mechanics above all, claim to have achieved it. Locomotion per se is reversible whereas true qualitative change, like that brought to light by Clausius's law, is ineffaceable.

Qualitative reversibility - not only the belief in the eternal return of most religions but the aim of medical and cosmetic arts - has normally constituted an idea that has intrigued human minds since times immemorial. And because irreversibility is the most important concept associated with that of entropy, ever its inception entropy has been a preferred topic of discussion in natural sciences as in the theological seminars.

Sir Arthur Eddington, as we may recall, suggested that the law of entropy shows the time's arrow, by which he meant the only direction in which time must go, only *forward* as Percy Bridgman later strongly insisted [7]. This connection, though ineluctably transparent, has been subjected to numberless fanciful amendments and interpretations. As two of these assays are related to our powers and limitations they deserve a comment here.

The first confirms further my view of thermodynamics as a scientific edifice with an anthropomorphic infrastructure. I know of no writer on the entropy law to have been aware of how closely related is its formulation to the running of our life (and probably to that of other species). Saying that the entropy ordinarily increases we can only mean this: knowing that the entropy of an *isolated* system was E' at t' and E'' at t'', then if t'' is later than t', E'' must be greater than E'. But how can we know which t was *later*? The answer is given only by the stream of the human consciousness, a necessary specification generally ignored [17]. Scholars, some of them often say, should not speak of consciousness. Thus, a physicist, Frank Adelman [2], took me to task for my connecting time's arrow with human consciousness. Some clock just suffices.

11. There is also the problem, already alluded to, of the irreversibility of entropic changes. Concerning these changes, the famous thermodynamicist, Ludwig Boltzmann, argued in his magnum opus that in the universe there must be plenty of regions within which entropy decreases and hence time there goes in the opposite direction to ours [5]. Most of the additional speculations, some pertaining to the flow of time as felt by us, have occupied magazines and volumes. Some of the presentations of the tenet that all changes are reversible, if taken literally, imply the admission that eventually the dead will resuscitate from their tombs to find a death in their previous births [17, 41].

To justify his belief in the complete absence of irreversibility in nature - which was tantamount to the dogma glorified by Laplace that everything in nature is governed by the laws of mechanics - Boltzmann likened the transformations of a gas to a random game, just like coin tossing, and concluded that there is nothing in nature but the play of the random element [4]. That was the birth of statistical mechanics which relies exclusively upon the theory of probability.

But let us look at it. Just ask any expert in statistical mechanics why the cold water in your glass does not suddenly revert into the warmer water and the ice cubes you had in it at first. "Don't you know", he will say, "the probability theorem according to which if you wait long enough any possible event will necessarily occur. You have not waited long enough". An immensely curious fact, the foundation of a legitimate science to consist of such an utter blunder of elementary logic. The invoked theorem is certainly true, but the blunder is to conclude that its converse is necessarily true, too. Yes, if we play bridge hands after hands it must happen that at some deal each player will get only one suit. It *must happen* some time because *that event is not inherently impossible*. There is absolutely nothing in the valid theory of probability to prevent it from happening at the next deal. To claim that it could not possibly happen is the grossest falsification of the concept of probability. And if any propounder of statistical mechanics had supposedly become aware of that distorted

probability, to patch it another analytical bloomer has been offered: The events of a small probability never happen. For this idea to have any value, one should specify the *finite* value, say s 0, below which the probability is small in that sense. But let consider any event of some probability e s. According to the established theory of probabilities the probability P of that event to occur in some of the n successive observations is $1-(1-e)^n$. And clearly P is greater than s if n is greatly enough, specifically, if $n \log(1-s) / \log(1-e)$.

This clearly exposes the incredible mess [17].

12. Understandably, the history of thermodynamics has been quite agitated, but although the main aggravation hinged on the entropy law, the other thermodynamic laws also have had some share in that respect. But a fact highly relevant for the topic of this paper is that everyone of those laws is, after the pattern of the entropy, a negation of a particular operation by humans.

