

References

- [1] CHAMBERLIN, EDWARD H., *The Theory of Monopolistic Competition*, 6th ed., Cambridge, Harvard University Press, 1948.
- [2] DORSEMAN, ROBERT, *Application of Linear Programming to the Theory of the Firm*, Berkeley, University of California Press, 1951.
- [3] FRISCH, RASNAK, *Theory of Production*, Chicago, Rand McNally, 1965.
- [4] GEORGESEN-ROEGEN, NICHOLAS, "Fixed Coefficients of Production and Marginal Productivity Theory," *Rev. Econ. Stud.* 3:40-49, Oct. 1935. Reprinted with a 1964 Postscript in Nicholas Georgesen-Roegen, *Analytical Economics: Issues and Problems*, Cambridge, Harvard University Press, 1966, pp. 279-299.
- [5] ———, Chapter 11 in this volume.
- [6] ———, Chapter 5 in this volume.
- [7] ———, Chapter 10 in this volume.
- [8] ———, "Chamberlin's New Economics and the Unit of Production," Ch. 2 in *Monopolistic Competition Theory: Studies in Impact*, ed. R. E. Kuenna, New York, John Wiley & Sons, Inc., 1967, pp. 31-62.
- [9] ———, Chapter 4 in this volume.
- [10] ———, *The Entropy Law and the Economic Process*, Cambridge, Harvard University Press, 1971.
- [11] LEFTWICH, RICHARD H., *The Price System and Resource Allocation*, rev. ed., New York, Holt, Rinehart and Winston, 1960.
- [12] MCLEOD, A. N., AND F. H. HAIN, "Proportionality, Divisibility, and Economics of Scale: Two Comments, I and II," *Quart. J. Econ.* 63:128-137, Feb. 1949.
- [13] ROBINSON, JOAN, *Economics of Imperfect Competition*, London, The Macmillan Company, 1933.
- [14] SAMURISON, PAUL A., *Foundations of Economic Analysis*, Cambridge, Harvard University Press, 1948.
- [15] ———, *Economics*, 8th ed., New York, McGraw-Hill Book Company, 1970.
- [16] STONIER, ALFRED W., AND DOUGLAS C. HAYNE, *A Textbook of Economic Theory*, 2nd ed., New York, Longmans, Green and Co., 1958.
- [17] WICKSTEAD, PHILIP, *An Essay on the Co-ordination of the Laws of Distribution*, (London, 1894), Reprints of Scarce Tracts, No. 12, London School of Economics and Political Science, London, 1932.

CHAPTER 3

(1970)

The Entropy Law and the Economic Problem

I

II

A curious event in the history of economic thought is that, years after the mechanistic dogma had lost its supremacy in physics and its grip on the philosophical world, the founders of the Neoclassical school set out to erect an economic science after the pattern of mechanics—in the words of Jevons, as "*the mechanics of utility and self-interest*." And while economics has made great strides since, nothing has happened to deviate economic thought from the mechanistic epistemology of the forefathers of standard economics. A glaring proof is the standard textbook representation of the economic process by a circular diagram, a pendulum movement between production and consumption within a completely closed system.² The situation is not different with the analytical pieces that adorn the standard economic literature; they, too, reduce the economic process to a self-sustained mechanical analogue. The patent fact that between the economic process and the material environment there exists a continuous mutual influence which is history-making carries no weight with the standard economist. And the same is true of Marxist economists, who swear by Marx's dogma that everything nature offers man is a spontaneous gift.³ In Marx's famous diagram of reproduction, too, the economic process is represented as a completely circular and self-sustaining affair.⁴

Earlier writers, however, pointed in another direction, as did Sir William Petty in arguing that labor is the father and nature is the mother of wealth.⁵ The entire economic history of mankind proves beyond question that nature, too, plays an important role in the economic process as well as in the formation of economic value. It is high time, I believe, that we should accept this fact and consider its consequences for the economic problem of mankind. For, as I shall endeavor to show in this paper, some of these consequences have an exceptional importance for the understanding of the nature and the evolution of man's economy.

