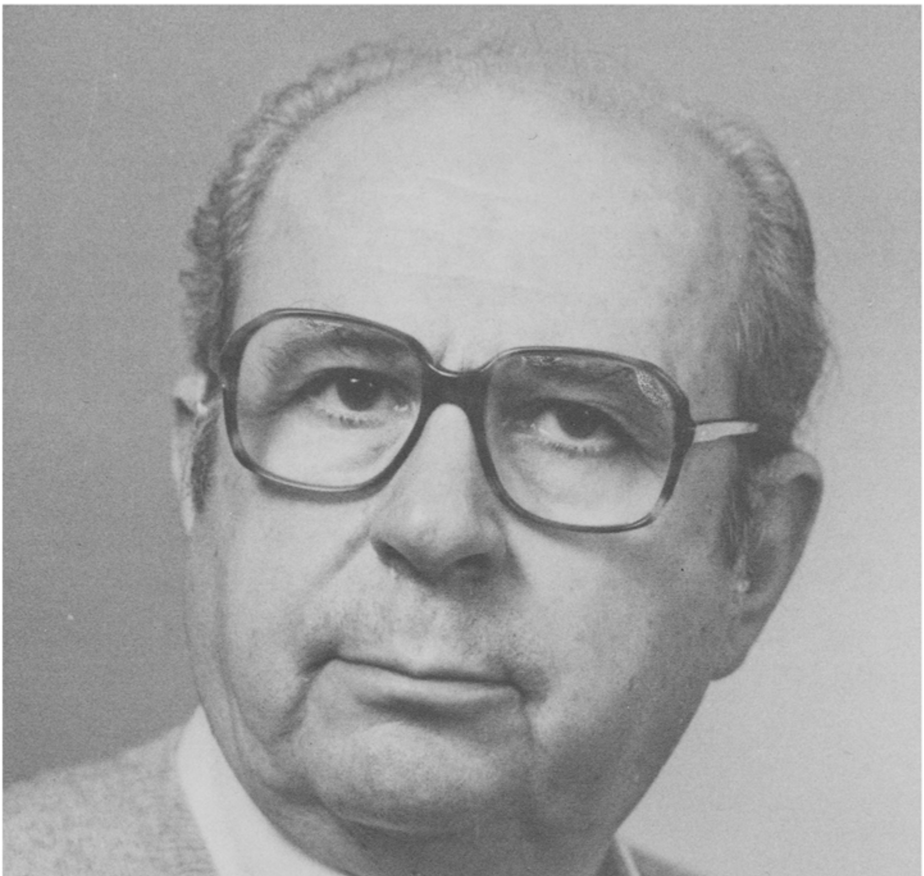

Nicholas Georgescu-Roegen
Invited Address
Sixteenth Economic Conference

Feasible Recipes Versus Viable Technologies

NICHOLAS GEORGESCU-ROEGEN*

I. Introduction: The Breaking of a Symmetry

Our Association has had many firsts among its American sisters. Another such first, a very distinctive one, is the choice of the theme "Facing the Future" for its Sixteenth Economic Conference. To underline this choice, I decided to devote my address to a topic that goes deep to the very core of facing the future. I will not use up your time with any prediction of demand and supply of oil or other fossil fuels by 1990 A.D., or 2000 A.D., or any other future year, nor with the elasticities of these factors computed by still another econometric model. You can find such information in the plethora of books that by now cause the academic libraries to burst at their seams. Instead, I propose to present to you a new analytical representation of the production process—that is, a new production function—that, among other things, enables us to discover not only the real nature of the present crisis but also its possible unfolding.

You may feel just dumbfounded by my project. What new idea can be added to our time-tested analytical representation of the process of production? Does not the concept of production come to us clear and clean from the natural sciences which are the last word on the matter of physico-chemical transformations? This is indeed the way economists have thought from the dawn of economics as a quantified science. But a breaking of symmetry—to borrow a fashionable expression in modern physics—has affected the evolution of economic thought.