For example, anyone would certainly like to obtain the greatest amount of work from a given amount of heat energy, hoping even to find a way to get more work than the amount of heat employed. But the first law, the principle of energy conservation, advises us that this hope is utterly futile.

13. The case of the second law is more involved and also highly instructive. That law pertains directly to the usual transformation of heat energy into work usually done through a piston-and-cylinder as set up in the classical steam engine that Carnot described in his famous cycle. That cycle is an idealized blueprint and hence has many practical limitations. Nonetheless it is a powerful tool which soon became the pillar of theoretical thermodynamics. That justifies my constant use of it in the sequel.

In the Carnot cycle, simply, the pressure in the cylinder pushes the piston which turns a cam by which a weight is lifted up to some height. We already know that the amount of potential energy, alias the amount of work obtained (represented by the weight at that height) cannot be greater than that of the heat employed, but could it be just equal to that? The answer to this question is supplied by a principle whose role in thermodynamic theory I judge to be that of a handyman. That principle says that if and only if the piston moves *infinitesimally slowly*, the amount of the work is equal to that of the heat. The handyman explains that in an infinitesimally slow motion there is no *friction* to rob some of the energy employed.

One could then reason that to avoid that robber of available energy we should use only engines that move infinitesimally slowly. But engines that move infinitesimally slowly take a virtually infinite time to go over a finite distance, no matter how small. Such engines might exist since the lower limit of speeds is zero. Yet we, the humans, being painfully limited in time, could not possibly use them. Let us now mark this point well: *the impossibility of using machinery that produces no waste is not a thermodynamic proscription, but an inherent limitation of the human nature.*

We must now get back to the piston. To have it pushed by heat energy we had to use a steam engine which in its ideal form draws the necessary heat energy from an infinite bath. We may freely assume that the push is made by the isothermal expansion which transforms an amount of heat energy from the bath *directly* into an equal amount of work. However, even in the respected literature the possibility of this *direct* transformation is at times denied and presented as one form of the entropy law. But the isothermal expansion of the Carnot engine consists of that impossible action. Therefore, having a very great, virtually infinite, bath, why should we not continue just to push the piston on and on so as to obtain more and more work in that uncomplicated manner. Planck found nothing wrong with that plan [39]. Yet it is not possible for us, humans, to use such a simple and highly efficient engine, highly efficient because it transforms all heat energy into work! *We are limited in space, not only in time, so we cannot use an engine with a piston of unlimited length.*

Therefore, after completing a reasonable distance from its initial position, the piston must be brought back. The new hitch is that to bring it back the same it went it would take exactly the same amount of energy that pushed it. All potential energy created earlier would then be lost and nothing would remain for the human operator. However, in the actual steam engines the piston *is* brought back *and* we are treated with some surplus work.

This is a puzzle that does not seem to have caught a scholar's eye. The answer, however, has been at hand all the time: in his memoir Carnot stated that "*The fall of caloric* [the amount of heat energy used] *produces more motive power at inferior than at superior temperatures*".

Hence the need for a lower temperature - of the cold body, the sink, or from the condenser - through which to bring the piston back without using all the potential energy obtained earlier [31].

Some writers seek to get laurels by setting forth connections that are likely to catch attention but without first verifying their validity. There have been several of such writers who have argued that the inventors of the steam engine and Carnot himself deserve no glory because the motive power of steam was known by Hero of Alexandria who almost two millennia ago used it in some tricks and in *Aeolipile*, a revolving child toy [37, p. 181]. That tale is an exceptional proof of how badly misunderstood is generally the reason why a lower temperature than that of the boiler is also needed.

The power of steam was known not only to Hero; wives around the world know the lid of any pot, including Papin's, but any such pot was not a systematic use of that power. The discovery of the necessity for the lower temperature was an epochal one, and Carnot was right to salute all, from Savery to Trevithick, as "the veritable creators of the steam engine".

