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The Entropy Law and the Economic Process

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To My Teachers

Contents

Appendices

Tables

Preface

The Entropy Law is still surrounded by many conceptual difficulties and equally numerous controversies. But this is not the reason why most natural scientists would agree that it occupies a unique position among all laws of matter. Sir Arthur Eddington even maintained that the position is "supreme." The important fact is that the discovery of the Entropy Law brought the downfall of the mechanistic dogma of Classical physics which held that everything which happens in any phenomenal domain whatsoever consists of locomotion alone and, hence, there is no irrevocable change in nature. It is precisely because this law proclaims the existence of such a change that before too long some students perceived its intimate connection with the phenomena peculiar to living structures. By now, no one would deny that the economy of biological processes is governed by the Entropy Law, not by the laws of mechanics.

The thought that the economic process, too, must be intimately connected with the Entropy Law is the origin of the inquiry that forms the subject of this book. To examine the numerous aspects of this connection has taken me—and will take the reader—in many fields beyond the boundary of economics. For this reason I felt that the task of introducing the topic of this book had to be left to a special chapter.

Here I may say that, precisely because of the special nature of the subject, working on this book has confirmed an old notion of mine, namely, that practically all works we usually call our own represent only a few scoops of originality added on top of a mountain of knowledge received from others. Going over the galley proofs was for me an occasion as no other to realize how immense is my debt to my teachers and also how numerous they are. It prompted me to seize upon this opportunity to express my gratitude to them by the dedication of this volume.

Many teachers will not have their name carved inside the pantheon of the great minds, even though many will be no less highly revered. Foremost in this category (and in my heart) are my parents—my father, who taught me to read, write, and calculate and who planted in me the seed of intellectual curiosity, and my mother, who, by her living example, taught me the value of hard work. Gheorghe Rădulescu, my elementary school teacher in a small town of old Romania, fostered with great skill my early mathematical inclinations by teaching us how to solve "tricky" problems which, as I learned later, are usually solved by algebra. From the long list of the inspiring and devoted teachers I had at Lyceum Mânăstirea Dealu I may mention Grigore Zapan and Gh. I. Dumitrescu, who with tremendous love for their profession guided my first steps in higher mathematics. I think that my share of good luck at the university level also was above the average. I studied with scholars whose names now occupy a place of honor in the history of science: Traian Lalescu, Octav Onicescu, and G. Țițeica (in Bucharest), Albert Aftalion, Émile Borel, Georges Darmois, and Maurice Fréchet (in Paris), and E. B. Wilson (in the U.S.A.). But two of my teachers had the most decisive influence on my scientific orientation: Karl Pearson, the man of broad knowledge who single-handedly laid the foundations of the science of statistics, and Joseph A. Schumpeter, whose unique vision of the economic process combined in a harmonious manner quantitative with qualitative evolutionary analysis.

Needless to say, one should consider as his teachers also those from whom he learned in any other way, chiefly through their writings. Like everyone else, I also learned a great deal from my professional colleagues (many things even from my students). From their number, which is legion, I cannot resist singling out two of my fellow economists (and econometricians)—Wassily W. Leontief and Paul A. Samuelson.

The reader does not need any hint to realize that a book of this nature cannot be written as a research project with a definite timetable. The ideas contained in it were worked out in my mind over many years (as many as twenty, I believe) and in various circumstances—sometimes while lecturing, sometimes while working in the garden. Some of these ideas have already appeared in print, mostly in the introductory essay to my *Analytical Economics*.

During all these years, Vanderbilt University has given me encouragement and provided me with facilities for work, many of which came from the Graduate Program in Economic Development. For all this I am

especially and variously indebted to my colleagues George W. Stocking, Rendigs Fels, Anthony M. Tang, and James S. Worley. A research grant from the National Science Foundation has enabled me to devote half of my teaching time during one and a half years to bringing this work to its present form. During this last phase I was assisted by Messrs. Aly Alp Ercelawn and Ibrahim Eriş.

I am grateful also to the Syndics of Harvard University Press for having considered it worthwhile to have the introductory essay of my *Analytical Economics* expanded and completed in the present volume.

My final thought of gratitude is for my wife, who has been a patient, attentive reader, a sympathetic but constructive critic, and a tireless proofreader, and who has provided me with a home atmosphere conducive to study and work.

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July 1970

NOTE

"AE" in the foctnotes stands for my *Analytical Economics: Issues and Problems*, published by Harvard University Press in 1966.

The Entropy Law and the Economic Process

Introduction

No science has been criticized by its own servants as openly and constantly as economics. The motives of dissatisfaction are many, but the most important pertains to the fiction of *homo oeconomicus*. The complaint is that this fiction strips man's behavior of every cultural propensity, which is tantamount to saying that in his economic life man acts mechanically. This is why the shortcoming is ordinarily exposed as the mechanistic outlook of modern economics. The criticism is irrefutable. However, the mechanistic sin of economic science is much deeper than this criticism implies. For the sin is still there even if we look at the economic process from the purely physical viewpoint only. The whole truth is that economics, in the way this discipline is now generally professed, is mechanistic in the same strong sense in which we generally believe only Classical mechanics to be.

In this sense Classical mechanics is mechanistic because it can neither account for the existence of enduring qualitative changes in nature nor accept this existence as an independent fact. Mechanics knows only locomotion, and locomotion is both reversible and qualityless. The same drawback was built into modern economics by its founders, who, on the testimony of Jevons and Walras, had no greater aspiration than to create an economic science after the exact pattern of mechanics. A most eloquent proof of how staunch the enthusiasm for mechanics was among the early architects is provided by Irving Fisher, who went to the trouble of building a very intricate apparatus just for demonstrating the purely mechanical nature of consumer behavior.[1]

[1] Irving Fisher, *Mathematical Investigations in the Theory of Value and Prices* (New Haven, 1925), pp. 38 f and *passim*. The work was first published in 1892.