Over the history of the inner conceptual conflicts of the economic profession the only bone of contention has continually been whether the actions of the individual human agent can be *properly* described by mathematical functions. The idea was that with their help the economic behavior of each individual and of all together may be predicted to some non-trivial distant future.[1]

A brief excursion in the history of economic thought (I should perhaps say "thoughts") clearly shows that the view of the nature of the human agent and of its role in the economic process divided economists into intellectually enemy camps. But just as analytical economics began to acquire some substance, loud voices were heard in protest against an economics reduced to "the mechanics of pleasure and pain" which thus refuses to recognize the nature of the individual as a social agent. "The Dismal Science" was Thomas Carlyle's famous fulmination against it: a less known one was "the Pig Philosophy" [Carlyle, 1899]. John Ruskin competed with "The Science of Political Economy *is* a Lie . . . the most cretinous, speechless, paralysing plague that has yet touched the brains of mankind" [*Works*, XVII]. A judicious verdict, however, was an older one, that of the Oxford historian Thomas Arnold: "the one-eyed" endeavor [A. P. Stanley, p. 66]. It is a judicious characterization because it has retained its currency ever since. Standard economists (see, for example, Coats, 1964) have indeed refused to see that economic value extends beyond the market mechanism.

The fight over whether economics ought to be "a Science of Man in Society" (as K. W.

*Vanderbilt University. Invited address at the Sixteenth Atlantic Economic Conference, October 6–9, 1983, Philadelphia.

[1] A generally ignored point may be stressed in this connection. The only functions that enable us to predict the future are the analytical functions. These very special functions have a harmonious structure that may be likened to that of a living organism. Just as an organism may generally be reconstituted from the knowledge of one of its (say) vertebras, an analytical function may be extrapolated (prolonged) even if we know its values only for an arbitrarily small interval [Georgescu-Roegen, 1966, p. 123].

Kapp put it), "a Life Science" (as envisioned by Herman Daly), or, instead, a "mechanics of utility and self-interest" of the atomistic individual (as Stanley Jevons preached) utlimately got rid of the violent polemical tone. But from the very first the controversy has centered on the use of mathematics.[2] Even before Adam Smith conquered the hearts of the British economists, Edmund Burke, in a premonition, argued that "The Excellence of Mathematics and Metaphysics is to have but one thing before you; but he forms the best judgment in all moral disquisitions who has the greatest number and varieties of considerations in one view." F. Y. Edgeworth used this quotation [Pigou, p. 66] to characterize Alfred Marshall's opposition to abusive abstract theorizing about human affairs. To recall, Marshall judged that Jevon's *Lectures* "would be improved if the mathematics were omitted, but the diagrams retained" [Pigou, p. 99]. In retrospect one can say that Marshall's dream was to achieve a harmonious alliance between the two schools of thought. But in the end, standard economists disavowed him. As Schumpeter [p.92] lamented, Marshall's "vision of the economic process, his methods, his results, are no longer ours."

In the end, mathematical reductionism triumphed although many great minds have kept swimming against the stream—Thorstein Veblen, Clarence Ayres, Friedrich von Hayek, and Gunnar Myrdal, to mention only those who have been most successful at it in our own era.[3] Yet the victors did not feel quite safe, which is why they have concentrated in disproportionate measure on defending their belief in the mathematical representation of the economic behavior of the human agent. Utility theory has thus become the most developed chapter of standard economics (with some simply unsuspected holes, though it is). The need to submit the process of production, too, to a closer analysis was not felt at all. Why, are not the natural laws of physics and chemistry formulated in mathematical terms?

II. The Production Function and the Analytical Representation of a Process

This is how the symmetry between the representation of utility and that of a production process—both consisting of a Dirichlet function—was broken. In contrast to the immense literature dealing with the utility function, $U = U(x, y, \ldots, z)$, the production function formed the object of no critical analysis ever since Philip H. Wicksteed [1894] introduced it almost one hundred years ago by the slick tautology:

"The Product being a function of the factors of production, we have $P = f(a, b, c, \ldots)$."

This cavalier definition of the production function is the only one found in economics textbooks as well as in the special literature.[4] Recently, even this definition has been reduced to saying that "output is a function of inputs," so that etymology, not phenomenology, now provides the necessary explanation. A few, more careful economic analysts did try to clarify at least the dimensional nature of the variables involved. According to some, the production function

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

relates rates of flow with respect to time; according to others,

$$Q = F(X, Y, \ldots, Z) \tag{2}$$

relates timeless quantities.[5] Ragnar Frisch [1965, p. 43] used both conceptions on the same page, a highly significant symptom of

[2] The economic science conceived so as to include the social coordiante with an economic basis has occasionally be censured for considering introspection a valid guide, for maintaining that not all relevant phenomena are necessarily reproducible, and that not all scientific laws must be cast in a mathematical matrix. It would take me too long to show here why these objections stand to no reason. But see Georgescu-Roegen, 1966, Part I and my 1979 article in *JEL*.