A more explicatory way for the fact that the origin of that necessity is undeniably anthropomorphic is this. Because we, humans, are strictly limited in time and space, we must have a difference of temperature for obtaining work from heat for with a single source of heat we could not bring back the piston. It is all this that Planck packed in his memorable formulation of the entropy law:

No engine working in a complete cycle can raise a weight only by cooling a heat reservoir [39].

To wrap up this analysis: there might be other sources of motive power - the secrets of the black holes and of the dark matter are still tantalizing the astrophysicists - but we,

the humans, can obtain motive power primarily from a difference of temperature. On the other hand, differences of temperature are continuously reduced by themselves (that is, even if no self-acting entity, like ourselves interfere with them) as Clausius's earliest formulation of the entropy states and *in addition* are irrevocably consumed by our engines and the soma of all living creatures in producing motive power accompanied by unavoidable wasteful friction. This is why the entropy law is the main factor for our ecological predicament, the irrevocable depletion of our finite dowry of fossil fuels [17, 19].

14. Early in this century some physicists who practised statistical mechanics which they believed to hide a scheme for defeating the entropy by which, as Percy Bridgman protested [7], they hoped to fill their pockets with money by bootlegging entropy. It is not at all surprising therefore that after the writing on the wall by the 1973/74 oil embargo people from all kinds of life walks should set out to sell multifarious recipes pretended to make much more energy accessible [35].

That the entropy law will be refuted one day as has happened in history with many laws is the favourite simplest refrain of many ecologists intent on nursing the flat optimism of those who are not critical enough to see the colour of that argument. Actually, if scrutinized, that argument boomerangs, for history confirms rather the permanency of the entropy Law: every time one's hand touched a hot stove it was the hand that was scorched, not the stove.

In this and other similarly flimsy ways, the growing number of green energetists kept preaching low and high that we should not worry about the depletion of the natural resources. Since these tyros have succeeded in having their scribbles published I came to the conclusion that the Panglossian lullaby brings subscribers. But they have not been alone in this drive; they have been even encouraged by celebrities of physical science such as Glenn Seaborg, who insisted that science will enable us to put everything back from where it was taken, so that the environment will remain forever completely habitable for ourselves [44].

Such opinions added prestige to the clatter of the ecological neophytes in their new "global" manifestations and both camps have fostered such a fierce whirlpool of ultraoptimism that it entrapped even analytical minds like that of Paul Samuelson who became convinced that science will undoubtedly show the way of how to reverse the entropy by making all unavailable energy available again [42].

Far more jolting was the pronouncement of Robert Solow, a highly esteemed economist, at the prestigious Richard T. Ely Lecture that "The world can, in effect, get along without natural resources, so that exhaustion is just an event, not a catastrophe" [46]. And as surprising as it may seem to us now, even physicists who had been called to positions of great responsibility have contributed to sustain the myth of an eternal cornucopia. Peter Auer, for example, must feel satisfied that he has convincingly proved that the entropy law does not affect the scarcity of natural resources [3].

On the issue of the refutability of the entropy law as on any other issue of scientific epistemology, if we want to seek the opinions of others as well, we should listen only to the scholars admirably versed in such delicate problems. It happens that Einstein, in his *Autobiographisches* [15], described thermodynamics as a science which he had greatly enjoyed studying and admired for its clear grasp of reality. He also thought that the epistemological construction of thermodynamics is above ordinary criticisms. Interestingly, he likened his famous law that negates the possibility of greater speeds than that of light with the negation of entropy to decrease by itself, which he thought to be both irrefutable laws.

15. The believers in the refutation of the entropy law deserve an unparsimonious digression here. For they doubtless also believe that life in the anentropic world is wholly paradisiac. There is an accumulation of thermodynamic ignorance in that belief, which is rather widespread at least implicitly.

