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The Entropy Law and the Economic Process in Retrospect

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Preamble

It is twenty years since I completed the introductory essay for my 1966 **Analytical Economics** which by way of a second edition turned into the 1971 volume **The Entropy Law and the Economic Process**. Thus, the main idea--namely, that the economic process is entropic in all its **material** fibers--was carried from the first to the second volume. The reaction of my fellow economists to this idea and especially to its messages relevant to the economic life has been such that a survey of my thesis as I have expanded it through several subsequent papers should make a clarification of some issues worthwhile.[1]

The Phenomenological Gist of the Entropy Law

The concept of entropy is so involved that even physicists may go wrong with it (NGR, 1966, p. 77; 1971, p. 147). Economists who have recently approached this topic were therefore wrong in beginning and ending with the analytical formula of entropy (which in some approaches is expressed in three different ways). But entropy, like energy, force, distance, and other physical concepts, has a phenomenological meaning, the only one of primary interest for both experts and outsiders.

Let us begin by getting down to the brass tacks, as any student should do on any new matter. The road to understanding what entropy is begins with the primary distinction between **available** and **unavailable** energy. This distinction is unmistakenly anthropomorphic (more so than any other concept in the natural sciences). Indeed, energy is available or unavailable according to whether or not we, humans, can use it for our own purposes.

Beyond and above all technical formulae, the essence of the main thermodynamic laws is this: in an isolated system, the amount of energy remains constant (the first law), while the available energy continuously and irrevocably degrades into unavailable states (the second law). Let us mark well that an isolated system can exchange neither energy nor matter with its "outside." Strictly speaking, the only isolated system is the whole universe, to which Clausius (1867, p. 365) significantly referred his famous formulation as a stanza of the thermodynamic laws:

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

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At this juncture we need only observe that, all technical details being glossed over, entropy is an index of the amount of available energy relative to the absolute temperature of the corresponding isolated system:

(1) Entropy = Unavailable energy/Temperature,

as the technical formula may also be written.

In saying that in an isolated system the unavailable energy increases by itself--hence, the available energy decreases to zero--we must necessarily specify that "increase" and "decrease" refer to the direction of time as is represented by the stream of human consciousness. This requirement is generally ignored, although there is no other way to know which way the time flows. The entropy law may then be formulated as follows:

(2) $t_1 \; C \; t_2 \rightarrow E_1 \leq E_2$

where t_1 and t_2 are two moments in the ordinal flow of time and C means "earlier than." Or,

(3) $E_1 < E_2 \rightarrow t_1 \; C \; t_2$.

For clearly, if $E_1 = E_2$, the system is one of maximum entropy, when all energy is unavailable and nothing can happen. In this case entropy cannot serve as a "time-arrow," to use the striking metaphor of Sir Arthur Eddington.

The condition that the system must be isolated is understandable: if energy or matter can come in and go out--as, for example, money does in a bank balance--we cannot speak of "constancy" or of a steady "increase." On the other hand, the systems of our experience are all either **closed** (in which case energy but not matter may be exchanged with the outside) or **open** (in which case both energy and matter may be so exchanged). Obviously, in these last systems entropy may very well decrease. It would seem then that the entropy law has no relevance whatsoever for any real system related to our activity, hence, for the economic process, too.[2] The point has excited numerous economists eager to defend the conventional economics against the criticism that it is a one-eyed discipline which sees only the market carried out by money.[3]

What those who deny the economic relevance of the entropy law fail to realize is that in any field whatsoever a measurable coordinate must be related to a situation that excludes any possible variation of its essence. Economists, of all scientists, should understand that the rest mass of a particle refers to the isolated particle. A bank balance cannot be determined while checks are being debited and credited. Actually, the general relevance of the entropy law may be illustrated by a bank despositor who has both a checking and a saving account and who has instructed the bank to transfer periodically a certain sum from checking to saving. Although his bank system is not isolated--deposits and withdrawals being made continually--there is an internal "degradation" of his checking dollars into savings dollars. And it is a routine matter to discover the amount of this degradation. This is a simple illustration of how entropic degradation goes on in absolutely all systems, a phenomenon expressed by the standard accounting formula:

(4) $\Delta S = \Delta S_e + \Delta S_i$,

where ΔS is the change in the entropy of the system (whatever its kind) during some time interval, $t_1 \; C \; t_2$, ΔS_e is the net entropy trade with the outside, and ΔS_i is the entropy created inside during that interval. All the elementary form of the entropy law says is that

(5) $\Delta S_i \geq 0$.

the equality being valid only if the initial state is one of maximum entropy. The situation is analogous with the general law of demand, where we know only that the substitution effect is negative or zero, but the total effect may be negative as well as positive. So here, although $\Delta S_i \geq 0$, ΔS may have any sign in a given situation.

The Entropy Law and the Finite Human Nature

We should bear in mind that all thermodynamic laws, unlike most other natural laws, express an impossibility. For example, the entropy law proclaims that $\Delta S_i < 0$ is impossible. The same law is formulated as still another impossibility: thermal energy of a uniform temperature cannot be converted into work. As Lord Kelvin observed long ago, it is not possible for ships to sail by using the energy of ocean waters, immense though that energy is; for some depth, that energy is of uniform temperature. Lord Kelvin's law recalls the principle enunciated by Sadi Carnot, the founder of thermodynamics as a physics of economic value (NGR, 1966, p. 92; 1971, p. 276). Carnot showed that work can be derived from two reservoirs of different temperatures. Lord Kelvin's statement, however, is stronger since it denies that it is possible to derive work otherwise.