Some economists have alluded to the fact that man can neither create nor destroy matter or energy—a truth which follows from the Principle of Conservation of Matter-Energy, alias the First Law of Thermodynamics. Yet no one seems to have been struck by the question—so puzzling in the light of this law—"what then does the economic process do?" All that we find in the cardinal literature is an occasional remark that man can produce only utilities, a remark which actually accentuates the puzzle. How is it possible for man to produce something material, given the fact that he cannot produce either matter or energy?

To answer this question, let us consider the economic process as a whole and view it only from the purely physical viewpoint. What we must note first of all is that this process is a partial process which, like all partial processes, is circumscribed by a boundary across which matter and energy are exchanged with the rest of the material universe.⁶ The answer to the question of what this material process does is simple: it neither produces nor consumes matter-energy; it only absorbs matter-energy and throws it out continuously. This is what pure physics teaches us. However, economists—let us say it high and loud—is not pure physics, not even physics in some other form. We may trust that even the fiercest partisan of the position that natural resources have nothing to do with value will admit in the end that there is a difference between what goes into the economic process and what comes out of it. To be sure, this difference can be only qualitative.

An unorthodox economist—such as myself—would say that what goes into the economic process represents *valuable natural resources* and what is thrown out of it is *valueless waste*. But this qualitative difference is confirmed, albeit in different terms, by a particular (and peculiar) branch of physics known as thermodynamics.

From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of *low entropy* and comes out of it in a state of *high entropy*."

To explain in detail what entropy means is not a simple task. The notion is so involved that, to trust an authority on thermodynamics, it is "not easily understood even by physicists."¹⁰ To make matters worse not only for the layman, but for everyone else as well, the term now circulates with several meanings, not all associated with a physical coordinate.¹¹ A recent edition of *Weber's Collegiate Dictionary* (1965) has three entries under "entropy." Moreover, the definition pertaining to the meaning relevant for the economic process is likely to confuse rather than enlighten the reader: "a measure of unavailable energy in a closed thermodynamic system 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 the absolute temperature to which it is absorbed." But (as if intended to prove that not all progress is for the better) some older editions supply a more intelligible definition. "A measure of the unavailable energy in a thermodynamic system"—as we read in the 1948 edition—cannot satisfy the specialist but would do for general purposes. To explain (again in broad lines) what unavailable energy means is now a relatively simple task.

Energy exists in two qualitative states—*available* or *free* energy, over which man has almost complete command, and *unavailable* or *bound* energy, which man cannot possibly use. The chemical energy contained in a piece of coal is free energy because man can transform it into heat or, if he wants, into mechanical work. But the fantastic amount of heat-energy contained in the waters of the seas, for example, is bound energy. Ships sail on top of this energy, but to do so they need the free energy of some fuel or of the wind.

When a piece of coal is burned, its chemical energy is neither decreased nor increased. But the initial free energy has become so dissipated in the form of heat, smoke and ashes that man

can no longer use it. It has been degraded into bound energy. Free energy means energy that displays a differential level, as exemplified most simply by the difference of temperatures between the inside and the outside of a boiler. Bound energy is, on the contrary, chaotically dissipated energy. This difference may be expressed in yet another way. Free energy implies some ordered structure, comparable with that of a store in which all meat is on one counter, vegetables on another, and so on. Bound energy is energy dissipated in disorder, like the same store after being struck by a tornado. This is why entropy is also defined as a measure of disorder. It fits the fact that a copper sheet represents a lower entropy than the copper ore from which it was produced.

The distinction between free and bound energy is certainly an anthropomorphic one. But this fact need not trouble a student of man, nay, even a student of matter in its simple form. Every element by which man seeks to get in mental contact with actuality can be but anthropomorphic. Only, the case of thermodynamics happens to be more striking. The point is that it was the economic distinction between things having an economic value and waste which prompted the thermodynamic distinction, not conversely. Indeed, the discipline of thermodynamics grew out of a memoir in which the French engineer Sadi Carnot (1824) studied for the first time the *economy* of heat engines. Thermodynamics thus began as a physics of economic value and has remained so in spite of the numerous subsequent contributions of a more abstract nature.