[3] A cloak of deadly silence has easily been cast over the old dissenters. Even in the sixteen volumes of the *International Encyclopedia of the Social Sciences* there is no mention of Carlyle or of Ruskin, not even of Richard Jones, the earliest critic whose splendid 1831 *Essay on the Distribution of Wealth and on the Sources of Taxation* greatly influenced the orientation of young Alfred Marshall.

[4] For a representative sample, see the references in my Richard T. Ely Lecture, reprinted in Georgescu-Roegen, 1976.

[5] References for these two approaches are found in Georgescu-Roegen, 1976, pp. 61-62, notes.

the economists' conviction that "function" is the only key word in Wicksteed's proposition.

Years ago it occurred to me that we should try to see whether the two formulae are equivalent, and if not, which one, if any, is the valid analytical representation. For if they are equivalent, we could pass from one formula to the other by only pure, logical operations. The result of my search was that they could not be equivalent except under the absurd assumption that all production processes are indifferent to scale [Georgescu-Roegen, 1976, Chapters 4, 5, 10]. But this still leaves us in the dark on whether any of these formulae represents adequately the production process.[6] The new problem thus is to see how a production process may be represented *analytically*, if it may be at all.

"Process" is the most abused term in science. Search as one may, one would not find "process" defined in the scientific literature. Since the concept is hardly distinguishable from that of change, which in turn is one of the most primitive features we see in reality, the term has always been used with the assurance that it needs no elaboration of any kind. Philosophical literature is of no help either.[7] Undoubtedly, no other concept is as full of epistemological thorns as that of process, about which we cannot discourse without getting entangled in the most complex notion, that of Change. Ever since Heraclitus--"the obscure"–confounded his contemporaries by teaching that "you cannot step twice in the same river," the analytically irreducible opposition between Being and Becoming has tormented the mind of every great philosopher.

However, science must embrace the analytical dualism, which is that there is both Being and Becoming: Water becomes Ice. Science also is concerned only with a slice of the whole Becoming, with a partial process. To speak of such a process we must first of all determine its boundary with respect to both time and entities of all kinds. In analysis, *no boundary, no process.* In addition, the boundary must, by assumption, be a void, for otherwise instead of having the partial process and its environment (also a partial process), we would have a third process–that taking place inside the boudary. Besides this complication, we would be engulfed in an endless regress, with new boundaries between the previous boundaries.[8] With a void boundary we always know whether, say, the automobile A at time t was part of the process P or of its environment.

But the boundary only identifies the process. It does not tell us the most important aspect, namely, what the process does. It is common knowledge that inside the boundary something goes on virtually all the time. But to identify those happenings with what the process does is to adopt a dialectical viewpoint. Analysis requires that we take another heroic step and ignore its *immediate* consequences. Once we have identified a process by a boundary we have implicitly renounced looking inside the boundary. What the process does can therefore be described only by what happens on the boundary. Should we like to learn something about what goes on *inside,* we have no other way than to draw other boundaries that would divide the initial process into several others [Georgescu-Roegen, 1971, Chap. IX].

The analytical representation of what a process does is thus reduced to happenings on the boundary, which can be only items crossing it one way or the other. Some imaginary cus-

[6] An example to clarify the issues. The object X is *defined* by A as a quadrangle with equal opposite sides. The same object is defined by B as a quadrangle symmetrical about one diagonal. Obviously, the two definitions are not equivalent: the first defines a parallelogram, the second, the shape of a kite. They would be equivalent if and only if all objects X were rhomboids. Further, since the definitions are not equivalent, at most only one defines X correctly (as when, for example, X is a parallelogram). But if X is a square, neither definition characterizes it.

[7] Even Alfred North Whitehead, the author of the great philosophical work *Process and Reality,* has not offered a definition of "process" suitable to science, beyond arguing, for example, that the "'principle of process'" means that a being is constituted by its becoming [*ibid.,* pp. 34-5] or saying (also as an example) that process "is a fundamental fact in our experience" [Whitehead, 1958, p. 73].

[8] The point recalls the fallacy that between "preference" and "nonpreference" *by logic* there must exist "indifference." By the same logic there must be another state of mind between "indifference" and "preference," and so on *ad infinitum.*

toms officials will report how much of each item has crossed the boundary until the time t, $0 \leq t \leq T$, where T is the duration of the process which by assumption begins at $t = 0$. The complete analytical description of a process (not necessarily a production process) thus is the vector of *functions,*

$$[E_i{}_0^T(t); I_i{}_0^T(t)], \quad (3)$$

instead of a vector of numbers, as is the standard representation. The functions E_i and I_i are defined over [0, T] and represent the transactions of "export"–output–and "import"–input–of the item i. By a justified convention, the input coordinates have always the minus sign.[9]

According to (3), the analytical description of what a process does requires only flows, a flow being defined at this juncture as any material entity that crosses the boundary in one way or the other. So, we may say, as before, *no boundary, no flow* (in that sense). The flow complex of standard economists [for which see Georgescu-Roegen, 1966, pp. 55, 88] would then be justified. But the structure of production processes has additional characteristic aspects.