But a point completely ignored by all interpreters of the entropy law is that it is not because of some purely technical reasons that thermal energy of uniform temperature is unavailable. That particular energy is unavailable only because of the finite human nature. The refutation of the notion that thermal energy of uniform temperature is unavailable is at close hand. The first expansion phase in an ideal heat engine (working in a Carnot cycle) does exactly this, it converts some energy of a hot bath (the boiler of uniform temperature) into the work of the piston (Van Ness, 1969, p. 37-38).

Why cannot the same conversion apply to sailing a ship by the energy of the ocean waters? To rely only on such a conversion we have two solutions. First, we should have a piston-and-cylinder of an immense length, so that work could be performed throughout by the same piston. One mystery of the relation between the entropy law and the human nature is thus set in plain vision. The energy of the superficial ocean waters is unavailable only because we, humans, are limited to moving within a relatively small distance. We cannot follow a piston that keeps moving on and on; we must bring it back after a while. To bring it back, however, requires some available energy. To be sure, the necessary amount can be obtained by converting the additional potential energy of the raised weight back into available energy. But then we would be in no better situation than at the beginning when the conversion of energy into work was triggered.

The impasse is resolved by a hardly noticed phenomenological mystery of the working of the entropy law. To bring the piston back through a lower temperature than when it moved forward, **less energy is needed than was produced by the forward motion.** Only part of the work obtained by the first phase of a Carnot cycle must thus be reconverted into energy. To explain, if by moving forward the piston some weight has been raised, say, five feet, to bring the piston back to exactly its initial position we need to lower that weight, say, four feet only. The weight does not have to recover its initial position, as the piston does; its final position is one foot above the initial one.

However, that trick is not free. The total energy supplied by the boiler is equivalent to that needed to raise the weight five feet. And as Lord Kelvin argued, the difference, equivalent to that for raising the weight four feet, is not lost; it only is no longer available to us for obtaining work by the same system of conversion. This energy left the boiler and ended in the condenser, which cannot serve well as another boiler. Yet that energy could become available again if and only if it could pass **by itself** from the colder condenser to the hotter boiler. This time-tested impossibility is the most transparent formulation of the entropy law (by Lord Kelvin and Clausius): Heat always passes **by itself** from the hotter to the colder body, never in reverse.

Thermodynamics expresses in still other ways its anthropomorphic basis, specifically, our finitude. To wit, in the example just given (of using some thermal energy to raise a weight by one foot) we could reverse the process. We could convert the potential energy gained by the weight back into the exact amount of thermal energy used to lift it, provided that our mechanism were frictionless. It is generally admitted that any mechanism would be frictionless if its movement would be infinitesimally slow. But in this case even a small movement would require a virtually infinite time, which is another antithesis of human nature. We, humans, are not immortal, a prohibition which leads to still another thermodynamic law, another impossibility.

The Fourth Law of Thermodynamics

Received thermodynamic theory is founded on four laws--the first, total energy is constant; the second, in actuality entropy steadily increases; the third, the absolute zero of temperatue cannot be reached; and the "zeroth" (so termed because it was added last but being the most fundamental it had to precede "the first") which states that thermodynamic equilibrium is a transitive condition. In my earlier writings I took for granted that thermodynamics had paid attention to what happens not only to

the quality of energy as things keep happening but also to that of matter (matter in bulk as distinguished from microscopic matter). I also thought that they had seen that friction does not degrade only energy but matter as well.

Subsequently, however, I saw that I was wrong. Thermodynamics have stopped short from considering all effects of friction. Undoubtedly because friction is a most elusive phenomenon. So elusive that, as R.P. Feyman (1966) put it, any law that was proposed about friction proved later to be "falser and falser." Not to forget, the Bruxelles school led by Ilya Prigogine has extended the domain of classical thermodynamics from that of closed to that of open systems. Yet even in that extension the flow of matter is considered not in itself but only as a carrier of energy.[4]

It is an elementary fact, I submit, that matter also exists in two states, available and unavailable, and that, just like energy, it degrades continuously nd irrevocably from the former to the latter state. Matter, just like energy, dissipates into dust, as is best illustrated by rust, by wear and tear of motors of automobile tires. There are preeminent authors, however, who have argued that we can recycle all matter provided sufficient available energy is forthcoming.[5] To be sure, we can reassemble the beads of a necklace that happened to break in a room; it will take some energy, some wear and tear (however imperceptible) of other things, and, above all, some time. Moreover, when assembled, the beads will not be exactly as before. But if the necklace broke somewhere in the United States, the time needed and the amount of wear and tear of all items used in the search exceed all imagination. To recycle this last worn and torn material would cause another wear and tear and require another long time spent in the new operation. This is a regress without limit. Perhaps, we could recycle everything if and only if we could dispose not only of a limitless amount of energy but also of an infinite time (just as was the condition for doing away with friction). What we can recycle, and often do, is matter still available but no longer in a form useful to us: broken glass, old newspapers, worn out motors, and the like. (NGR, 1966, pp. 95-6; 1971, pp. 279-80; and, especially, 1980). The conclusion is immediate: just as steady work cannot be continued indefinitely without being continuously fed with unavailable energy, such work also needs a continuous supply of available matter. The point is that both available energy and available matter are irrevocably degraded into unavailable states.

A new fourth law--as I have called it--completes the old laws of classical thermodynamics:

Perpetual motion of the third kind is impossible.

By perpetual motion of the third kind I understand a **closed** system that does work forever at a steady rate.[6] And we should not fail to note that this statement does not require a measure of material degradation. Although such a measure would be highly advantageous, it does not seem attainable at present. The obstacle is that the various forms of macroscopic matter (matter in bulk), unlike energy, are not reducible qualitatively to a single form. But the validity of the irrevocable dissipation of matter is not affected thereby.