III

Thanks to Carnot's memoir, the elementary fact that heat moves by itself only from the hotter to the colder body acquired a place among the truths recognized by physicists. Still more important was the consequent recognition of the additional truth that once the heat of a closed

system has diffused itself so that the temperature has become uniform throughout the system, the movement of the heat cannot be reversed without external intervention. The ice cubes in a glass of water, once melted, will not form again by themselves. In general, the free heat-energy of a closed system continuously and irrevocably degrades itself into bound energy. The extension of this property from heat-energy to all other kinds of energy led to the Second Law of Thermodynamics, alias the Entropy Law. This law states that the entropy (i.e., the amount of bound energy) of a closed system continuously increases or that the order of such a system steadily turns into disorder.

The reference to a closed system is crucial. Let us visualize a closed system, a room with an electric stove and a pail of water that has just been boiled. What the Entropy Law tells us is, first, that the heat of the boiled water will continuously dissipate into the system. Ultimately, the system will attain thermodynamic equilibrium—a state in which the temperature is uniform throughout (and all energy is bound). This applies to every kind of energy in a closed system. The free chemical energy of a piece of coal, for instance, will ultimately become degraded into bound energy even if the coal is left in the ground. Free energy will do so in any case.

The law also tells us that once thermodynamic equilibrium is reached, the water will not start boiling by itself.¹² But, as everyone knows, we can make it boil again by turning on the stove. This does not mean, however, that we have defeated the Entropy Law. If the entropy of the room has been decreased as the result of the temperature differential created by boiling the water, it is only because some low entropy (free energy) was brought into the system from the outside. And if we include the electric plant in the system, the entropy of this new system must have decreased, as the Entropy Law states. This means that the decrease in the entropy of the room has been obtained only at the cost of a greater increase in entropy elsewhere.

Some writers, impressed by the fact that living organisms remain almost unchanged over short periods of time, have set forth the idea that life eludes the Entropy Law. Now, life may have properties that cannot be accounted for by the natural laws, but the mere thought that it may violate some law of matter (which is an entirely different thing) is sheer nonsense. The truth is that every living organism strives only to maintain its own entropy constant. To the extent to which it achieves this, it does so by sucking low entropy from the environment to compensate for the increase in entropy to which, like every material structure, the organism is continuously subjected. But the entropy of the entire system—consisting of the organism and its environment—must increase. Actually, the entropy of a system must increase faster if life is present than if it is absent. The fact that any living organism fights the entropic degradation of its own material structure may be a characteristic property of life, not accountable by material laws, but it does not constitute a violation of these laws.

Practically all organisms live on low entropy in the form found immediately in the environment. Man is the most striking exception: he cooks most of his food and also transforms natural resources into mechanical work or into various objects of utility. Here again, we should not let ourselves be misled. The entropy of copper metal is lower than the entropy of the ore from which it was refined, but this does not mean that man's *economic* activity eludes the Entropy Law. The refining of the ore causes a more than compensating increase in the entropy of the surroundings. Economists are fond of saying that we cannot get something for nothing. The Entropy Law teaches us that the rule of biological life and, in man's case, of its economic continuation is far harsher. In entropy terms, the cost of any biological or economic enterprise is always greater than the product. In entropy terms, any such activity necessarily results in a deficit.

IV

The statement made earlier—that, from a purely physical viewpoint, the economic process only transforms valuable natural resources (low entropy) into waste (high entropy)—is thus completely vindicated. But the puzzle of why such a process should go on is still with us. And it will remain a puzzle as long as we do not see that the true economic output of the economic process is not a material flow of waste, but an immaterial flux: the enjoyment of life. If we do not recognize the existence of this flux, we are not in the economic world. Nor do we have a complete picture of the economic process if we ignore the fact that this flux—which, as an entropic feeling, must characterize life at all levels—exists only as long as it can continuously feed itself on environmental low entropy. And if we go one step further, we discover that every object of economic value—be it a fruit just picked from a tree, or a piece of clothing, or furniture, etc.—has a highly ordered structure, hence, a low entropy.¹²

There are several lessons to be derived from this analysis. The first lesson is that man's economic struggle centers on environmental low entropy. Second, environmental low entropy is scarce in a different sense than Ricardian land. Both Ricardian land and the coal deposits are available in limited amounts. The difference is that a piece of coal can be used only once. And, in fact, the Entropy Law is the reason why an engine (even a biological organism) ultimately wears out and must be replaced by a *new* one, which means an additional tapping of environmental low entropy.