To begin with, land in the Ricardian sense (that is, as some pure terrestrial area) enters any economic process and comes out of it without any alteration whatsoever. The same is true of catalysts. Other inputs, although coming out changed, can be identified as the same object. This is the case of a spade, for example, which may enter a process sharpened and, necessarily, comes out dull. But we can still recognize it as a spade.

Now, in order to arrive at a representation adapted to the needs of economic analysis, we shall introduce a new heroic assumption concerning the production process. Namely, we shall consider a process in which labor and materials are continuously devoted to maintaining the objects that normally are worn out by the process in a constant state of efficiency. Thus, the spade of the earlier example will come out just as sharp and with just as good a handle as when it entered the process. The assumption is heroic, but not too remote from actuality. In every enterprise, in every household, a substantial amount of labor-time and materials are steadily devoted to keeping the buildings, the machines, the durable goods, in a useful, workable state.[10]

The snag of this idea comes from a different direction. To maintain a piece of fixed capital in constant condition, we need other such pieces. They have, in turn, to be maintained, which would call for others, and so forth, and so on. The process in question would have to be extended until it comprises almost the entire production sector of the economic process (as will be the case in the sequel). If we gloss over this snag, in the assumed process, capital equipment displays the same property as the Ricardian land. By another analytical license, we may consider that laborers also belong to the same category. Undoubtedly, when a worker leaves a process, he is a tired individual. But we may take into account the fact that when the same individual returns to work next day he is again a rested worker after being restored in an adjacent household.

To force (as I have just done) Ricardian land, capital equipment, and labor power into the same analytical category has a great advantage. All these element are *agents* of production, the factors of production in the strict interpretation of the classical school. For their distinguishing property, I propose to call them funds [Georgescu-Roegen, 1971, pp. 224-30;

[9] The convention is justified by the fact that when two processes are *consolidated,* as when the common boundary is removed, the interprocess transactions disappear from the consolidated from (3). Inputs and outputs cancel by simple addition of the initial coordinates.

[10] By now, the idea of maintaining capital constant is an accepted analytical artifice in all quarters. But it was Karl Marx who, in a strikingly inconsistent section [*Capital,* II, pp. 171-76] alluded to it as a preparation for his diagram of simple reproduction.

1976, Chaps. 2, 4, and 5].[11] All other factors are factors that either cross the boundary from outside but never come out or cross the boundary from inside without having entered the process. Flour and firewood correspond to the former, bread and ashes (waste) to the latter case in the process of a bakery. Such factors will be referred to as flow-factors (an expression which should not be confused with the earlier term of "flow" alone).[12]

The next analytically powerful concept is that of *elementary process,* which is the process defined by a boundary such that only one unit or only one normal batch is produced. The most instructive illustration is the sequence of operations by which an automobile is produced on an assembly line.

There are a series of salient consequences, which here can only be mentioned briefly. One point that should not escape our attention is that by the very nature of things during any elementary process some funds are *necessarily* *idle,* which raises the issue of the idleness of capital. All types of production processes are composed of elementary processes. There are three typical patterns in which the elementary processes are arranged. The individual process *P* may be arranged (1) in series (Figure Ia), (2) in parallel (Figure Ib), or (3) in line (Figure Ic). The arrangement in series portrays the situation of the artisan working alone because the intensity of demand is not greater than one unit during the time interval represented by duration *T.* It explicates Adam Smith's idea that the extension of the market brings about an increased division of labor. The arrangement in parallel obviously represents the facts of agricultural life, with its inevitable burden of multiplied idleness imposed by immutable climatic rhythms. The arrangement in line is the only one that eliminates *technical* idleness completely.[13] It is the factory system, which together with money represents the two greatest economic (not technical!) inventions.