And these architects succeeded so well with their grand plan that the conception of the economic process as a mechanical analogue has ever since dominated economic thought completely. In this representation, the economic process neither induces any qualitative change nor is affected by the qualitative change of the environment into which it is anchored. It is an isolated, self-contained and ahistorical process—a circular flow between production and consumption with no outlets and no inlets, as the elementary textbooks depict it. Economists do speak occasionally of natural resources. Yet the fact remains that, search as one may, in none of the numerous economic models in existence is there a variable standing for nature's perennial contribution. The contact some of these models have with the natural environment is confined to Ricardian land, which is expressly defined as a factor immune to any qualitative change. We could very well refer to it simply as "space." But let no one be mistaken about the extent of the mechanistic sin: Karl Marx's diagrams of economic reproduction do not include even this colorless coordinate. So, if we may use a topical slogan for a trenchant description of the situation, both main streams of economic thought view the economic process as a "no deposit, no return" affair in relation to nature.

The intriguing ease with which Neoclassical economists left natural resources out of their own representation of the economic process may not be unrelated to Marx's dogma that everything nature offers us is gratis. A more plausible explanation of this ease and especially of the absence of any noticeable attempt at challenging the omission is that the "no deposit, no return" analogue befits the businessman's view of economic life. For if one looks only at money, all he can see is that money just passes from one hand to another: except by a regrettable accident, it never gets out of the economic process. Perhaps the absence of any difficulty in securing raw materials by those countries where modern economics grew and flourished was yet another reason for economists to remain blind to this crucial economic factor. Not even the wars the same nations fought for the control of the world's natural resources awoke economists from their slumber.[2]

All in all, the wholesale attachment of almost every economist of the last one hundred years to the mechanistic dogma is still a historical puzzle. Once, it is true, physicists, mathematicians, and philosophers were one in singing the apotheosis of mechanics as the highest triumph of human reason. But by the time Jevons and Walras began laying the cornerstones

[2] To top all the intriguing facts of this history: not more than six years before Jevons published his pathbreaking *Lectures*, he wrote a highly interesting analysis of the consequences for Great Britain of a speedy depletion of her coal reserves. W. Stanley Jevons, *The Coal Question*, ed. A. W. Flux (3rd edn., London, 1906), originally published in 1865, was Jevons' first major work in economics.

of modern economics, a spectacular revolution in physics had already brought the downfall of the mechanistic dogma both in the natural sciences and in philosophy. And the curious fact is that none of the architects of "the mechanics of utility and self-interest" and even none of the latter-day model builders seem to have been aware at any time of this downfall. Otherwise, one could not understand why they have clung to the mechanistic framework with the fervor with which they have. Even an economist of Frank H. Knight's philosophical finesse not long ago referred to mechanics as "the sister science" of economics.[3]

Revolution is a fairly recurrent state in physics. The revolution that interests us here began with the physicists' acknowledging the elementary fact that heat always moves by itself in one direction only, from the hotter to the colder body. This led to the recognition that there are phenomena which cannot be reduced to locomotion and hence explained by mechanics. A new branch of physics, thermodynamics, then came into being and a new law, the Entropy Law, took its place alongside—rather opposite to—the laws of Newtonian mechanics.

From the viewpoint of economic science, however, the importance of this revolution exceeds the fact that it ended the supremacy of the mechanistic epistemology in physics. The significant fact for the economist is that the new science of thermodynamics began as a physics of economic value and, basically, can still be regarded as such. The Entropy Law itself emerges as the most economic in nature of all natural laws. It is in the perspective of these developments in the primary science of matter that the fundamentally nonmechanistic nature of the economic process fully reveals itself. As I have argued in the introductory essay of my *Analytical Economics*, only an analysis of the intimate relationship between the Entropy Law and the economic process can bring to the surface those decisively qualitative aspects of this process for which the mechanical analogue of modern economics has no room. The object of that essay—to examine this relationship with a view to filling a conspicuous lacuna of the economic discipline—will be pursued in this volume with greater detail and in more varied directions.

The fact that a natural law is involved in every aspect of man's behavior is so common that we would not expect the study of the influence of the Entropy Law on man's economic actions to present any unusual complications. Yet manifold avenues open up almost as soon as one begins to tackle the problem. What is more, these avenues lead beyond the boundary

[3] Frank H. Knight, *The Ethics of Competition* (New York, 1935), p. 85.

not only of economics but of the social sciences as well. And if one endeavors to explore them however cursorily, one discovers that issues which are generally considered to be specific to economics (or to the social sciences) spring up even in some areas of the natural sciences. Any searcher would find it hard to close his eyes to such an exciting vista and proceed undisturbed with his ordinary business.

It goes without saying that to undertake a project of this nature requires venturing into territories other than one's own, into fields in which one is not qualified to speak. The most one can do in this situation is to build on the writings of the consecrated authorities in every alien field and, for the reader's sake, to suppress no reference to any source (notwithstanding the current literary wisdom to minimize the number of footnotes or even to do away with them altogether). Even so, one runs some substantial risks. Yet the project is definitely worth undertaking. It reveals that the relationship between the economic process and the Entropy Law is only an aspect of a more general fact, namely, that this law is the basis of the *economy* of life at all levels. There are also some epistemological object lessons to be learned from the same analysis, all converging to one general conclusion which should interest every scientist and philosopher, not only the student of life phenomena (as the economist is). This conclusion is that in actuality only locomotion is qualityless and ahistorical: everything else is Change in the fullest sense of the word.

To some, the term "entropy" may seem esoteric. Once it was, but now it is becoming increasingly popular in one field after another. What should now give us reason for concern in meeting the term is the fact that its meaning varies substantially, at times even within the same domain of intellectual endeavor. In *Webster's Collegiate Dictionary* alone we find four distinct entries under "entropy." In part, this situation reflects the most unusual history of the Entropy Law, continuously punctuated by celebrated controversies, not all dead yet. In view of the confusion which has accumulated in some quarters, a preliminary survey to contrast the main meanings of "entropy" may prove useful even for the reader already familiar with some of them.