Man's continuous tapping of natural resources is not an activity that makes no history. On the contrary, it is the most important long-run element of mankind's fate. It is because of the irreversibility of the entropic degradation of matter-energy that, for instance, the peoples from the Asian steppes, whose economy was based on sheep-raising, began their Great Migration over the entire European continent at the beginning of the first millennium. The same element—the pressure on natural resources—had, no doubt, a

role in other migrations, including that from Europe to the New World. The fantastic efforts made for reaching the moon may also reflect some vaguely felt hope of obtaining access to additional sources of low entropy. It is also because of the particular scarcity of environmental low entropy that ever since the dawn of history man has continuously sought to invent means for sifting low entropy better. In most (though not in all) of man's inventions one can definitely see a progressively better economy of low entropy.

Nothing could, therefore, be further from the truth than the notion that the economic process is an isolated, circular affair—as Marxist and standard analysis represent it. The economic process is solidly anchored to a material base which is subject to definite constraints. It is because of these constraints that the economic process has a unidirectional irrevocable evolution. In the economic world only money circulates back and forth between one economic sector and another (although, in truth, even the bullion slowly wears out and its stock must be continuously replenished from the mineral deposits). In retrospect it appears that the economists of both persuasions have succumbed to the worst economic fetishism—money fetishism.

V

Economic thought has always been influenced by the economic issues of the day. It also has reflected—with some lag—the trend of ideas in the natural sciences. A salient illustration of this correlation is the very fact that, when economists began ignoring the natural environment in representing the economic process, the event reflected a turning point in the temper of the entire scholarly world. The unprecedented achievements of the Industrial Revolution so amazed everyone with what man might do with the aid of machines that the general attention became confined to the factory. The landslide of spectacular scientific discoveries triggered by the new technical facilities strengthened this general awe for the power of technology. It also induced the

literati to overestimate and, ultimately, to oversell to their audiences the powers of science. Naturally, from such a pedestal one could not even conceive that there is any real obstacle inherent in the human condition.

The sober truth is different. Even the lifespan of the human species represents just a blink when compared with that of a galaxy. So, even with progress in space travel, mankind will remain confined to a speck of space. Man's biological nature sets other limitations as to what he can do. Too high or too low a temperature is incompatible with his existence. And so are many radiations. It is not only that he cannot reach up to the stars, but he cannot even reach down to an individual elementary particle, nay, to an individual atom.

Precisely because man has felt, however unsophisticatedly, that his life depends on scarce, irrevocable low entropy, man has all along nourished the hope that he may eventually discover a self-perpetuating force. The discovery of electricity enticed many to believe that the hope was actually fulfilled. Following the strange marriage of thermodynamics with mechanics, some began seriously thinking about schemes to unbind bound energy.¹³ The discovery of atomic energy spread another wave of sanguine hopes that, this time, we have truly gotten hold of a self-perpetuating power. The shortage of electricity which plagues New York and is gradually extending to other cities should suffice to sober us up. Both the nuclear theorists and the operators of atomic plants vouch that it all boils down to a problem of cost, which in the perspective of this paper means a problem of a balance sheet in entropy terms.

With natural scientists preaching that science can do away with all limitations felt by man and with the economists following suit in not relating the analysis of the economic process to the limitations of man's material environment, no wonder that no one realized that we cannot produce "better and bigger" refrigerators, automobiles, or jet planes, without producing also "better and bigger" waste. So, when everyone (in the

countries with "better and bigger" industrial production) was, literally, hit in the face by pollution, scientists as well as economists were taken by surprise. But even now no one seems to see that the cause of all this is that we have failed to acknowledge the entropic nature of the economic process. A convincing proof is that the various authorities on pollution now try to sell us, on the one hand, the idea of machines and chemical reactions that produce no waste, and, on the other, salvation through a perpetual recycling of waste. There is no denial that, in principle at least, we can recycle even the gold dispersed in the sand of the seas just as we can recycle the boiling water in my earlier example. But in both cases we must use an additional amount of low entropy much greater than the decrease in the entropy of what is recycled. There is no free recycling just as there is no wasteless industry.