It may be hard to believe, but the truth is that *life is possible only in an entropic environment,where it could rely upon its physics, the thermodynamics*. Why should anyone desire to refute the entropy law? I certainly would fear to live in an anentropic environment for there taking a bath my toes might be frostbitten while my neck would be scorched. And, surely, I would not wish to live in a world without friction in which I could not go where I wanted, nor put my thoughts on paper.

16. Naturally, not everyone could be receptive to the labyrinthine attacks on the entropy law. Even most sellers of optimism could not get a taste of them, so they contrived other pills about whose efficiency they paid no attention. Their prescriptions have consisted of what they could scheme in a forced abstractness with pencil-and-paper. Herman Daly proposed the *steady state* prescription for mankind's ecological salvation [13]. There must have been several enthusiastic supporters who later realized that for a large part of mankind, like the people from Bangladesh, for example, that prescription meant a sentence to eternal misery. So, they chose a new, truly alluring, logo: *sustainable development*, suggested by Leister Brown [8]. Since its subliminal is *sustainable growth*, of the old growthmania, both the people from Bangladesh and those living in the New York penthouses might have gone along with it. But although both programmes have remained only diverting things on paper, they have brought in abundant funding for one global forum after another.

A general, and simple, reaction to the menacing crisis of available energy has been to urge greater economy in consumption and an intensified exploitation of the minor sources, mainly the tidal and the geothermal. But again, because people normally love to hear a lullaby, ecologists in general presented one energy converter after another with the claim that everyone could replace - in part and, eventually, completely - the energy from the old sources. A vast literature about the alternative sources, as these converters were called, has striven to convince µs that such alternatives that will save mankind from its entropic predicament are just around the corner [35]. Of course, by now we know that no such ecological saver has been around any corner.

In making the last statement I do not ignore that several formations of wind towers, like that at Altamora Pass, California, have been able to provide the necessary electricity

for a whole community. Nor do I ignore that an automobile drove across Australia using only solar energy. And nor do I ignore the useful uses - quite uncommon - of thermal furnaces like that at Odeillo in France. However, the reason for the apparent contradiction is far from being simple; nor, I think, has it ever been appreciated. To that issue now I turn.

17. The techniques that have been used by modern humans are so numerous that the whole life of a researcher will not suffice to make a list of all. Yet only three techniques have had the power to found and support viable technologies. As suggested by that term, chosen on a biological analogy, a viable technology is a complex of techniques that can support the life of the associated biological species as long as some specific "fuel" is forthcoming.

I have termed those techniques Promethean for the good reason that their distinctive property is best illustrated by fire, the gift of the legendary titan Prometheus. That property is represented by the fact that with just a small flame of a match we can set on fire a whole forest, nay, potentially all forests. Promethean techniques have all this explosive virtue: *Everyone enables us to obtain a surplus of accessible energy, to get more accessible energy than that used in the operation.* A simple business proposition of thermodynamics! (Of course, no creation of energy is meant.) Another Promethean technique, so common that we may not think of it as one of the thermodynamic miracles, is husbandry which allowed humans to obtain more animals and plants on end as long as their food (form of energy) is available.

Promethean techniques, however, are self-defeating. Humans, in contrast with most other animals, generally crave to have just more of everything desirable, so that after getting hold of a Promethean technique, they would use it again and again thus speeding the depletion of the special fuel of that technique. Such an exhaustion has been caused by husbandry in several localities, say, the overgrazed steppes of Central Asia which led to the Great Migration.

When humans became aware of the Promethean property of husbandry, mankind entered its first systematic viable technology, agriculture. Agriculture solves in large measure the drudgery of getting food and also prepared mankind for life in the kind of community that has remained particularly ours. The mastery of fire was much older, it happened roughly 500,000 years ago. For long it helped the protohumans to keep warm, to cook food and, with time, to bake ceramics. It was only about 3,500 years ago that fire began its industrial role, to smelt ore, to melt and forge metals and to bake lime. Mankind then entered its second viable technology which gave a lasting impetus to its exosomatism. As wood was then the primary source of heating fire, that technology was the technology of *wood*.