The important upshot is that, as the Earth is virtually a closed system, some materials vital for the current hot technology will sooner rather than later become extremely scarce (in the available form), even scarcer than the available energy from fossil fuels.[7] The same conclusion also exposes the logical weaknesses of the promose of ecological salvation by a steady-state economy so convincingly marshalled by Herman Daly (1973).[8]

The Fallacy of the Energy Theory of Economic Value

Preeminent natural scientists (Ludwig Boltzmann and, especially, Erwin Schrödinger) have pointed out that a living organism does not need just energy but low entropy, which it sucks from the environment and degrades into high entropy (waste). This continuous flow of low entropy maintains the biological body in good order and also supports all activities of the organism. We understand then why a **necessary** conditon for a thing to have value for us is to have a low entropy. However, the condition is not also sufficient; witness poisonous mushrooms. Clearly then, the entropy law is the root of economic scarcity in a much stronger sense than simple finiteness. To wit, Ricardian land (i.e., terrestrial space) is finite but only at a given moment; over time it is not, since we can use it over and over again without diminishing its amount.[9] By contrast, since low entropy of energy or matter can be used only once, the scarcity of these elements steadily increases. This is the most important object lession of thermodynamics for the modern economist.

While I thus insisted (as I said in the Preamble) that the economic process is entropic in all its material fibers, I hastened to add that it cannot be reduced to the degradation of low entropy; that would be to look at it as a physicist. However, the true "output" of the economic process is not a material flow of waste, but a unique flux, the flux of the enjoyment of life. Without including this flux as well as many specifically human propensities into our analytical armamentarium we are not in the economic world (NGR, 1966, p. 97; 1971, p. 282). It is thus clear that the writers who (e.g., Burness et. al., 1980) attributed to me the idea that the economic value of a commodity is determined by the amount of energy (low energy) embodied in it have not read my writings with a modicum of care.

To be sure, the formal analogy between the basic equations of thermodynamics and some of those used in economics has periodically fired the imagination of some students.[10] Apparently, the first to argue on this ground that money is the economic low entropy was G. Helm (1887), a prominent chemist in his time. L. Winiarski (1900) carried the analogy to the point that "Gold is ... the incarnation of socio-biological energy." About the same time, E. Solvay (1902), the millionaire patron of the famous congresses of illustrious physicists, used an accounting scheme similar to that of Karl Marx's labor theory of value to conclude the equivalence of economic value to embodied energy. By the middle of this century, the idea of the analogy of thermodynamics and economics again reached a momentary fashion started by H.T. Davis (1941), a pioneer of econometrics. His point was that the utility of money is the economic entropy.[11] With the subsequent critique by J.H.C. Lisman that, remarkable thought it may be, the analogy thermodynamics-economics is faulty, the case remained closed until recently when M. Lichnerowicz (1971) reached the highest mark by proposing to represent the economic process point by point by a vast system of thermodynamic equations--a purely formal exercise devoid of any specifically economic substance.

On this matter, the most interesting case is that of Sergei Podolinsky, a biologist of Marxist persuasion. His essay "Menschliches Arbeit und Einheit der Kraft," **Die Neue Zeit** (1883), was the valuable find of J. Martinez-Alier and J.M. Naredo (1982), who have also presented an admirable analysis of it. As a biologist, he based his argument on the relation between food energy and human labor in a way that recalls some recent contributions on the energy flow in agriculture. His aim was to replace labor by energy in Marx's theory of value (see Martinez and Naredo, p. 213). Engels, who referred to an earlier Italian version published in **La Plebe** (1881),[12] wrote to Marx that he found "all [Podolinsky's] economic conclusions false."[13] But thoughts such as Podolinsky's must have been ventilated earlier, for Engels (1954, p. 408) had already protested in an 1875 note: "Let someone try to convert any skilled labor into kilogram-meters and then to determine wages on this basis!," a thought that ought to kill in the bud any temptation to replace economics by some energetics.

In our own time, F. von Hayek (1952, p. 51) also protested against "the various forms of social `energetics' [as propounded by] Ernest Solvay, Wilhelm Ostwald and Frederick Soddy." As I mentioned earlier, Solvay did merit the indictment, but not the other two Nobelite chemists. Both Ostwald and Soddy only pointed out the vital role played by energy especially in human life. Although he was the leader of the school that reduced everything **in physics** to energy, Ostwald (1908, p. 164) warned that "we would err if we measured value only in proportion to the [involved] amount of free energy." But protests such as those of Engels, Ostwald, and von Hayek had no influence on some who cast around for a facile literary performance.

It is far from my thought ot quarrel with the idea, expounded by Fred Cottrell (1953) and set on a broader basis by H.T. Odum (1973), that only the net energy--the difference between the energy obtained and that part of it used to obtain it--counts for us. Models for computing the net or, alternatively, the gross energy necessary to produce (by a given technology) a unit of some commodity are fruitful (if properly laid out) as broad guides for policy. Yet we should not overlook that they cannot serve well as calculating devices (NGR, 1979). The oil embargo of 1973/74 brought energy analysis into greater attention with the result that some were induced to propound anew the equation "economic value = net energy." Martha Gilliland (1975) rushed to hail the energetic economics for relieving the economist of the acrobatics of adding apples and pears; it would be splendid if everything were measured in watt-hours. The related intervention by David Huettner (1976) represents a significant document which exposed the confused state of the issue. While mentioning the reasons why an energetic economics could not be an adequate representation of the economic process, Huettner offered a mathematical proof of the proportionality between optimal prices and the corresponding "energy content."