VI

The globe to which the human species is bound floats, as it were, within the cosmic store of free energy, which may be even infinite. But for the reasons mentioned in the preceding section, man cannot have access to all this fantastic amount, nor to all possible forms of free energy. Man cannot, for example, tap directly the immense thermonuclear energy of the sun. The most important impediment (valid also for the industrial use of the "hydrogen bomb") is that no material container can resist the temperature of massive thermonuclear reactions. Such reactions can occur only in free space.

The free energy to which man can have access comes from two distinct sources. The first source is a *stock*, the stock of free energy of the mineral deposits in the bowels of the earth. The second source is a *flow*, the flow of solar radiation intercepted by the earth. Several differences between these two sources should be well marked. Man has almost complete command over the terrestrial dowry; conceivably, we may use it all within a single year. But, for all practical purposes, man has no control over the flow of solar radiation.

Neither can he use the flow of the future *now*. Another asymmetry between the two sources pertains to their specific roles. Only the terrestrial source provides us with the low entropy materials from which we manufacture our most important implements. On the other hand, solar radiation is the primary source of all life on earth, which begins with chlorophyll photosynthesis. Finally, the terrestrial stock is a paltry source in comparison with that of the sun. In all probability, the active life of the sun—during which the earth will receive a flow of solar energy of significant intensity—will last another five billion years.¹⁴ But hard to believe though it may be, the entire terrestrial stock could yield only a few days of sunlight.¹⁵

All this casts a new light on the population problem, which is so topical today. Some students are alarmed at the possibility that the world population will reach seven billion by A.D. 2000—the level predicted by United Nations demographers. On the other side of the fence, there are those who, like Colin Clark, claim that with a proper administration of resources the earth may feed as many as forty-five billion people.¹⁶ Yet no population expert seems to have raised the far more vital question for mankind's future: How long can a given world population—be it of one billion or of forty-five billion—be maintained? Only if we raise this question can we see how complicated the population problem is. Even the analytical concept of optimum population, on which many population studies have been erected, emerges as an inept fiction.

What has happened to man's entropic struggle over the last two hundred years is a telling story in this respect. On the one hand, thanks to the spectacular progress of science man has achieved an almost miraculous level of economic development. On the other hand, this development has forced man to push his tapping of terrestrial resources to a staggering degree (witness offshore oil-drilling). It has also sustained a population growth which has accentuated the struggle for food and, in some areas, brought this pressure to critical levels. The solution, advocated unani-

mously, is an increased mechanization of agriculture. But let us see what this solution means in terms of entropy.

In the first place, by eliminating the traditional partner of the farmer—the draft animal—the mechanization of agriculture allows the entire land area to be allocated to the production of food (and to fodder only to the extent of the need for meat). But the ultimate and the most important result is a shift of the low entropy input from the solar to the terrestrial source. The ox or the water buffalo—which derive their mechanical power from the solar radiation caught by chlorophyll photosynthesis—is replaced by the tractor—which is produced and operated with the aid of terrestrial low entropy. And the same goes for the shift from manure to artificial fertilizers. The upshot is that the mechanization of agriculture is a solution which, though inevitable in the present impasse, is anti-economical in the long run. Man's biological existence is made to depend in the future more and more upon the scarcer of the two sources of low entropy. There is also the risk that mechanized agriculture may trap the human species in a cul-de-sac because of the possibility that some of the biological species involved in the other method of farming will be forced into extinction.

Actually, the problem of the economic use of the terrestrial stock of low entropy is not limited to the mechanization of agriculture only; it is the main problem for the fate of the human species. To see this, let S denote the present stock of terrestrial low entropy and let r be some average annual amount of depletion. If we abstract (as we can safely do here) from the slow degradation of S , the *theoretical* maximum number of years until the complete exhaustion of that stock is S/r . This is also the number of years until the *industrial* phase in the evolution of mankind will forcibly come to its end. Given the fantastic disproportion between S and the flow of solar energy that reaches the globe annually, it is beyond question that, even with a very parsimonious use of S , the industrial phase of man's evolution will end long before the sun will cease to shine. What

will happen then (if the extinction of the human species is not brought about earlier by some totally resistant bug or some insidious chemical) is hard to say. Man could continue to live by reverting to the stage of a berry-picking species—as he once was. But, in the light of what we know about evolution, such an evolutionary reversal does not seem probable. Be that as it may, the fact remains that the higher the degree of economic development, the greater must be the annual depletion r and, hence, the shorter becomes the expected life of the human species.