There is, first, the original meaning with which "entropy" was introduced more than one hundred years ago by the German physicist Rudolf Clausius. This meaning is grounded in a bedrock of physical facts. All other meanings constitute a separate category that stands in opposition to it. These are related in a purely formal way to a simple algebraic formula which is the cloak under which "entropy" is now becoming familiar to an increasing number of social scientists. Just recently, the term—with such a formal meaning—was brought within the economist's field of vision by the invitation to include a special "theory of information" in his tool box.[4]

The physical concept is generally judged to be quite intricate. If we take the word of some specialists, not even all physicists have a perfectly clear understanding of what this concept exactly means. Its technical details are, indeed, overwhelming. And even a dictionary definition suffices to turn one's intellectual curiosity away: "a measure of the unavailable energy in a closed thermodynamic sytem so related to the state of the system that a change in the measure varies with change in the ratio of the increment of heat taken in to the absolute temperature at which it is absorbed."[5] All this does not alter the fact that the nature of most thermodynamic phenomena is so simple that the layman may grasp the concept of entropy in its broad lines without much difficulty.

Let us take the case of an old-fashioned railway engine in which the heat of the burning coal flows into the boiler and, through the escaping steam, from the boiler into the atmosphere. One obvious result of this process is some mechanical work: the train has moved from one station to another. But the process involves other undeniable changes as well. To wit, the coal has been transformed into ashes. Yet one thing is certain: the total quantity of matter and energy has not been altered. That is the dictate of the Law of the Conservation of Matter and Energy—which is the First Law of Thermodynamics and which, we should stress, *is not* in contradiction with any of the laws of mechanics. The conclusion can only be that the change undergone by matter and energy must be a *qualitative* change.

At the beginning, the chemical energy of the coal is *free*, in the sense that it is *available* to us for producing some mechanical work. In the process, however, the free energy loses this quality, bit by bit. Ultimately, it always dissipates completely into the whole system where it becomes *bound* energy, that is, energy which we can no longer use for the same purpose. To be sure, the complete picture is more involved. And in fact, the merit of the introduction of entropy as a new variable of state lies precisely in the analytical simplification and unification achieved thereby. Even so, the other, more intuitive concepts of free and bound energies have never lost their transparent significance. For, in a broad yet substantive perspective, entropy is an index of the relative amount of bound energy in an isolated structure or, more precisely, of how evenly the energy is distributed in such a structure. In other words, *high* entropy means a structure in which most or all energy is bound, and *low* entropy, a structure in which the opposite is true.

The common fact that heat always flows by itself from the hotter to the

[4] H. Theil has devoted a whole volume to expounding this particular idea. See his *Economics and Information Theory* (Chicago, 1967).

[5] *Webster's Seventh New Collegiate Dictionary.*

colder body, never in reverse, came to be generalized by the Entropy Law, which is the Second Law of Thermodynamics and which *is* in contradiction with the principles of Classical mechanics. Its complete enunciation is incredibly simple. All it says is that the entropy of the universe (or of an isolated structure) increases constantly and, I should like to add, irrevocably. We may say instead that in the universe there is a *continuous* and *irrevocable* qualitative degradation of free into bound energy. Nowadays, however, one is more likely to come across a modern interpretation of this degradation as a continuous turning of *order* into *disorder*. The idea is based on the observation that free energy is an ordered structure, while bound energy is a chaotic, disordered distribution.

In rounding out this picture, we should note that the full meaning of the Entropy Law is not that the qualitative degradation occurs only in connection with mechanical work performed consciously by some intelligent beings. As exemplified by the sun's energy, the entropic degradation goes on by itself regardless of whether or not the free energy is used for the production of mechanical work. So, the free energy of a piece of coal will eventually degrade into useless energy even if the piece is left in its lode.

There are some good reasons why I stress (here as well as in some chapters of this volume) the irrevocability of the entropic process. One reason interests the economist in particular. If the entropic process were not irrevocable, i.e., if the energy of a piece of coal or of uranium could be used over and over again ad infinitum, scarcity would hardly exist in man's life. Up to a certain level, even an increase in population would not create scarcity: mankind would simply have to use the existing stocks more frequently. Another reason is of more general interest. It concerns one of man's weaknesses, namely, our reluctance to recognize our limitations in relation to space, to time, and to matter and energy. It is because of this weakness that, even though no one would go so far as to maintain that it is possible to heat the boiler with some ashes, the idea that we may defeat the Entropy Law by bootlegging low entropy with the aid of some ingenious device has its periodical fits of fashion. Alternatively, man is prone to believe that there must exist some form of energy with a self-perpetuating power.[6]

It must be admitted, though, that the layman is misled into believing in entropy bootlegging by what physicists preach through the new science known as statistical mechanics but more adequately described as statistical thermodynamics. The very existence of this discipline is a reflection of the fact that, in spite of all evidence, man's mind still clings with the

[6] As Jevons reports (*Coal Question*, pp. 106 f), in his own time many thought that electricity has such a power. My personal experience suggests that some economists (at least) now believe that atomic energy fits the case.

tenacity of blind despair to the idea of an actuality consisting of locomotion and nothing else. A symptom of this idiosyncrasy was Ludwig Boltzmann's tragic struggle to sell a thermodynamic science based on a hybrid foundation in which the rigidity of mechanical laws is interwoven with the uncertainty specific to the notion of probability. Boltzmann took his life in bitterness over the mounting criticism of his idea. But after his death, the same human idiosyncrasy induced almost everyone to trample over all logical flaws exposed by that criticism so that Boltzmann's idea might become a recognized branch of physics. According to this new discipline, a pile of ashes may very well become capable of heating the boiler. Also, a corpse may resuscitate to lead a second life in exactly the reversed order of the first. Only, the probabilities of such events are fantastically small. If we have not yet witnessed such "miracles"—the advocates of statistical mechanics contend—it is only because we have not been watching a sufficiently large number of piles of ashes or corpses.

In contrast with Classical thermodynamics, even a summary discussion of statistical thermodynamics cannot do without numerous technical points, some of them highly technical. Boltzmann's main premise, however, has to be brought into the picture even at this stage. This premise is that, aside from a factor representing a physical constant, the entropy of an isolated gas of N molecules is given by the formula

$$\text{Entropy} = S = \ln W, \tag{1}$$

where

$$W = \frac{N!}{N_1!\,N_2!\cdots N_s!} \tag{2}$$

and the N_i's represent the distribution of the gas molecules among the s possible states. And since the combinatorial coefficient W is a familiar sight in the calculus of probabilities, relation (1) has been translated as "entropy is equal to the thermodynamic probability."