The third Promethean technique is the steam engine, already mentioned. It deserves special attention because its history singularly illuminates the link of the economic evolution with the entropy law. The habitual human ultimately led to the wood crisis of which I spoke in the first paragraph above. With the growing scarcity of wood, people turned to coal which had been known as a source of fire for centuries. But coal had a serious drawback. All mines became flooded at a relatively small depth. In most mines there was more water to be drained than the coal accessible. Many mines kept large herds of horses to turn a wheel fitted with leather buckets which lifted out the water. We would understand why they sought even the advice of Galileo who advised them to use a powerful air pump because, he said, nature abhors a vacuum. But as they reported back that even the most powerful pump would not lift the water above some ten meters, Galileo corrected himself by saying that nature then abhors a vacuum only up to ten meters!

That crisis of wood, which was in toto similar to the present one of fossil fuels, can teach not only the peddlers of optimist pills, but us all, a landmark lesson:

A new technology requires a new Promethean technique, not just one already familiar alternative. The Promethean technique that saved the wood crisis is the steam engine invented by two simple mortals, Thomas Savery and Thomas Newcomen, who fully deserve the title of Prometheus II.

What *we* need now therefore is a Prometheus III who may come any time, only we do not know when.

18. Among the techniques supposed to wait around the corner worthy of attention are the controlled fusion and the direct harnessed solar energy. How to control fusion is a vastly complicated technical problem, yet I have some valid (I claim) reasons for believing that that project may never be achieved. Fusion power is too vehement for that operation. Who knows how huge might be the reactor if control is ever achieved? There is also the analogous situation that neither the power of the dynamite, nor that of the thunders, nor that of the hurricanes can be controlled for industrial use. Fusion power might remain forever good as a bomb or for blasting just as is now the case of dynamite [19].

A creditable student asserted that solar technology - the technology of directly harnessed radiation, not of the radiation captured by the green plants - is already here [33]. We have even set a Sun's Day. But as my thermodynamic analysis shows, no known reaction of solar radiation makes more energy accessible than the total consumed. Like electricity, solar energy harnessed directly is a parasite (occasionally, quite economical) of other, the conventional energies. Whenever solar radiation is used effectively, an additional amount of other available energies must also be consumed [23, 29].

I am often besieged with requests for experimental proofs for some of my ideas. But I cannot possibly satisfy such requests not only because of the position I am serving in science, but especially because those conditions are not susceptible of being directly realized on the workbench. All the more outstanding is the costly experiment undertaken by Solarex Corporation, the most knowledgeable organization in that field, to find out whether an assay of silicon solar cells can harness enough solar radiation to reproduce just the cells used in that experiment. The final report stated that the harnessed energy is insufficient for reproducing the assay *even if all the materials necessary are supplied gratis* [45].

19. That I have been struggling with thermodynamics for a quite long time does not need, I think, any affidavit. I have been attracted to it from two directions: an abstract one, the paperback *Mécanique Statistique* of my former professor Emile Borel, and one from practicality, the ultimate plight of all oil producing societies as illustrated by Romania

which, from the third world oil exporter at the beginning of this century, ultimately sank to be an oil importer.

Of course, not having any formal training in physics I approached my new bailiwick as a novice who, as Schumpeter said about novices, could not see much of what the old guard took for granted but saw much that they did not. And what they seemed not to see, but I did, was that thermodynamic phenomena include matter as well. In the received literature matter is mentioned only indirectly in connection with that elusive concept, friction. But since friction was recognized to cause additional dissipation of available energy, I was greatly surprised to see a discipline whose primary object is the study of engines paying no attention to *what happens to the matter in bulk that participates in a thermodynamic process*.

The belief that matter poses no problem as long as we take care of energy is even today strong. In one of the most perceptive volumes [8], we read "All we need do is to add sufficient energy to the system and we can obtain whatever materials we desire," and those authors did not have in mind Einstein's microcosmic identity. Kenneth Boulding, quoted in [14], clearly asserted that "There is, fortunately, no law of increasing material entropy".