VIII

The upshot is clear. Every time we produce a Cadillac, we irrevocably destroy an amount of low entropy that could otherwise be used for producing a plow or a spade. In other words, every time we produce a Cadillac, we do it at the cost of decreasing the number of human lives in the future. Economic development through industrial abundance may be a blessing for us now and for those who will be able to enjoy it in the near future, but it is definitely against the interest of the human species as a whole, if its interest is to have a lifespan as long as is compatible with its dowry of low entropy. In this paradox of economic development we can see the price man has to pay for the unique privilege of being able to go beyond the biological limits in his struggle for life.

Biologists are fond of repeating that natural selection is a series of fantastic blunders since future conditions are not taken into account. The remark, which implies that man is wiser than nature and should take over her job, proves that man's vanity and the scholar's self-confidence will never know their limits. For the trace of economic development that is the hallmark of modern civilization leaves no doubt about man's lack of foresight. It is only because of his biological nature (his inherited instincts) that man cares for the fate of only some of his immediate descendants, generally not beyond his grandchildren. And there is neither cynicism nor

pessimism in believing that, even if made aware of the entropic problem of the human species, mankind would not be willing to give up its present luxuries in order to ease the life of those humans who will live ten thousand or even one thousand years from now. Once man expanded his biological powers by means of industrial artifacts, he became *ipso facto* not only dependent on a very scarce source of life support but also addicted to industrial luxuries. It is as if the human species were determined to have a short but exciting life. Let the less ambitious species have a long but uneventful existence.

Issues such as those discussed in this lecture pertain to long-run forces. Because these forces act extremely slowly we are apt to ignore their existence or, if we recognize them, to belittle their importance. Man's nature is such that he is always interested in what will happen until tomorrow, not in thousands of years from now. Yet it is the slow-acting forces that are the more fatal in general. Most people die not because of some quickly acting force—such as a pneumonia or an automobile accident—but because of the slow-acting forces that cause aging. As a Jain philosopher remarked, man begins to die at birth. The point is that it would not be hazardous to venture some thoughts about the distant future of man's economy any more than it would be to predict in broad lines the life of a newly born child. One such thought is that the increased pressure on the stock of mineral resources created by the modern fever of industrial development, together with the mounting problem of making pollution less noxious (which places additional demands on the same stock), will necessarily concentrate man's attention on ways to make greater use of solar radiation, the more abundant source of free energy.

Some scientists now proudly claim that the food problem is on the verge of being completely solved by the imminent conversion on an industrial scale of mineral oil into food protein—an inept thought in view of what we know about the entropic problem. The logic of this problem justifies instead the prediction that, under the

pressure of necessity, man will ultimately turn to the contrary conversion, of vegetable products into gasoline (if he will still have any use for it).¹² We may also be quasi-certain that, under the same pressure, man will discover means by which to transform solar radiation into motor power directly. Certainly, such a discovery will represent the greatest possible breakthrough for man's entropic problem, for it will bring under his command also the more abundant source of life support. Recycling and pollution purification would still consume low entropy, but not from the rapidly exhaustible stock of our globe.

Footnotes

1. W. Stanley Jevons, *The Theory of Political Economy* (4th edn., London, 1924), p. 21.
2. E. E. R. T. Bye, *Principles of Economics* (5th edn., New York, 1966), p. 253; G. L. Bach, *Economics* (2nd edn., Englewood Cliffs, N. J., 1957), p. 60; I. H. Dodd, C. W. Haskel, T. J. Hanstons, *Economics* (Chicinnati, 1957), p. 125; R. M. Hayes, J. S. Henderson, D. L. Canner, *Economics* (New York, 1966), p. 49; Paul A. Samuelson, *Economics* (8th edn., New York, 1970), p. 42.
3. Karl Marx, *Capital* (3 vols., Chicago, 1906-1939), I, 94, 199, 230, and *passim*.
4. *Ibid.*, II, ch. XX.
5. *The Economic Writings of Sir William Petty*, ed. C. H. Hall (2 vols., Cambridge, Eng., 1899), II, 377 (Continuously, Marx went along with Petty's idea; but he claimed that nature only "helps to create use-value without contributing to the formation of exchange value." Marx, *Capital*, I, 227. See also *ibid.*, p. 94.
6. E. F. Alfred Marshall, *Principles of Economics* (8th edn., New York, 1924), p. 63.
7. On the problem of the analytical representation of a process, see my *The Entropy Law and the Economic Process* (Cambridge, Mass., 1971), pp. 211-231.
8. This distinction together with the fact that no one would exchange some natural resources for waste, disposes of Marx's assertion that "no chemist has ever discovered exchange value in a pearl or a diamond." *Capital*, I, 95.
9. D. ter Haar, "The Quantum Nature of Matter and Radiation," in *Turning Points in Physics*, ed. R. J. Blin-Stoyle et al. (Amsterdam, 1959), p. 37.