Although Huettner's proof seemed to butter the bread of the upholders of energetic economics the gift was in fact poison. The proof is based on resilient fallacy of modern economics. The fallacy, ingrained in the popular production function proposed by Philip Wicksteed,

$$(1)\ q = f(x, y, z, \ldots),$$

is to ignore the difference between flows and funds completely (NGR, 1970; 1971). In that function all elements generally represent flows. But as even the baker of a small village would tell us, he must pay not only for the flows of flour, salt, fuel, etc., but also for the services of the agents (funds)--labor, installations, and space. Because prices are not functions of flows alone, Huettner's proof based on a flow production function actually exposes the energetic heresy.

But this heresy seems to have a perdurable appeal by doing away with all the intricate problems specific to the economic process. The year after I exposed the flaw in Huettner's mathematical demonstration,[14] R. Costanza (1980), set out to prove the equation "embodied energy = economic value" and, moreover, to show that actual economic data verify it. Like Huettner's, his scheme reduces everything to flows but in the multiple dimensions of a linear inout-output system,

$$(2)\ e_j x_j - \textstyle\sum_i e_i x_{ij} = E_j.$$

The notations x_j and x_{ij} have the familiar meanings--output of sector j and output of sector i into sector j; e_j is the embodied energy in a unit of x_j; and E_j is the intput of primary energy (i.e., the energy from the environment) into the j sector. We must mark well that absolutely all quantities, x_j, x_{ij}, E_j, are measured in money terms; hence, e_j, must be the equivalent energy of a dollar and, according to the energetic dogma must be unity for all j.

Now, if all actual receipts and costs are included in (2), it stands to standard reason that

$$(3)\ E_j = x_j - \textstyle\sum_i x_{ij}$$

and nothing more is needed to prove that $e_j = 1$ for all j. However, Costanza turned to actual data to prove that "as more of the indirect energy costs are taken into account the ratio of embodied energy to dollar becomes more nearly constant from sector to sector" (p. 1222).[15] However, if cost includes still other elements than x_{ij} (payments for services: wages, interest, rent)--say, c_j in all--the new standard monetary equality of cost and receipts yields

$$(3a)\ E_j = x_j = \textstyle\sum_i x_{ij} - c_j.$$

And if $e_j = 1$ for all j, as Costanza claimed to have proved on the basis of (1), then from (1) and (3) it follows that $c_j = 0$ for all j, which is the weirdest economic condition.[16] Undoubtedly, Costanza's analyses doubled by cloudy statistics is at bottom an algebraic swindle, probably the greatest of mathematical economics.[17]

The Economic Object Lession of Thermodynamics

Many writers, who have made a vocation of "rescuces for the future", have opined that thermodynamics cannot teach anything to an economist. Their claim reflects the principle, traditional in modern economics, of ignoring the scarcity of natural resources completely. The mainstream view is that there is only superficial scarcity, because anything is obtainable if one is prepared to invest the necessary capital in labor and equipment. The much stronger thesis that technological innovations can always do away with scarcity of any item (H. Barnett and C. Morse, 1963) has become the first article of economic faith of virtually all economists (and, as we shall presently see, it is still so).

These conceptions were only effluents of the paramount conviction of the economic profession that "Economic growth is the grand objective. It is the aim of economic policy as a whole," as Sir Roy Harrod (1965, p. 77) proudly announced. Indeed, to increase the welfare of every human forever is a promise second in grandeur only to that of making everyone immortal. How groundless was that promise is proved by the fact that subjects related to models of economic growth which once served to establish the scientific excellence of their authors no longer entice would-be writers.

One would have normally expected that at least after the oil embargo of 1973/74, my repeated messages from 1965 to 1971 should have provoked some soul-searching by the economic profession. It required the heavy advertising of the excellent volume **Limits of Growth** (1972) to cause several economic luminaries to rise in defense of the one-eyed discipline. The first theorist to get on the ramparts was a well-known past master on growth, Robert M. Solow (1973, 1974).[18]

Passing over the rhetoric used in the first, Solow's two papers provide a pertinent ground for elucidating the consequences of viewing the economic process not as a thermodynamic transformation, but as a mechanical system. Indeed, in a mechanical system absolutely nothing happens besides changes of place, which is not the essence of the economic life.

Both papers contain a great deal of conventional explanation of how the market might react to changes of natural resources. This expatiation was aimed at proving that the market knows best, even all, so that there is no need to worry about the irrevocable entropic degradation. And as if he were fully aware of the insubstantiality of this view, Solow admits in several places that, nonetheless, the market errs and as regards natural resources errs grossly. Moreover, he also thinks that the flaws of the market could in general be only repaired by outside socio-political intervention, an idea which places him not far from "ecological freaks." But probably an ecological freak would strongly object to Solow's proposal for correcting the indifference of the market to pollution. Solow rejects the idea of imposing quantitative restrictions on effluents; instead, he wants to have the polluter pay for the amount of the damage caused. But the "polluter pays" principle would mean, for example, that we should do away with the obligatory catalytic converter in automobiles and instead have each owner pay for the pollution caused by the car's exhaust. That principle is certainly bad economics and equally bad thermodynamics. It is bad economics because the rich could pollute at will (which is bad economics unless the effects of income inequality are no concern of economics). It is bade market economics also for the reason that there is no market for pollution. And it is bad thermodynamics because pollution cannot be in general reconverted: both energy and matter cannot **all** be upgraded. For a salient example, there is absolutely no way to cool a planet that heats up. We cannot therefore know the cost of reconverting irrevocable pollution so as to charge it to the polluter.[19]

To be sure, Solow does not downright deny the working of the entropy law. In the end he even says that "it takes economics as well as the entropy law" to look at the economic process (Solow, 1974, p. 11). Yet he does not reason always on that precept. He hammers the familiar argument that if we run out of natural resources "other factors of production, especially labor and reproducible capital, can be substituted" for them (Solow, 1974, p. 10). Of course, this is bade thermodynamics: capital cannot be reproduced without an additional supply of natural resources.[20] On this view of solow, the ultimate future of the economic world is one similar to the Garden of Eden (NGR, 1976, chap. 1). This should not be taken in stride; Solow (1974, p. 11) does not mince words saying that "The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe."