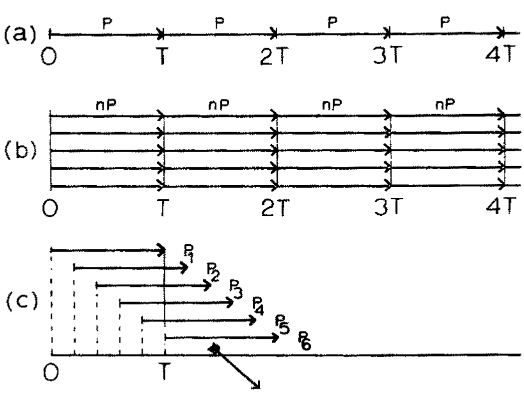

FIGURE I

The Typical Arrangements of Elementary Processes

Since processes are arranged in line (and in a proper fashion), the flow that moves through the process moves without any waste of time from one agent to another. The agents are thus never idle [Georgescu-Roegen, 1971, Chap. IX; 1976, Chaps. 4 and 5.][14] In this lies the essential difference between manufacturing and farming processes. In agriculture elementary processes cannot be started at any time of the year as is ordinarily the case in manufacture. A telling exception is the chicken factory, which has replaced the old chicken farm and lowered the cost of chickens precisely because it eliminated the idleness of capital. Of course, rice, for example, may be grown by a factory system wherever the climate (as on Bali Island) is virtually invariable [Georgescu-Roegen, 1976, pp. 68-9].

The factory process being a reproducible process (a stationary or a steady-state one), all fac-

[11] As I was finding my way toward this conception, I used the term "stock-factor" instead of "fund-factor" [Georgescu-Roegen, 1966, p. 399]. It was an unfortunate terminological choice, for a fund is a special stock—a stock that is active in a process but maintained qualitatively and quantitatively constant. "Stock" should be reserved for a quantum that may be decreased or increased by flows. In spite of my subsequent clarification [Georgescu-Roegen, 1971, pp. 226-27], the essential difference between "fund" and "stock" is not always grasped.

[12] Not all pieces of equipment are funds: artillery shells or space rockets. In the process of war, *horresco referens,* the human element is in part a flow-factor.

[13] Technical idleness should not be confused with institutional (or economic) idleness: plants that work with only one shift during twenty-four hours, for example.

[14] Further important developments of this general theme have been made by Gordon C. Winston, especially in his 1982 volume, and by Roger R. Betancourt and Christopher K. Clague [1981].

TABLE 1

The Analytical Representations of a Reproducible Process

Factors	(A)	(B)
Flows		
Inflows from nature	$-r$	$-R=rt$
Inflows from other processes	$-i$	$-I=it$
Outflows of products	$+q$	$+Q=qt$
Outflows of waste	$+w$	$+W=wt$
Funds		
Labor power	H	$H=Ht$
All capital	K	$K=Kt$
Ricardian land	L	$L=Lt$

tors proceed at constant rates with respect to time. These coordinates, shown in column A of Table 1, do not, however, reveal what the process may have actually done or can do during a chosen time interval, *t*. They show only what the process can do if, first, the funds are in place *and,* second, the inflows are forthcoming at the necessary rates. The activity of the process during the time interval t is shown by the coordinates of column B. These are *quantities,* specifically, for the flows they represent physical amounts, for the funds the amounts of *services.* Which calls for the observation that H, K, and L in column A are timeless; they measure rates of services with respect to time.[15] The time rate of labor service in a plant using 100 workers is 100 workers.

To recall, the analytical representation of any process (say, that of constructing a Golden Gate bridge or producing a pair of shoes in a factory) is the functional (3). But in the special case (and only then) of a steady-state process, that functional degenerates into the simple vector of column B. It is therefore only in this particular case that we may arrive at a production function of the same form as Wicksteed's.

The production function may be viewed as an analytical "catalog" of all known recipes by which a product may be produced [Cf. Samuelson, 1948, p. 57]. Let us imagine that the recipes for producing a given product by some factory process are all written on individual cards. An expert in that industrial field needs only look at the fund coordinates to determine what the corresponding factory can do. This means that we have the relation

$$q = F(H, K, L). \qquad (4)$$

Furthermore, for production the agents require a precise set of input flows. Their technical nature determines also the flow rate of waste. There is thus another function

$$q = f(r, i; w), \qquad (5)$$

which completes the analytical picture of how the product under consideration may be produced by one factory or another. The important conclusion is that the correct production function displays the restriction to which Ragnar Frisch referred as ***limitationality***: there is no substitution between flow and fund factors of invariable quality (a point to be retained for a later argument).[16]

The upshot is that the correct analytical description of a steady-state process is Equation (1), not (2). Naturally, there must be some relations analogous to (4) and (5) between the quantities of column B. But since these quantities are a function of t, that is, they are not constants with respect to time, time must enter as a parameter in the new formulae. Thus instead of (4) we have

$$Q = G(H,K,L\,; t) \qquad (6)$$

[15] K_i contains also the peculiar fund to which I have referred as "the process fund" [Georgescu-Roegen, 1976, Chap. 4]. It consists of what is usually understood by "goods in process." This item is actually a static portrait of the change performed by the process. Without it, the process is not primed, which would call for some waiting.