A princely exception, Max Planck argued that there are irreversible processes in which the final and initial states show exactly the same form of energy, *e.g.* the diffusion of two perfect gases, or further dilution of a dilute solution. Such processes are accompanied by no perceptible transference of heat, nor by external work, nor by any noticeable transformation of energy [39], and followed with a footnote saying "In this case it would be more to the point to speak of a dissipation of matter than of a dissipation of energy".

To my knowledge, it is still the unique reference to the analogy between energy and matter dissipation. It was a great excitement for me to come across it. From a few pristine thoughts, with which all natural knowledge begins, I had reached the idea that matter, too, exists in available and unavailable qualities. For instance, the rubber of a new automobile tyre and the same rubber after it has been completely dispersed in imperceptible bits over the surface of the roads. From other such homely processes as the chalk scratched on blackboards, as the impalpable bits of gold dispersed from jewels on every corner of the world where jewel-bearing people have moved, I came to hold firmly that matter, too, is subject to irreversible degradation [21, 25]. Actually, as is easily seen, it would take a far more formidable demon than Maxwell's to separate absolutely *all* the molecules, say, of oxygen from those of nitrogen in a gas mixture.

Let us note, therefore, that what we can actually recycle is not *unavailable* matter - the rubber molecules dissipated over the highways or the imperceptible bits of glass from breakages - but only *available* matter that no longer is in a useful form: pieces of broken glass, old newspapers, old motors, etc., that is, what we find in garbage cans and in junk yards.

We should also observe that any mechanical work dissipates and mixes some available matter through the inevitable friction, fatigue, cracking, and blistering. Hence, any feasible reassembling process must dissipate some available matter, which leads to an infinite regress of continuous depletion of the accessible stock.

I have crystallized these simple observations into a new law of thermodynamics -

the Fourth - which states that in a *closed* system (as the Earth practically is) mechanical work cannot proceed at a constant rate forever. It was to expose the thermodynamic flow of any salvation programme based on the substitution of terrestrial energy by solar radiation - as Daly's steady state, for instance, implied - that I first set it forth [22]. And it was in step with tradition to call *perpetual motion of the third kind* a system that would contradict that law.

20. I have presented my new law with all the analytical arguments I could muster in several places [22, 24, 27, 30]. But have I proved the impossibility of its reversibility? How can one actually prove that something is *factually impossible*? The only way to do it is that by which the impossibility expressed by other thermodynamic laws has been proved. We may recall that Simon Stevinus proved that an apparatus consisting of a chain of balls on two inclined planes failed to keep moving. That was sufficient to convince the scholarly world that perpetual motion of the first kind is impossible. On this ground, I considered the reaction box of Henrikus vant' Hoff which had been thought to prove that material entropy, the entropy of a gas mixture, can be actually reversed provided we have enough energy. In that box the most critical part is the semi-permeable membrane supposed to let each gas pass in only one direction. The difficulty of the claim stems from the fact that that particular membrane might not be available for every mixture and, in addition, ultimately clogs ceasing to be serviceable [39].

The reaction to my idea has been one of rather indifference. That the sellers of formulae for ecological salvation would not even think of referring to it was to be expected. But surprising was the conspicuous silence of the legitimate specialists of that field. Quite on the margin, some of the new ecologists protested that my law was not new, that it had been known for long, yet none said where and when it had already been set forth. If they had in mind to invoke the application of the statistical formula to the frequencies of different molecules in the mixture, they were guilty of the same epistemological blunder that many a thermodynamicist is committing today. Others interjected that the law is not true. A few of these argued that you can surely reassemble all the iron filings from the floor of a shop if you use a powerful magnet. As surely they must have believed that after the passing of the magnet there would be no iron bit left there. A more powerful magnet of the future may pick up more filings of both those just produced by the experiment and of those that were there before it. Why not? However, these critics are at least in good company, namely, with Galileo who did not believe in the friction of the arrow against the air, because at that time no thermometer could reveal that temperature increase.