Most curiously, however, in spite of the economic and thermodynamic obstacles not denied but glossed over by him, Solow maintains that economic growth can proceed exponentially to the Doomsday (Solow, 1973, p. 45), as is evidenced by formula e^{At} standard in all writings on growth. This must be affirmed with all vigor because it saves us from two unpleasant and unwelcome issues. The first issue is the fate of the poor. Pushing the idea of the feasibility and desirability of economic growth reflects the perspective characteristic of developed (and hence economically and militarily powerful) nations, which is the dismal axiom that the fate of the poor can be improved only if every rich individual becomes richer (Solow, 1973, p. 41).[21] The second, by analogy, is the fate of posterity.

Of course, it is a matter of choice to rule that inequality between contemporaries does not concern the economic discipline. But would the economic profession go so far as to adopt this position overtly and fully justify thereby the fulminations of Thomas Carlyle and John Ruskin? And if we do not deny that the inequality between two contemporary communities--say, the U.S.A. and Ethiopia--is our natural

business, why refuse to consider the inequality between noncontemporary ones?. We may nowadays quote ad nauseam John Trumbull's sarcastic query "What has posterity done for me?" But let us ask why this would be applicable only to the human species. By their invariable behavior all other species tell us that they strongly care for their posterity. Solow (1974), like many other defenders of standard economics, resorts to an old paper by Harold Hotelling (1931) to convince us that neoclassical economists have not ignored the problem of intergenerational allocation. But he overlooks the important point that Hotelling's analysis referred to some known amount of resources owned by an individual who discounts future royalties. Of course, Hotelling was completely correct about the last point. Any individual must certainly discount the future for the indisputable reason that, being mortal, he stands a chance of dying any day. But a nation, let alone the whole of mankind, cannot behave on the idea that it might die tomorrow. They behave as if they were immortal and, hence, value future welfare situations without discounting. Of course, if the discount rate is zero, Hotelling's beautiful mathematical construction collapses. But that does not mean that a program that tends to treat all generations on virtually the same footing is senseless (NGR, 1982b).

That modern economists would not even consider this program is understandable: the program rejects growth.[22] What is hard to understand is why they hail Hotelling's model which concludes with a declining depletion schedule. A teasing out of the thoughts connected with this issue reveals that a multiple paralogism has circulated uncontrolled. The rate of discounting the future must be positive to account for the positive interest rate. But Hotelling's theorem notwithstanding, we maintain not only that we just want to grow: we must, because we can. Isn't it true that in the past almost every generation was better off than the preceding one? Isn't it true that each generation has used up a greater amount of natural resources than it needed and has thus increased its inheritance? Of course, all this leads to another paralogism if we also affirm that the entropy law does not stop at the fence of the economic.[23] The fact that the economic welfare of most parts of the world has increased regularly does not prove that it stops there. During the past two hundred years, at least, mankind has enjoyed a fantastic mineral bonanza which has been the great source of an equally fantastic economic growth. Especially, after the Second World War, growth was not only fantastic but also high-handedly and ineptly misdirected. The wide-spread illusion that the supply of cheap crude oil (in terms of BTUs) will continue forever quelled any concern for economizing energy. The pride of the automobile industry, the clearest delinquent, was to manufacture mammoth gasoline guzzlers for those who already had too much of other things. Interest in improving the efficiency of coal as an industrial source of energy sank to incredible lows with the result that tragic poverty plagued the hills of Appalachia (Miernyk, 1976; 1982).

To be sure, technology was the effective lever of that economic growth, but it could not come into play without that mineral bonanza.

Especially after the miraculous technological advances of the recent decades, our faith in technology (and science, its sister) to go beyond or even to refute any known law became a general obsession. For a glaring example: I portrayed the working of the entropy law in an **isolated system** by an hourglass in which the stuff of the upper half stands for low entropy and by pouring down it degrades into high entropy (waste). To express the irrevocability of the process, I specified that, in contrast to the usual ones, the "thermodynamic hourglass" cannot be turned over. Paul A. Samuelson, as he finally came to speak of entropy in the last edition authored by him alone of his celebrated textbook, **Economics** (1980, p. 747), asserted that "Science can temporarily turn the [hour]glass over." From what we know we cannot affirm either what science may do nor what it may not do in the long run. About this development we can only rely on the founded speculations of the highest echelons in each field. So, take Sir Arthur Eddington who advised that "if your theory is found to be against the second law of thermodynamics ... there is nothing for it but to collapse in deepest humiliation." Albert Einstein also opined that thermodynamics "is the only physical theory of universal content [that] will never be overthrown." That is, heat will never pass by itself from the colder condenser to the hotter boiler. If a refrigerator moves heat to hotter spaces, it is only because far more heat passes from some boiler to a condenser elsewhere.

In agreement to the view just mentioned, I insist that any rational program **we** may offer today must be based only on our present knowledge, not on some wishful futuristic exercise. Futurists, as futurists, may speak about the possible discovery of cavorite, the material which in the imagination of H.G. Wells could screen off gravitation; but until this actually happens we should not induce people to build multi-story houses with neither stairs nor elevators.

The present agitation about alternative technologies--that is, alternative to that prevailing now--knows no skeptical restraints and no literary limits. The sin of thes preoccupations is, time and again, their ignorance of thermodynamical principles. An immense effort has been devoted to distill and redistill recipes known for ages with the intention to convince us that any of them waits around the corner with the solution for the impending crisis of oil and gas.