[16] Formula (4) presupposes the measurability (ordinal, at least) of all funds. If they change qualitatively, the catalog of all recipes no longer leads to a proper subspace in the factor space. To argue that an automobile is equivalent to four motorcycles on the basis of prices is to shift the cart before the horse and believe that it will still move. On the problem of quality, see Georgescu-Roegen, 1976, Chap. 11.

And since, as Marx [*Capital*, I, p. 202] argued long ago, in two weeks a reproducible process produces twice as much as in one week, G is a homogeneous function of the first degree. Hence, (6) yields

$$q = G(H, K, L; 1) = F(H, K, L). \qquad (4a)$$

Author after author has claimed that F is a homogeneous function, which is a catastrophic error. The function F shows the scale of the process, and as we have learned from Aristotle, Leonardo da Vinci, Herbert Spencer, and in our own time from Edward Chamberlin [1948, App. B], humans cannot operate at the size of an ant, nor ants at the size of a human. However, the function corresponding to (5)

$$Q = g(R, I; W) \qquad (7)$$

is necessarily homogeneous of the first degree, for energy and macroscopic matter can neither be created nor annihilated. Thus if we double the inputs of energy and matter as well as the outputs of waste, the amount of product must also double. Hence, by division with t all through (7) yields (5) which is now seen to be a homogeneous function of the first degree.[17]

III. The Analytical Representation of a Steady-State Economic Process

By now one needs no apologies for beginning one's analysis of a process with a steady-state case. The steady-state provides the indispensable point of reference for any other process. Actually, there are crucial issues that cannot be pinned down except in relation with a steady state. It goes without insisting that the steady-state process considered here is an analytical abstraction. This type does not exist in actuality, where everything changes continuously.

For the general perspective adopted in this section, the economic process will be separated from the environemnt by a global boundary

[17] "Double the inputs, double the output" is a textbook refrain. The principle is true but only if applied to proper conditions--doubling the time of production or doubling all material flows (the cases invoked above). On the issue of homogeneity see also Samuelson, 1948, p. 84.

TABLE 2

The Relationship Between the Economic Process and the Environment

Elements	(P_0)	(P_1)	(P_2)	(P_3)	(P_4)	(P_5)
			Flow Coordinates			
CM	x_{00}	*	$-x_{02}$	$-x_{03}$	*	*
CE	$-x_{10}$	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
MK	$-x_{20}$	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
C	*	*	*	x_{33}	*	$-x_{35}$
RM	*	*	$-x_{42}$	$-x_{43}$	x_{44}	*
ES	*	$-e_1$	*	*	*	*
MS	$-M_0$	*	*	*	*	*
GJ	w_0	w_1	w_2	w_3	$-w_4$	w_5
DE	d_0	d_1	d_2	d_3	d_4	d_5
DM	s_0	s_1	s_2	s_3	s_4	s_5
R	r_0	r_1	r_2	r_3	r_4	r_5
			Fund Coordinates			
Capital fund	K_0	K_1	K_2	K_3	K_4	K_5
People	H_0	H_1	H_2	H_3	H_4	H_5
Ricardian land	L_0	L_1	L_2	L_3	L_4	L_5

and divided into six subprocesses by internal boundaries. The result is the matrix of Table 2.[18] The subprocesses have the following objectives:

P_0: transforms matter in situ, *MS*, into controlled matter, *CM*;

P_1: transforms energy in situ, *ES*, into controlled energy, *CE*;

P_2: produces maintenance capital, *MK*;

P_3: produces consumer goods, *C*;

P_4: recycles the garbojunk, *GJ*;[19]

P_5: maintains the population, *H*.

A few points should now be well marked. Energy and macroscopic matter (i.e., matter in bulk), as we know, can be neither created or annihilated. But they exist in two essentially distinct states: available, if they can be used for our own purposes, and unavailable, if they cannot. Moreover, both available energy and available matter continuously and irrevocably degrade into unavailable states which is the classical entropy law extended so as to include matter. All great physicists have argued, as none other than Albert Einstein did [Schilpp, 1970], that this law "will never be overthrown." Nonetheless, some have sought to gain attention by arguing the opposite, an alluring optimist promise. Indeed, how wonderful would our life be if we could drive an automobile by the energy contained in the exhaust and recycle the rubber molecules worn out from the tires!