In this way, Boltzmann's approach opened the door to an almost endless series of interpretations of what entropy means and, concomitantly, to different formal definitions of the term. Some of the disciples of this approach have gone so far as to deny that the Entropy Law expresses a natural law. Instead, they maintain, it reflects only the difficulty of the human mind in describing a state which involves an increasing number of details. Certainly, these are muddled waters in which any user of the term "entropy" should navigate carefully.

If we take formula (1) as a formal definition of entropy, we may bring this concept into any situation with which W can be associated in some way or another. For a telling example, let us consider five distinct points in a plane. If we put $N = 5$, $N_1 = 2$, and $N_2 = 3$, then W gives the maximum number of distinct straight lines determined by these points. We may therefore speak of

$$S = \log_{10} \frac{5!}{2!\,3!} = 1 \tag{3}$$

as the "entropy of a pentagon." This shows how easy it is to concoct meanings of "entropy" that are wholly vacuous.

However, the emergence of (1) in problems connected with the transmission of sequences of signals (or symbols) is a normal event that should not surprise us: if the number of distinct signals is s, then W is the number of distinct sequences of length N in which each i-th symbol enters N_i times. What should surprise us is that S has been equated with the *amount of information* contained in such a sequence. According to this equation, if we take, say, Newton's *Principia Mathematica* and scramble its letters and symbols, the result still represents the same amount of information! Even more perplexing is a subsequent argument by which the total information is identified with *negentropy* (i.e., the negative value of *physical* entropy).

The concept of entropy has even penetrated into domains in which there is no room for combinatorial analysis and, hence, for W. This is due to the fact that the most popular definition of the concept as a "measure" of the amount of information is given by a special transformation of (1). The definition is[7]

$$E = -\sum f_i \log f_i \tag{4}$$

where $f_i > 0$ for every i and $\sum f_i = 1$.

This expression has several interesting properties which account for the attraction it has exercised on many minds. But its most interesting feature is that we can apply it to any percental distribution—say, the distribution of a country's exports by destinations or of personal incomes by income brackets. It is by such a complicated metamorphosis, of which not all users of the term "entropy" may be aware, that we have come to speak of the *amount of information* of almost any statistical data. And we march on, without even noticing that this terminological mess compels us to say, for instance, that for a country in which income is more equally distributed the statistics of income distribution contains a greater amount of information![8]

[7] This transformation assumes that every N_i is large enough for $N_i!$ to be approximated by Stirling's formula. This formula is reproduced in Appendix G, note 29, in this volume.

[8] This statement follows from the fact that the property unmistakably reflected by E is the degree of evenness (indirectly, the degree of concentration) of the distribution described by the f_i's. Cf. Appendix B in this volume.

The code of Humpty Dumpty—which allows one to use a word with any meaning one wishes—is much too often invoked as a supreme authority on terminological prerogative. But nobody seems to have protested that ordinarily the only consequence of this prerogative is confusion. An advertising tendency may have been the father to denoting the numerical value of expressions such as (1) or (4) by "amount of information." Be this as it may, this terminological choice is probably the most unfortunate in the history of science.

One can now see why it is imperative to emphasize that the position taken in the present study is that in the physical world there is a coordinate which corresponds to Clausius' concept of entropy and which is not reducible to locomotion, much less to probability or to some subjective element. Another way of saying the same thing is that the Entropy Law is neither a theorem deducible from the principles of Classical mechanics nor a reflection of some of man's imperfections or illusions. On the contrary, it is as independent a law as, for example, the law of universal attraction, and just as inexorable. The entropic phenomenon of a piece of coal burning irrevocably into ashes is neither a flow of probability from a lower to a higher value, nor an increase in the onlooker's ignorance, nor man's illusion of temporal succession.

As we shall gradually come to realize in the course of this volume, the position occupied by the Entropy Law among all other laws of nature is unique from numerous viewpoints. And this fact accounts for the wealth of questions and issues that overwhelm any student interested in assessing the importance of the Entropy Law beyond the strictly physical domain.

No one would deny that entropy, together with its associated concepts of free and bound energies, is a much more mysterious notion than locomotion. The only way man can consciously act on the material environment is by pushing or pulling, even when he starts a fire. But this limitation is no reason for clinging to the idea that the entropic process must be reducible to locomotion. Monism has long since ceased to be the password in science. Even the argument that science must be free of any contradiction is no longer commanding. Physics itself now teaches us that we must not insist on molding actuality into a noncontradictory framework. Just as we are advised by Niels Bohr's Principle of Complementarity that we must accept as a brute fact that the electron behaves both as a wave and as a particle—concepts irreducible to one another—so must we at present reconcile ourselves to the existence of thermodynamic and mechanical phenomena side by side, albeit in opposition.

From the epistemological viewpoint, the Entropy Law may be regarded as the greatest transformation ever suffered by physics. It marks the recognition by that science—the most trusted of all sciences of nature—that there is qualitative change in the universe.[9] Still more important is the fact that the irrevocability proclaimed by that law sets on a solid footing the commonsense distinction between locomotion and true happening. According to this distinction, only that which cannot be brought back by reverse steps to a previous state represents true happening. What "happening" thus means is best exemplified by the life of an organism or the evolution of a species (as distinct from mere mutational changes, which *are* reversible). This opposition between true happening and locomotion is likely to be censured as an anthropomorphic idea. In fact, positivistic purists have denounced thermodynamics itself as an anthropomorphic amalgam. One writ contends that even Time is only man's illusion, and hence there is no sense in speaking of reversibility or irreversibility of natural phenomena. On the other hand, there is no denying that it was the importance which the distinction between free and bound energy has for man's economy of mechanical power that set thermodynamics going. Yet it would be utterly wrong to maintain that only thermodynamics is in this situation. Locomotion, particle, wave, and equation, for example, are concepts no less anthropomorphic than the two faces of entropy, the two qualities of energy. The only difference is that of all sciences of inert matter thermodynamics is the nearest to man's skin—literally, not figuratively.