The history of mankind's technology consists of so many recipes that to list them all would be a task of a lifetime. I am referring to **feasible** recipes, such as baking bread, felling trees, vaccinating against smallpox, putting a man on the Moon, or, last but not least, heating homes and flying planes with the aid of only direct solar energy. There are, to be sure, recipes nonfeasible at present: to vaccinate against cancer, to control thermonuclear explosion, or to redress the Earth's axis.

It is appropriate to define "technology" as an ensemble (a matrix) of **feasible** recipes such that any non-primary input of any recipe is the product of some other recipe. I now set forth the following

seeming paradox: Although it consists only of feasible recipes, a technology is not necessarily **viable**. To explain: a viable technology must have the same qualities as those characterizing a living organism which, in addition to performing certain specific activities, also maintains its material scaffold (its body) intact from one minute to the next. The best economic illustration is Karl Marx's simple reproduction, the stationary state of latter day economics.[24]

Naturally, since no recipe exists to create energy or matter any viable technology needs a continuous supply of environmental low entropy. For this it must include some recipe (or a group of recipes) that converts the environmental energy and matter into energy and matter at our disposal for other activities. Such a recipe must satisfy a very strict condition, to which, for a reason to become clear presently, I propose to refer as Promethean (NGR, 1978).

As curious as it may seem, among the vast number of feasible recipes that constitute the pride of mankind's intellectual exploration of matter and energy only two inventions have so far represented a crucial technological advance. And it may also be surprising that the first such invention was a most ordinary phenomenon: the mastery of fire, which the ancient Greeks attributed not to a mortal, but to Prometheus, a divine Titan.

What is there that makes fire an extraordinary invention in mankind's technological evolution? First, fire achieves a **qualitative** conversion of energy, the conversion of (cold) combustible materials into caloric power. Second, fire creates a chain reaction: with just a spark we could cause a whole forest (nay, all forests) to burn. Fire enabled humans not only to keep warm and cook their food but, above all, to smelt and forge metals, to bake bricks, ceramics, and lime.[25]

During the new technological era, supported primarily by fuel from wood, new recipes of all sorts were invented at an increasing pace. Finally, the ensuing development depleted its own support just as rapidly. Forests began disappearing so fast that by the seventeenth century conservation measures were introduced almost everywhere in Western Europe. It was only the normal outcome of any Promethean gift--to speed up the depletion of its own supporting fuel. The crisis was analogous in toto to the present one.

An alternative source of heat--coal--was known in Europe since the thirteenth century, but coal was beset with two difficulties. It burned dirty, and second, coal mines were readily flooded by underground water. In some mines, there was more flooding water than the mineable coal.[26]

The crisis was one of fuel (wood and charcoal) but the immediate problem was how to get more power than that available at the time: from muscles, falling water, and wind. The giants of science, Galileo Galilei and Christian Huygens, could not think of a solution. This came from Prometheus II--two nonacademic mortals, thomas Savery and

Thomas Newcomen-who discovered another qualitative conversion, of heat into motion by the heat engine. It was the second Promethean recipe, for it also led to a chain reaction. With just a little coal and a heat engine we may mine far more coal as well as other ores to make more heat engines in a chain development.

This second Promethean gift enabled the human species to obtain motor power from a more abundant and far more powerful source: fire fed by mineral fuels. We still live in the viable technology engendered by that recipe. But, like all Promethean recipes, that of the heat engine gave rise to an accelerating technological development that speeded up the depletion of its very support. We are now approaching a new technological crisis, an energy crisis as it is commonly called.

In view of the fantasy that economics has nothing to do with thermodynamics one point deserves unparsimonious emphasis. From all the foregoing arguments it is clear that without thermodynamics (complemented by the fourth law) we cannot grasp the true nature of the emerging crisis (or of any other Promethean crisis for that matter). For a Promethean crisis does not consist just of some ordinary scarcity as, for example, that following a famine crop. It also is only through thermodynamics that the possible unfolding alternatives of a Promethean crisis are revealed to us on a rational basis. Indeed, whenever it happens that a viable technology is approaching the exhaustion of its specific "fuel,"--as is now the case of the prevailing technology--mankind's exosomatic future depends upon whether or not a new Promethean recipe is discovered in useful time. Just an ordinary feasible recipe would not do.

The best illustration of the ignorance of this elementary principle of thermodynamics is the belief which has been spread at first from casual mention to casual mention and, in the last years, from publication to publication: solar technology is here, we can use it now. As I have mentioned earlier, there are several feasible recipes for using direct solar energy, but a Promethean recipe does not exist yet. The direct use of solar energy does not fulfill the minimal strictly necessary condition of a Promethean recipe, which is that some solar collectors could be reproduced only with the aid of the energy they can harness. But in spite of the loud din about the solution of the energy crisis by the "cheap and renewable" solar energy, none of the recipes tried out proved that any could be Promethean.[27] The main obstacle is the extremely weak radiation of the solar energy reaching the soil.[28] The obvious upshot is that we need a disproportionate amount of matter to harness solar energy in some appreciable amount. A salient illustration is the solar-thermal plant whose boiler sits on a 250-foot tower and receives the reflected rays from 1818 heliostats, each of 40 square meters, which by a complicated mechanism steadily track the sun (Mark A. Fischetti, 1983).