Each column of Table 2 is the analytical representation of the corresponding process in the form developed earlier in Table 1. A simple look at that table reveals that the economic process is entropic in all its *material* fibers. Materially, it degrades the environmental energy and matter (e_1 and M_0 respectively) into "waste,"[20] namely, dissipated energy, *DE*, dissipated matter, *DM*, and refuse, *R*. Refuse is the output which although it contains available energy and matter, for technical or economic reasons, has no place in the economic process (for example, nuclear garbage or crushed rock from an open pit mine).

The general entropic principle is not only that we cannot use twice the same amount of energy or matter, but that some energy and matter is necessarily degraded through any process. This explains the inevitable outflow of dissipated energy and dissipated mattter. It also explains a far more important fact. In Table 2, the reason for the capital industry, P_2, is that the flow x_{22} is necessary for the maintenance of the funds K_i.[21] In the same way, the flows x_{i5} maintain the *whole* population, H_5 (which is larger than ΣH_i, $i < 5$).[22]

IV. Concluding Corollary: The Promethean Destiny of our Technology

Nowadays, the main hope for a solution to the menacing crisis of energy is set on the technological progress. Evidently, any solution to the crisis of our present industrial fever can come only from technology. However, we do not seem to realize the nature of the technological progress that can solve the crises. The epit-

[18] This mode of representing a multi-process analytically is kin to the input-output matrix devised by Leontief, but it avoids the analytically incongruous notion of "internal flow" [see Georgescu-Roegen, 1971, Chap. IX]. It also is a clearer picture of a multi-process than the anfractuous diagram used by ecologists in which flows are shown by line arrows.

[19] Since dissipated matter by wear and tear is in the unavailable state, that is, it cannot be recycled, we can recycle only available matter that exists in a form no longer useful to us: broken glass, old papers, worn out motors, and the like, items found among garbage or junk. See note 21.

[20] To be sure, the proper product of the economic process is not an outflow of waste, but an immaterial flux, namely, the enjoyment of life [Georgescu-Roegen, 1966].

[21] For the relation between the available energy used and the resulting unavailable energy, see Georgescu-Roegen, 1979a. The same article deals with the extension of the traditional entropy law from energy to macroscopic matter—in technical terms with what I have called the Fourth Law of the Thermodynamics. That law, like the First and the Second Laws, proclaims the impossibility of a perpetual motion, that of the third kind, which is defined as a system that performs mechanical work indefinitely at a constant rate but can exchange only energy with its environment. One corollary is that not all matter can be recycled.

[22] In passing, I may observe that x_{22} and K_i are two different economic elements. K_i is, say, a bridge; x_{2i} is the flow of things for the maintenance of the bridge. And just as Karl Marx noted that no one has been able to catch fish from a lake without fish, so we should observe that no one has been able to cross a river on the flow of maintenance items.[25]

ome of the false position now constitutes a refrain found in several papers contributed to the *Symposium of the Economis of Exhaustible Resources.*[23] It is the general thesis of standard economists based on a ultrafamiliar Cobb-Douglas production function

$$Q = CK^a H^b R^c, a + b + c = 1, \quad (8)$$

where K stands for capital, H for labor, and R for natural resources. The algebraically obvious conclusion is that with increasing capital and labor we may even increase the global product with as small input of natural resources as we may wish. From the analytical viewpoint (the only one compatible with the position of the pure mathematical economist) the argument sins against the principle established earlier in this essay, namely, that flows and funds are not substitutable. We cannot weave more cloth with less yarn by adding some identical looms. If relation (8) is viewed dialectically, that is, as an expression of the general truth that with qualitatively improved funds (capital and skilled labor power) we can get a greater amount of product from the same amounts of flow inputs (by reducing the waste outflow), the quantitative ratiocination does not apply. The special stumbling block thus comes to the surface: from all we know, to tap nature for her treasures (fossil fuels and even waterfalls) "tools" of greater and greater dimensions had to be used. More efficient machines need a greater amount of matter and energy to go through the whole economic process.[24] A thermonuclear reactor may very well be as great as the whole Manhattan.

A substantial approach calls for some new elementary notions. I shall refer to a matrix such as that of Table 2 in which every necessary input of every process is obtained from nature or produced by some *feasible* process as a technology. Clearly, a process (or a recipe) is feasible if *at the time of the discussion,* we know all its specific flow and fund coordinates. Thus, to bake bread, to transmit messages by electromagnetic waves, to smelt iron ore, are all feasible recipes. But to control thermonuclear energy or to prevent earthquakes is not. Furthermore, although all the processes included in any technology must be feasible, not every technology is necessarily *viable.*

To explain, a technology is viable if and only if it can maintain the corresponding material structure and necessarily the human species. An instructive illustration of the property of viability is found in a living organism or a biological species. What seems necessary to stress is that every viable technology is supported by some fuel, by some environmental resources, but that no technology can create its own "fuel."