We know that people can live even if deprived of sight, or of hearing, or of the sense of smell or taste. But we know of no one able to live without the feeling of the entropy flow, that is, of that feeling which under various forms regulates the activities directly related with the maintenance of the physical organism. In the case of a mammal this feeling includes not only the sensations of cold and warm, but also the pangs of hunger and the contentment after a meal, the feeling of being tired and that of being rested, and many others of the same kind.[10] Things are not stretched therefore if one argues that the entropic feeling, in its conscious and unconscious manifestations, is the fundamental aspect of life from amoeba to man.

Be this as it may, the fact is that the material basis of life is an entropic process. As Erwin Schrödinger crystallized this idea, any life-bearing structure maintains itself in a quasi-steady state by sucking low entropy from the environment and transforming it into higher entropy. Some

[9] By now this notion is no longer a rarity in the science of elementary matter. The two presently contending speculations in cosmology speak even of creation—one by arguing that the universe was created by a Big Bang, the other, that matter is continuously created and annihilated.

[10] On the basis of the above definition, one should expect that the "senses" of taste and smell cannot be absent at the same time.

writers—the French philosopher Henri Bergson, in particular—even contended that life actually opposes the trend of qualitative degradation to which inert matter is subject. Think of the nucleus of some primeval strain of amoeba which may still be around in its original pattern. No inert structure of as many molecules can boast the same tour de force—to resist the disrupting work of the Entropy Law for perhaps as long as two billion years.

The thought that life may be "characterized by a capacity for evading this law"—once generally denounced as sheer obscurantism—is now endorsed by almost every authority in physicochemistry.[11] It is nonetheless true that, if expressed in this terse form, the thought may easily be distorted. A living being can evade the entropic degradation of its own structure only. It cannot prevent the increase of the entropy of the whole system, consisting of its structure and its environment. On the contrary, from all we can tell now, the presence of life causes the entropy of a system to increase faster than it otherwise would.

The truth of the last point is especially evident in the case of the human species. Actually, hardly anything need be added now to make us see also that the economic struggle is only about low entropy and that the nature of the economic process viewed as a whole is purely entropic. Yet, among the economists of distinction, only Alfred Marshall intuited that biology, not mechanics, is the true Mecca of the economist. And even though Marshall's antimechanistic proclivities were reflected mainly in his famous biological analogies, we must impute to them his salient discovery of the irreversibility of long-run supply schedules. Unfortunately, Marshall's teaching caused no lasting imprint and the fact that irreversibility is a general feature of all economic laws received no attention.

Lacking Marshall's understanding, economists have seen no point in following the developments in biology and have thus missed many fertile ideas. This is the case with the highly interesting way in which Alfred J. Lotka, a physical biologist, explained why the economic process is a continuation of the biological one. In the last process—Lotka pointed out—man, like any other living creature, uses only his *endosomatic* instruments, i.e., the instruments that are part of each individual organism by birth. In the economic process man uses also *exosomatic* instruments—knives, hammers, boats, engines, etc., which he produces himself. Lotka's framework will help us understand why only the human species is subject to an irreducible social conflict.

A peculiar feature of the determinative powers of the Entropy Law is

[11] The above quotation from Sir James Jeans, *The New Background of Science* (New York, 1934), p. 280, is one among numerous such endorsements.

responsible for the fact that the relationship between this law and the domain of life phenomena is yet deeper than the facts just mentioned reveal. Geometry (conceived in its etymological sense), astronomy, and Classical mechanics accustomed us to the power of science to determine "exactly" where and when a definite event will take place. Later, quantum phenomena taught us to be content with the weaker position in which scientific laws determine merely the probability of an occurrence. But the Entropy Law constitutes a singular case. It determines neither *when* (by clock-time) the entropy of a closed system will reach a certain level nor exactly *what* will happen.[12] In spite of this drawback (and contrary to what some have contended), the Entropy Law is not idle: it does determine the general direction of the entropic process of any isolated system.

But the drawback acquires a momentous importance in connection with the fact that the only other thermodynamic law to bear upon an entropic process is the Law of the Conservation of Matter and Energy.[13] This means that all we can say about such a process is that, as time goes by, its total energy remains constant while the distribution of this energy becomes more even. The thermodynamic principles, therefore, leave some substantial freedom to the actual path and the time schedule of an entropic process. According to the position taken in this study about the nature of thermodynamic phenomena, this freedom is not to be confused with random uncertainty. We may refer to it as the *entropic indeterminateness*.

This is an extremely important feature of actuality. For without the entropic indeterminateness it would not be possible for a living creature to maintain its entropy constant. Nor would it be possible for man to "reverse" entropy from high to low, as in the production of steel from iron ore and coal. Above all, it would be impossible for the living forms to go after environmental low entropy and use it in manners as strikingly diverse as that of a bacterium, a lobster, a butterfly, a tumbleweed, a *Homo sapiens*, and so on down the potentially limitless list. We must, however, recognize that this indeterminateness by itself does not ensure the existence of the infinitude of forms and functions displayed by the organic domain. In point of fact, it does not even ensure the existence of any living being whatsoever. The existence of life-bearing structures is a primary fact that must be postulated, just as we do for other "mysterious" components of actuality—say, space or matter.

But even with this postulate we cannot explain why the room left by the

[12] The first point follows directly from the simple enunciation of the law, the second from the fact that the entropy is only an average index of the distribution of the total energy within a system.

[13] In addition to the two laws already mentioned, there is only one other fundamental law of thermodynamics, Nernst's Law, which in essence says that the minimum of entropy is not achievable in actuality.

entropic indeterminateness is filled with numberless species and varieties instead of one single form. For the material structure of any living being must obey not only the laws of thermodynamics but also every other law of inert matter. And if we look beyond thermodynamics we see, first, that Classical mechanics leaves nothing indeterminate, and second, that the freedom allowed by quantum mechanics is limited only to random, not to permanent, variations. It would seem, therefore, that the variability of living creatures is still a puzzle. Yet the puzzle has a solution, which is provided by a fundamental, albeit unremarked, principle: *the emergence of novelty by combination.*

The meaning of this principle is as simple as it is unmistakable. Most of the properties of water, for example, are not deducible by some universal principles from the elemental properties of its components, oxygen and hydrogen; with respect to the latter properties, the former are therefore novel. The principle is at work everywhere with a degree of diversity that increases constantly from the physics of the atom in the inorganic field to the social forms in the superorganic domain. In view of all this, the oft quoted statement that "living organisms are the greatly magnified expressions of the molecules that compose them"[14] appears as one of the most inept slogans of the aggressive scholarship for which this half of the century will pass down into history. If the statement were true, then also a molecule should be only the expression of the elementary particles that compose it, and a society the expression of the biological organisms of its members. Telescoping all this, we reach the conclusion that societies, organisms, molecules, and atoms are only the expressions of elementary particles. But then, one should not study biomolecules either. One should study only elementary particles by themselves!