On some rare occasion one conversant with recent developments in thermodynamics observed (time and again, not publicly) that I neglect to take into account the new thermodynamics of The Brussels School led by Ilya Prigogine which does precisely this, to consider matter, too. As is their more important claim, they have advanced from classical thermodynamics (which considers only closed systems) to the thermodynamics of *open* systems that exchange also *matter* with their environment.

Not only did I not ignore that momentous achievement, but after examining it I felt

that it needed some exegesis. And I did point out that the Prigogine thermodynamics does not consider *matter in itself*, but *matter as a vehicle* for energy [24, 32]. Specifically, it does not consider the entropic transformations of matter by friction or other such irreversible processes. To recall, the fundamental formula of classical thermodynamics

$$\Delta U = Q + W,$$

where U is the internal energy of a closed system, Q, the heat transferred, and W the work performed. In his celebrated monograph [42], Prigogine just replaces it by

$$\Delta U = \Phi + W$$

where Φ can be only energy, like all other terms in that relation. Therefore, what that term represents in the new Prigogine's reaction is not matter subject to material entropic transformations, but the energy carried by some matter, say, by a piece of hot iron. Of course, one may interpret Prigogine's equation according to the Einstein equivalence, when my exegesis would vanish, but so would necessarily do that claim: If there is no matter anywhere, none can be in Prigogine's equation either.

My position met with no opposition when I presented it at the *World Conference on Future Sources of Organic Raw Materials* [25]. Nor have the physicists of the Los Alamos Laboratory found anything wrong with it after my two lectures there [6]. I should necessarily mention that at the Colloquium ENST, University of Paris IX, November 1976, I presented an invited paper "Is Perpetual Movement of the Third Kind Possible?" [20] - which was a first version of that read six months later [25]. I was one of the three panelists who included also Prigogine. I shall never understand why Prigogine did not cut my neck there and then, especially since Professor Jacques Grinevald, from the Geneva University, heard Prigogine in an interview of *Radio France* claimed that my proposed law is wrong.

A period of great indecision preceded all classical motions, claims and counter-claims abounded. Of course, I like to think that my law is true, but I am much more interested in a clear decision of whether it is true or not. Whatever the answer to this issue, the conception of the Fourth Law and of the perpetual motion of the third kind could not be denied as contribution of mine to provoke at least further vital considerations.

21. If *homo* were not only *sapiens sapiens*, but also wise, we would have seen since long that the entropic predicament is a perennial condition for our species. The life spans of species are ordinarily long and ours should not be exceptional in that respect. It is from this eonic viewpoint that we should base any programmes for maximizing Our survival. If so, then all kinds of scarcities should be envisioned, not only that of energy but that of matter as available matter in bulk as well. Things even of the recent past seem covered by an easy oblivion, but if we try to remember the earliest concern with the scarcity of natural resources was not with energy, but with some materials that seemed to affect the plan for armaments. It was that concern that generated a sustained interest in natural scarcity of

which the famous Putman Report was the first product. Resources for the Future was another salient product, which - we should not forget - only much later became exclusively interested in the supply of energy with a predominant overoptimism [26].

To continue calling *doomsayers* authors of the same persuasion as mine would only do harm. Nor should we try to sell the snake oil idea that we can stop the entropic work. Mohammed is supposed to have said that if the mountain does not come to him, he must go to the mountain. The rational policy then should be to teach humans to renounce their extravagant craving for luxuries and even many conveniences. But would *homines sapientes sapientes* accept such a regimen? Perhaps, the destiny of humans is to have a short, but fiery, exacting and extravagant life rather than a long, uneventful and vegetative existence. Let other species, the amoebas, for instance, which have no spiritual ambitions inherit an earth still bathed in plenty of sunshine [19, p. 35].

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