A simple example of a nonviable technology is this. Imagine a technology in which the only capital tool is a hammer that hammers the same type of hammers from freely found stones. The same hammer is used to crack some very hard nuts which are the only food of the population. If one hammer cannot last long enough to hammer another hammer *and* crack a specific amount of nuts to maintain the population, then that technology is not viable. This illustrates the drawback of the direct use of solar energy. A very careful scholar, Denis Hayes, claimed a few years ago that "solar technology is here, . . . we can use it now," [*Washington Post,* February 26, 1978]. What is here *now* are only several feasible recipes for the direct harnessing of solar energy—solar cells and various solar collectors. But a viable technology based on solar energy is not yet here. The proof lies in the fact that, in spite of the substantial funds spent by ERDA and other institutions to sell the sun as a substitute for fossil fuels, no one has thought of building even a pilot plant that would use exclusively its harnessed solar energy to reproduce *at least* its collectors [Georgescu-Roegen, 1978]. By now the necessity of this acid test has been recognized even by some of the staunchest propagandists of solar energy. The basic shortcoming of solar energy is the low intensity with which it reaches the ground and (a point neglected) the absence of any self-collection property. Rain also reaches the earth in a very weak average intensity, but it cumulates by it-

[23] *Review of Economic Studies,* 1974.

[24] The computer seems to be the only exception to the cited rule.

self gradually until we obtain the intensive free energy of some Niagara.

The history of our technology is studded with inventions of all sorts, so numerous that to list them all seems an insuperable project. However, the spectacular innovations of the recent decades have impressed us so much that their links with the past no longer attract our curiosity. Otherwise, we would have discovered that, surprising though it may seem, only two inventions have led to viable technologies. Perhaps even more surprising is that the first crucial invention consisted of what is now a most ordinary phenomenon: the mastery of fire.

The mastery of fire was an extraordinary invention because first, fire achieves a *qualitative* energy conversion, the conversion of the chemical energy of combustible materials into caloric power. Second, fire leads to a chain reaction: with just a small flame we can cause an entire forest, nay, all forests, to burn. Fire enabled humans not only to keep warm and to cook their food but, above all, to smelt and forge metals and bake bricks, ceramics and lime. No wonder the ancient Greeks attributed to Premetheus—a divine Titan, not a mortal—the bringing of *fire* to man. We may refer to the technology opened by Prometheus I (as he should be called) as the Wood Age. For centuries wood served as the only source of caloric power, so that, with industrial development growing continuously, forests began disappearing with increasing speed. During the second half of the seventeenth century the cutting of forest trees had to be regulated, even restricted, both in England and on the Continent.

Coal was already known as a source of caloric power, but one major obstacle prevented its substitution for wood in industry. Mines quickly flood. The power required to drain them was not available in a sufficient intensity from the sources used at that time—the muscular power of humans and beasts of burden, the wind, and the falling water. Many mines in England kept hundreds of horses for turning the wheelworks for raising the flood water to the surface.

The impending crisis was entirely analogous to the present impasse: the technology based on wood was running out of its supporting fuel. It was solved in time by the second crucial invention, the ingenious, unpredictable gift of another Prometheus—Prometheus II—actually, two mortals, Thomas Savery and Thomas Newcomen: the heat engine. This engine, like fire, has enabled us to perform an entirely novel qualitative energy conversion—the conversion of caloric power into motor power. Like fire, the heat engine leads to a chain reaction. With just a little coal and a heat engine, we can mine more coal and also other minerals from which to make several heat engines, with which we can make still more such engines. The gift of Prometheus II enabled us to derive motor power from a new and more intensive source, the fire fed by mineral fuels. We still live mainly with that viable technology by obtaining work from heat.

The problem now is whether a new Prometheus will solve the present crisis as Prometheus II solved that of the Wood Age. But it is not pessimism to point out that no one can be sure one way or the other and that no one can be sure about the nature of the future Promethean gift (if it is ever invented). Neither Galileo nor Huygens was able to think of a solution to the crisis of the Wood Age. We cannot command the coming of Prometheus III to present mankind with a new viable technology.[25]

[25] Ranganath Murthy, my associate, was of great help in the preparation of the final manuscript.

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