Of course, we should study molecules, not only those of organisms but wherever we find them. But, at the same time, we should not fail to see that, because of the novelty created by combination, the properties of molecules qua molecules cannot enable us to know how organisms, too, behave or, more generally, how a molecule will behave in relation to any other molecule. For one of the numerous topical examples: did the study of thalidomide by itself at the molecular level enable us to foresee the novelties produced by that substance in contact with every kind of molecule of the human organism? Science is not served if we do not recognize

[14] The original statement is in George Wald, "Phylogeny and Ontogeny at the Molecular Level," in *Proceedings of the Fifth International Congress of Biochemistry*, vol. III, *Evolutionary Biochemistry*, ed. A. I. Oparin (New York, 1963), p. 12. I should hasten to add that perhaps Wald himself does not embrace it wholly. Witness, as one example, his statement that "It is the bargain that the whole organism strikes with its environment, in competition with its neighbors, that decides its fate; and that fate is then shared by its molecules, including its genetic DNA." *Ibid.*, p. 13.

that the properties of an electron (or of any of the manifold elementary particles) must include every property of a material structure, inert or living. The basis of knowledge cannot be reduced to either the whole alone or to the parts by themselves.[15] The biologist must study molecules and cells and organisms, just as the economist must study the economic units and the entire economies.

Even though the relevance of the two principles just outlined—the entropic indeterminateness and the novelty by combination—is far greater for the world of life phenomena than for that of mere matter, we must not forget that their roots are in the last phenomenal domain. It is all the more interesting, therefore, that these principles inevitably invite us to take a new look at some other issues which are generally regarded as spuriously generated by the biologists and social scientists of the so-called romantic school.

One such issue is the myth that science is measurement, that beyond the limits of theory there is no knowing at all. "Theory" is here taken in its discriminating meaning: a filing of all descriptive propositions within a domain in such a way that every proposition is derived by Logic (in the narrow, Aristotelian sense) from a few propositions which form the logical foundation of that science. Such a separation of all propositions into "postulates" and "theorems" obviously requires that they should be amenable to logical sifting. And the rub is that Logic can handle only a very restricted class of concepts, to which I shall refer as *arithmomorphic* for the good reason that every one of them is as discretely distinct as a single number in relation to the infinity of all others. Most of our thoughts, however, are concerned with forms and qualities. And practically every form (say, a leaf) and every quality (say, being reasonable) are *dialectical* concepts, i.e., such that each concept and its opposite overlap over a contourless penumbra of varying breadth.

The book of the universe simply is not written as Galileo claimed—only "in the language of mathematics, and its characters are triangles, circles, and other geometrical figures."[16] In the book of physics itself we find the most edifying dialectical concept of all: probability. And no book about the phenomena of life can dispense with such basic yet dialectical concepts as species, want, industry, workable competition, democracy, and so on. It would be, I maintain, the acme of absurdity to decree that no such book be written at all or, if it is written, that it simply disseminates nonsense.

[15] Wald's statement quoted in the preceding note illustrates this point splendidly.

[16] Galileo Galilei, *Il Saggiatore*, in *The Controversy on the Comets*, trs. S. Drake and C. D. O'Malley (Philadelphia, 1960), p. 184.

Lest this position is misinterpreted again by some casual reader, let me repeat that my point is *not* that arithmetization of science is undesirable. Whenever arithmetization can be worked out, its merits are above all words of praise. My point is that wholesale arithmetization is impossible, that there is valid knowledge even without arithmetization, and that mock arithmetization is dangerous if peddled as genuine.

Let us also note that arithmetization alone does not warrant that a theoretical edifice is apt and suitable. As evidenced by chemistry—a science in which most attributes are quantifiable, hence, arithmomorphic—novelty by combination constitutes an even greater blow to the creed "no science without theory." A theoretical edifice of chemistry would have to consist of an enormous foundation supporting a small superstructure and would thus be utterly futile. For the only *raison d'être* of theory is economy of thought, and this economy requires, on the contrary, an immense superstructure resting on a minute foundation.

Still another issue that becomes immediately salient against the background sketched so far is that of determinism, which interests us here because of its bearing upon the power of science to predict and manipulate.

For some time now, physicists have been telling us that an atom of radium explodes, not when something causes it to do so, but when it likes. However, the complete story is that the frequency of explosions has a *dialectical* stability and this stability enables us to predict at least the behavior of radium in bulk. The point is that the strongest limitation to our power to predict comes from the entropic indeterminateness and, especially, from the emergence of novelty by combination. These are the most important reasons why our prehensions of nature cannot be reduced to the efficient cause as we know it from Aristotle.

In the case of novelty by combination (of contemporaneous or consecutive elements), things simply happen, without either a *causa efficiens* or a *causa finalis*. What is more, the most numerous and basic elements of our knowledge belong to this category. Their truth can be justified by repeated observations, not by ratiocination, nor by relating them to a purpose. Naturally, an intelligent being who has never witnessed oxygen and hydrogen combining into a substance having the properties of water would regard that reaction as somewhat of a mystery after he is confronted with it once only. By the same token, evolution appears so mysterious to us only because man is denied the power of observing other planets being born, evolving, and dying away. And it is because of this denial that no social scientist can possibly predict through what kinds of social organizations mankind will pass in its future. To be sure, our knowledge constantly advances, but at any one time it can encompass only part of the Whole. Moreover, this advance is such that multifarious new questions grow out of every solved problem.