Whether we consider a solar breeder, a thermal plant, or even a home solar system, it seems beyond doubt that the working of the fourth law is such that it cannot be compensated by the harnessed energy. True, in a photovoltaic cell there is nothing that moves, so friction is virtually out of the question; but there are structural modifications due to all kinds of unavoidable radiations. Surprising though it may be in the present sanguine effervescence about solar energy, the truth is that solar energy systems are more likely to fail than the traditional ones (P.S. Chopra, 1980). This particular drawback was the factor that brought to an end the vogue of solar water heaters that prevailed in California one hundred years ago (Butti and Perlin, 1977).

Undoubtedly, direct solar energy has its unique advantageous uses in situations in which other kinds of energy could not be technically adapted (in spacecrafts) or would be exceedingly wasteful (in isolated observation posts). If an increasing number of people nowadays include a solar energy system in their home instead of some of the other sources, it is, I maintain, only because of financial advantages that combine inflation with the perspective of high prices for ordinary fuels in the future. However, at this juncture, solar energy is still a parasite of the other primary sources--just as electricity is and will ever be (NGR, 1978).

In a tour of the present technical horizon, nuclear energy emerges as a possible technical support for continuing the prevailing unusual exosomatic comfort of one part of the world.[29] But we should not ignore that the ordinary nuclear reactor by itself is not a Promethean recipe; it only replaces the fossil fuels as a source of heat. The "breeder" reactor, however, is a Promethean recipe: it performs a qualitative conversion, of fertile into fissionable nuclear material, and, just like the heat engine, it produces more fuel than it consumes. But the use of nuclear energy in any type of reactor raises issues about the safety of all life on this planet, issues that are far from even moving toward a settlement.[30]

Of course, this situation may change any day. But given the problems surrounding the nuclear breeder and the complexity of the problem, the only reasonable strategy (to say "rational" would be intellectual arrogance) would be to economize as much as possible the fossil fuel resources. We would thus allow more time for finding an acceptably safe Promethean recipe. Alternatively, the sliding from the present hot technology to a cool one could take place without any calamities that are inherent to any quick change. My minimal bioeconomic program (1976) should answer some recent calls for a new paradigm (Nugent, 1979; Forscher, 1984). It does not propose the salvation through an extensive reshuffling of the present bureaucratic institutions of the world, a solution now **en vogue** (as instructively seen from Jan Tinbergen, 1985) in which I have no faith whatever and which is apt to deflect our attention from the true issue. Instead, my program calls for a new human commandment that leads, among others, to outlawing not only wars but also the production of any kind of armaments, thus releasing energy and matter to help the underdeveloped nations reach a humane standard of life. The people from the lands of plenty would only have to give up the craving for flimsy gadgetry, such as the automobile that accelerates from zero to 80 miles before its cigarette lighter gets hot (NGR, 1976).

My proposal also brings into evidence the most tragic problem for humans. To economize energy (or to conserve it, as is the usual term) is not a task for one nation or even for some nations. The task requires the cooperation of all nations, a point which reveals that there is a far more dreadful crisis than that of energy, namely, the crisis of the wisdom of **homo sapiens sapiens.**

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Notes

[1] To be sure, the 1971 volume contained several additional thoughts among which I should mention, first, an epistemological critique of the probabilistic interpretation of thermodynamic phenomena. This critique lent support to the exposure by Percy Bridgman of the idea he called "bootlegging entropy" (NGR, 1966, pp. 94-96; 1971, p. 7: and especially 1976, p. 15). Second, the same volume presents a new analytical representation of the production process based on the essential distinction between *flows* (the elements that undergo changes) and funds (the agents which perform the change while being maintained by the process itself). See NGR, 1971, ch. ix; 1976, chs. 2, 4, 5.

To simplify the diction, NGR will be used in references to my own works.

[2] It should be noted that the Earth is virtually a closed system (NGR, 1977, p. 268). All biological organisms as well as the economic process (wholly or in its parts) are open systems.

[3] For a recent illustration, see Stehle (1983). But the champion of the futility of the entropy law for biological and economic systems is, curiously, Edward Goldsmith (1981), the editor of The Ecologist. I say "curiously" because years earlier he reprinted two of my articles on the entropic nature of the economic process as front page matter. But his subsequent denial may have aimed at attracting applause by describing the future in highly optimist colors.

[4] Because the members of that school do not seem to be fully aware of this condition, I emphasized it in a communication to an international symposium (NGR, 1982a), with the purpose of making clear the essential difference between the roles of matter in Prigogine's theory and in my own view of material entropic degradation. Curiously, although my view was made known as far back as 1976, protests against it have been made solely in casual oral assertions--a fact that strengthens my faith in that direction.

[5] The most illustrious example is Glenn T. Seaborg (1972), a Nobelite. But rank and file outside physics generally believe in complete recycling arguing, as Kenneth Boulding (1966) once did, that matter is subject to no entropic degradation. D.B. Brooks and P.W. Andrews (1972) uttered that it is preposterous to think that we may run out of matter, the entire planet is made of matter. The entire planet is made of energy, too, so we should never run out of terrestrial energy either.

[6] Let us recall that perpetual motion of the first kind is a system that does work without absorbing energy. Perpetual motion of the second kind is a finite system that provides work by continuously using heat only from a source of uniform temperature.

[7] I have in mind the metals that resist both high temperature and corrosion. These happen to exist in very low crustal abundance. For example, in parts per million, there are vanadium (150), tungsten (69), columbium (24), cobalt (23), and tantalum (2.1). Deposits of mineable contents are naturally rarer still.

[8] For the thermodynamical critique, see NGR, 1976, pp. 22-26; 1977. The fact that large sections of mankind have lived for long historical periods in virtually steady states does not prove that the same may happen forever. Daly's thesis has naturally been highly applauded in the economically advanced countries where it is viewed as an optimistic promise--to continue forever at the present extravagant comfort.