In this situation, we must not insist on asking always "why." For some problems we may achieve a greater insight if we ask "for what purpose." Even biologists bent on avoiding anything that might smack of vitalism admit that there is some advantage in classifying some biological phenomena as quasi finalistic. But this verbalist legerdemain may do only for other species than man. Man knows (and by the most direct way) that a *causa finalis*, not a *causa efficiens*, makes him work for an academic degree or save for old age. To deny that man, in his deliberate actions, is animated by a purpose would be a flight from truth. The recurrent writer who announces that his purpose is to prove that the concept of purpose is a bogey constitutes—as Whitehead amusingly observed—a highly interesting subject of study.

Actually, the sorry plight of the student of a contemporary society may be mitigated only by an empathic interpretation of its propensities and its mood, a task that cannot be delegated to any instrument. Only a human mind can find out what other men feel and what their purposes are. And only in this way can a student determine at least the broad direction of the immediate social trend.

The verdict is indisputable: no social science can subserve the art of government as efficaciously as physics does the art of space travel, for example. Nevertheless, some social scientists simply refuse to reconcile themselves to this verdict and, apparently in despair, have come out with a curious proposal: to devise means which will compel people to behave the way "we" want, so that "our" predictions will always come true. The project, in which we recognize the continual striving for a "rational" society beginning with Plato's, cannot succeed (not even under physical coercion, for a long time) simply because of its blatant *petitio principii:* the first prerequisite of any plan is that the behavior of the material involved should be completely predictable, at least for some appreciable period.

But aggressive scholarship will never run out of new plans for the "betterment of mankind." Since the difficulties of making an *old* society behave as we want it can no longer be concealed, why not produce a *new* society according to our own "rational" plans? Some molecular biologists even assure us that our ability to produce "Einsteins from cuttings" is around the corner. But they close their eyes to many elementary obstacles, among which are the supercosmic dimensions of some aspects of the problem and the novelty by combination. Most interesting of all, they do not even seem to suspect that a society made only of geniuses, nay, of people fit only for an intellectual occupation, could not live even for one day. On the other hand, if the man-made society includes also a "productive" class, the inevitable social conflict between the two classes will stop that society from being "rational" (unless the same biological wizards can remodel the human species after the genetic pattern of the social insects).

Many an economist has indirectly alluded to the First Law of Thermodynamics by noting that man can produce neither matter nor energy. But even Irving Fisher—who was first a pupil of J. Willard Gibbs, one of the founders of statistical thermodynamics—did not perceive that the Entropy Law is still more important for the economic process. One of the pioneers of econometrics, Harold T. Davis, seems to be alone in seeking to establish a formal similarity between the fundamental thermodynamic equations and some equations used in economic models. He considered the budget equations of macroanalysis and suggested that the utility of money represents economic entropy.[17] But as J. H. C. Lisman noted later in commenting on Davis' solitary attempt,[18] none of the variables used in the mathematical economic models seems to play the same role as entropy in thermodynamics. In the light of the ideas developed in the preceding pages, this conclusion is inevitable: in a mechanical analogue nothing could correspond to the concept that opposes thermodynamics to mechanics.

Instead of looking for a thermodynamic homology in the usual mathematical systems of economics, we may now try to represent the economic process by a new system of equations patterned after that of thermodynamics. In principle, we can indeed write the equations of any given production or consumption process (if not in all technical details at least in a global form). Next, we may either assemble all these equations into a gigantic system or aggregate them into a more manageable one. But to write any set of the initial equations, we must know the exact nature of the individual process to which it refers. And the rub is that in the long run or even in the not too long run the economic (as well as the biological) process is inevitably dominated by a qualitative change which cannot be known in advance. Life must rely on novel mutations if it is to continue its existence in an environment which it changes continuously and irrevocably. So, no system of equations can describe the development of an evolutionary process. If it were not so, biologists (who have long since put thermodynamics to good work) would have already come out with a vast system to represent the course of the biological process until doomsday.

The representation of a *given* production or consumption process by its

[17] Harold T. Davis, *The Theory of Econometrics* (Bloomington, 1941), pp. 171–176.

[18] J. H. C. Lisman, "Econometrics and Thermodynamics: A Remark on Davis' Theory of Budgets," *Econometrica*, XVII (1949), 59–62.

thermodynamic system may aid an engineer, perhaps a management expert as well, in deciding which process may be more efficient in entropic terms. But the way in which the acknowledgment of the entropic nature of the economic process may enlighten the economist as a student of man is not through a mathematical system which reduces everything to entropy. Man, we should not forget, struggles for entropy but not for just any form of it. No man can use the low entropy of poisonous mushrooms and not all men struggle for that contained in seaweed or beetles.

Nor does the intimate connection between the Entropy Law and the economic process aid us in managing a *given* economy better. What it does is, in my opinion, much more important. By improving and broadening our understanding of the economic process, it may teach to anyone willing to listen what aims are better for the economy of mankind.

The simple fact that from the purely physical viewpoint the economic process is not a mechanical analogue forces upon us a thorny question of fundamental importance for science in general. What is "process" and how can we represent it analytically? The answer uncovers some unsuspected omissions in both Neoclassical and Marxist analyses of production. It also enables us to arrive at an equation of value (we should rather say "quasi equation") against which we can project, compare, and evaluate all doctrines of value propounded so far. This equation settles some points of the controversy-torn problem of value.

Since the economic process materially consists of a transformation of low entropy into high entropy, i.e., into waste, and since this transformation is irrevocable, natural resources must necessarily represent one part of the notion of economic value. And because the economic process is not automatic, but willed, the services of all agents, human or material, also belong to the same facet of that notion. For the other facet, we should note that it would be utterly absurd to think that the economic process exists only for producing waste. The irrefutable conclusion is that the true product of that process is an immaterial flux, the enjoyment of life. This flux constitutes the second facet of economic value. Labor, through its drudgery, only tends to diminish the intensity of this flux, just as a higher rate of consumption tends to increase it.

And paradoxical though it may seem, it is the Entropy Law, a law of elementary matter, that leaves us no choice but to recognize the role of the cultural tradition in the economic process. The dissipation of energy, as that law proclaims, goes on automatically everywhere. This is precisely why the entropy reversal as seen in every line of production bears the indelible hallmark of purposive activity. And the way this activity is planned and performed certainly depends upon the cultural matrix of the society in question. There is no other way to account for the intriguing differences between some developed nations endowed with a poor environment, on the one hand, and some underdeveloped ones surrounded by an abundance of natural riches. The exosomatic evolution works its way through the cultural tradition, not only through technological knowledge.

The Entropy Law does not help an economist to say what precisely will happen tomorrow, next year, or a few years hence. Like the aging of an organism, the working of the Entropy Law through the economic process is relatively slow but it never ceases. So, its effect makes itself visible only by accumulation over long periods. Thousands of years of sheep grazing elapsed before the exhaustion of the soil in the steppes of Eurasia led to the Great Migration. The Entropy Law enables us to perceive that a development of the same nature and of far greater consequences is running its full course now. Because of the pressure of population on agricultural land the area of which cannot be appreciably increased, man can no longer share the agricultural low entropy with his traditional companions of work, the beasts of burden. This fact is the most important reason why mechanization of agriculture must spread into one corner of the world after another, at least for a long time to come.

The Entropy Law also brings to the fore some fundamental yet ignored aspects of the two problems that now preoccupy the governed, the governments, and practically every scientist: pollution and the continuous increase of population.

It is natural that the appearance of pollution should have taken by surprise an economic science which has delighted in playing around with all kinds of mechanistic models. Curiously, even after the event economics gives no signs of acknowledging the role of natural resources in the economic process. Economists still do not seem to realize that, since the product of the economic process is waste, waste is an inevitable result of that process and *ceteris paribus* increases in greater proportion than the intensity of economic activity. That is why at this time pollution does not plague Tibet or Afghanistan, for instance. Had economics recognized the entropic nature of the economic process, it might have been able to warn its co-workers for the betterment of mankind—the technological sciences—that "bigger and better" washing machines, automobiles, and superjets must lead to "bigger and better" pollution. When contemporary scientists gather in symposia for finding a solution to the impasse, they do little besides blaming their predecessors for too aggressive a scholarship and too narrow a foresight. The future being for us as unpredictable as it is, one may only wonder what the future scientists will have to say about the aggressiveness and the foresight of the present generation.

The most extremist views of the literary group of Vanderbilt Fugitives, many of whom decried the effects of modern technology on the pastoral life of the countryside, would simply pale in comparison with those professed now by some members of the rising class of pollution experts. Other members seem to think that, on the contrary, mankind can simply get rid of pollution without any cost in low entropy provided we use only pollutionless industrial techniques—an idea that betrays the belief in the possibility of bootlegging entropy of which I spoke earlier. The problem of pollution is one of very, very long run and intimately connected with the way mankind is going to make use of the low entropy within its reach. It is this last problem that is the true problem of population.

It is fashionable nowadays to indulge in estimating how large a population our earth can support. Some estimates are as low as five billions, others as high as forty-five billions.[19] However, given the entropic nature of the economic process by which the human species maintains itself, this is not the proper way to look at the problem of population. Perhaps the earth can support even forty-five billion people, but certainly not ad infinitum. We should therefore ask "*how long* can the earth maintain a population of forty-five billion people?" And if the answer is, say, one thousand years, we still have to ask "what will happen *thereafter*?" All this shows that even the concept of optimum population conceived as an ecologically determined coordinate has only an artificial value.

There are even some dangers for the human species in narrowing the problem of population to how large a population can be maintained by A.D. 2000 or at any other time. The issue of population extends beyond A.D. 2000. Moreover, to have a maximum population at all times is definitely not in the interest of our species. The population problem, stripped of all value considerations, concerns not the parochial maximum, but the maximum of life quantity that can be supported by man's natural dowry until its complete exhaustion. For the occasion, life quantity may be simply defined as the sum of the years lived by *all* individuals, present and future.[20] Man's natural dowry, as we all know, consists of two essentially distinct elements: (1) the *stock* of low entropy on or within the globe, and (2) the *flow* of solar energy, which slowly but steadily diminishes in intensity with the entropic degradation of the sun. But the crucial point for the popula-

[19] To my knowledge, forty-five billions is the highest figure ever mentioned as a possible size of the world population. Its propounder is Colin Clark. See his "Agricultural Productivity in Relation to Population," in *Man and His Future*, ed. G. Wolstenholme (Boston, 1963), p. 35.

[20] It may be well to note that this total is independent, first, of when each individual lives, and second, of whether the same number of years are lived by one or several individuals. What individual average life span is optimal constitutes one of the many subsidiary issues.

tion problem as well as for any reasonable speculations about the future exosomatic evolution of mankind is the relative importance of these two elements. For, as surprising as it may seem, the entire stock of natural resources is not worth more than a few days of sunlight!

If we abstract from other causes that may knell the death bell of the human species, it is clear that natural resources represent the limitative factor as concerns the life span of that species. Man's existence is now irrevocably tied to the use of exosomatic instruments and hence to the use of natural resources just as it is tied to the use of his lungs and of air in breathing, for example. We need no elaborated argument to see that the maximum of life quantity requires the minimum rate of natural resources depletion. By using these resources too quickly, man throws away that part of solar energy that will still be reaching the earth for a long time after he has departed. And everything man has done during the last two hundred years or so puts him in the position of a fantastic spendthrift. There can be no doubt about it: any use of the natural resources for the satisfaction of nonvital needs means a smaller quantity of life in the future.[21] If we understand well the problem, the best use of our iron resources is to produce plows or harrows as they are needed, not Rolls Royces, not even agricultural tractors.

The realization of these truths will not make man willing to become less impatient and less prone to hollow wants. Only the direst necessity can constrain him to behave differently. But the truth may make us foresee and understand the possibility that mankind may find itself again in the situation in which it will find it advantageous to use beasts of burden because they work on solar energy instead of the earth's resources. It also exposes the futility of the human pride that overcame some scholars on learning that by A.D. 2000 we may be able to feed people with proteins derived from crude oil and thus solve the population problem completely and forever. Highly probable though this conversion is, we can rest assured that sometime, perhaps sooner than one may think, man will have to reorient his technology in the opposite direction—to obtain gasoline from corn, if he will still be around and using internal combustion engines. In a different way than in the past, man will have to return to the idea that his existence is a free gift of the sun.

[21] The distinction between vital and nonvital needs—I hasten to admit with pleasure—is a dialectical one. Certainly, to plow a corn field is a vital need, but to drive a Rolls Royce, not.