[9] To recall the old controversy over whether or not rent is part of cost, we should observe that we obviously cannot attach an entropy value to terrestrial space. But although this space does not conform to my necessary condition, it derives its great usefulness from the fact that it catches the most important element for life: solar energy, which is of extremely low entropy(NGR, 1971, p. 278).

[10] See NGR, 1971, pp. 17, 283.

[11] Worthy of a special mention on this score is Andrew Pikler, a psychologist, who as early as 1932 and 1933 published his ideas in some Hungarian periodicals of limited circulation. As he explained later (Pikler, 1950), arguing that the "money molecules" move in zigzags just as gas molecules, he concluded in a more specific manner than Davis that (1) total amount of money corresponds to total energy, (2) the marginal utility of money to the reciprocal of absolute temperature, and (3) total utility to the entropy.

[12] Apparently, Engels was not aware of a still earlier verison, in French, published in La Revue Socialiste, June 1980. Since Podolinsky's essay was thus brought to light in an important popular periodical it is all the harder to account for its thorough oblivion for nearly a hundred years.

[13] Engles's letter to Marx, 19 December 1882. Marx, who died shortly thereafter, had no chance to look at Podolinsky's article.

[14] This was done in NGR, 1979, although I dealt with that flaw first in a 1978 invited lecture (NGR, 1980).

[15] By that juncture, Costanza seems to have forgotten that his thesis was $e_j = 1$, not $e_j = \text{const}$.

[16] Several letters of protest, including mine, reached the editor of Science. But although Philip Abelson said that he was going to publish at least one, they have published none. Perhaps, the natural scientists of that editorial staff believed that the economic process reduces to a simplistic system of energy exchange.

[17] Costanza's statistical procedure raises several damaging questions. On many crucial points we are kept in the dark. Is the energy involved primary (that of the coal in the ground) or secondary (of the heat obtained from it) or tertiary (jof the electricity obtained from heat)? No explanation is offered for the puzzling amounts of solar energy inputs of many sectors but especially of all labor services. Puzzling too is that the differences between columns B and A and between columns D and C (page 1221) are not equal even though they represent the solar energy inputs. Costanza also seems to ignore that his high correlation coefficients prove (at most) that energy is an important stochastic item of cost, a fact that no one would dispute.

[18] For a few others who threw their hats into the same arena about that time see NGR, 1976, chap. 1.

[19] For its logical beauty, I cannot pass over Stehle's utterance on this issue: "perfectly durable capital goods can be price, so there is no reason why this can't be done for perfectly durable bads" (1983, p. 180).

[20] To think that we can continue the civilization based (as the present one is) on engines operating at high temperatures (such as jet planes use) is to ignore that the list of stable chemical elements is complete and that the vitamin metals mentioned in my note 7 are very rare. So that the complete depletion of columbium would not be as inconsequential as Solow (1973, p. 45) thinks.

[21] For the many ways in which that axiom has been adorned for public pacifying, see J.K. Galbraith (1976).

[22] It must be noted that treating the future on the same footing with the present must be regarded as a virtual guiding principle, for otherwise it would imply an actual steady-state.

[23] Amusingly, a review in *Contemporanul* (Bucharest0 said that my 1971 volume explains how the capitalist system thrashes in the claws of the entropy law.

[24] But let us not ignore that no *individual* organism, not even a biological species, can possibly live forever. It is the fourth law that explains why its body ultimately degrades irrevocably, as we very well know. Recalling Schumpeter's splendid characterization "Economic life is a unique process that goes on in historical time and in a disturbed environment," the notion of viable technology can serve only as a useful analytical abstract.

[25] I gave them fire ... and from it they shall learn my crafts ... man's hidden blessing, copper, iron, silver, and gold." Aeschylus, *Prometheus* Bound, 500-505.

[26] Many mines kept hundreds of horses for operating the wheelworks used to drain the flood water. That is the origin of the unit "horse power."

[27] I have submitted this opinion, first, in the opening address, "A New Wood Age Ahead?" to the annual meeting of the Solar Energy Society of Canada (Edmonton, August 22, 1977), and in an invited lecture (NGR, 1980) at the World Conference on Future Sources of Organic Raw Materials (Toronto, July 10-13, 1978). I have elaborated it in several subsequent papers: e.g., NGR, 1978; 1979. Whether or not in connection with my argument, simple assertions appeared now and then suggesting that a technology based only on solar energy is viable. Maycock and Stinewalt (1981, p. 129) assert that some photovoltaic cells "can have energy payback in a matter of weeks." The Press also exulted in announcing that Solarex Corporation has set functioning a "solar breeder" which produces photovoltaic cells without any energy input from the outside (e.g, *Omni*, Oct. 1982, p. 42). However, even at this time the "solar breeder" is not yet in operation. Besides, it is not a Promethean recipe since, as explained in the excellent study by Solarex (1977, p. 3), the "breeder" must obtain from outside "materials of production and equipment."

[28] To overcome this obstacle P.E. Glaser (1968) proposed that solar energy be collected by a satellite and sent to ground level by microwaves. unfortunately, striking though that idea is, at present it is doubtful whether Glaser's recipe is even feasible (Committee on Satellite Power Systems, 1981).

[29] Geothermal, tide, and wind energy are workable in some way, but only in very special geographical conditions.

[30] I have not mentioned the superlative hope, namely, the controlled thermonuclear energy. Years ago I ventured to say that this energy may serve only as a bomb, just as gunpowder and dynamite (NGR, 1976). I repeated on purpose that thought in my lecture at the *Orbis Scientiae* Symposium attended also by Edward Teller, who to my surprise did not protest. His recent 1980 volume reveals that he no longer entertains the old hope about the inevitable success of controlling fusion.