10. One meaning that has recently made the term extremely popular is "the amount of information." For an argument that this term is misleading and for a critique of the alleged connection between information and physical entropy, see *The Entropy Law and the Economic Process*, Appendix B.

11. This position calls for some technical elaboration. The opposition between the Entropy Law—with its unidirectional qualitative change—and mechanics—where everything can move either forward or backward while remaining self-identical—is accepted without reservation by every physicist and philosopher of science. However, the mechanistic dogma retained (as it still does) its grip on scientific activity even after physics reclaimed it. The result was that mechanics was soon brought into thermodynamics in the company of randomness. This is the strangest possible company, for randomness is the very antithesis of the deterministic nature of the laws of mechanics. To be sure, the new edifice (known as statistical mechanics) could not include mechanics under its roof and, at the same time, exclude reversibility. So, statistical mechanics must teach that a pair of water may start boiling by itself, a thought which is slipped under the rug by the argument that the miracle has not been observed because of its extremely small probability. This position has fostered the belief in the possibility of converting bound into free energy or, as P. W. Bridgman wittily put it, of bootlegging entropy. For a critique of the logical fallacies of statistical mechanics and of the various attempts to patch them, see *The Entropy Law and the Economic Process*, ch. VI.

12. This does not mean that everything of low entropy necessarily has economic value. Poisonous mushrooms, too, have a low entropy. The relation between low entropy and economic value is similar to that between economic value and price. An object can have a price only if it has economic value, and it can have economic value only if its entropy is low. But the converse is not true.

13. See note 11, above.

14. George Cannon, *Matter, Earth, and Sky* (Englewood Cliffs, N. J., 1958), pp. 493 f.

15. Four days, according to Eugene Ayres, "Power from the Sun," *Scientific American*, August 1950, p. 16. The situation is not changed even if we admit that the calculations might be in error by as much as one thousand times.

16. Colin Clark, "Agricultural Productivity in Relation to Population," in *Man and His Future*, ed. G. Wolfshohlme (Boston, 1963), p. 35.

17. That the idea is not far-fetched is proved by the fact that in Sweden, during World War II, automobiles were driven by the poor gas obtained by heating wood with wood.

CHAPTER 4

(1969)

THE ECONOMICS OF PRODUCTION

RICHARD T. ELY LECTURE

For the last twenty years or so I have singled myself out among my fellow economists for arguing with all the means at my disposal that not every element of the economic process can be related to a number and, consequently, that this process cannot be represented in its entirety by an arithmetomorphic model. At the same time, I have insisted that in our haste to mathematize economics we have often been carried away by mathematical formalism to the point of disregarding a basic requirement of science; namely, to have as clear an idea as possible about what corresponds in actuality to every piece of our symbolism. Curiously, in the home of quantity, in the natural sciences, this position does not constitute a singularity. On the contrary, essentially the same words of caution have come from many a high authority in physics—such as Max Planck or Percy William Bridgman, for example.¹ But even some engineers have raised their voices against blind symbolism. The recent remarks by a well-known British engineer are worth quoting at length:

Contrary to common belief it is sometimes easier to talk in mathematics than to talk in English; this is the reason why many scientific papers contain more mathematics than is either necessary or desirable. Contrary to common belief it is also often less precise to do so. For mathematical symbols have a tendency to conceal the physical meaning that they are intended to represent; they sometimes serve as a substitute for the arduous task of deciding what is and what is not relevant. . . . It is true that mathematics cannot lie. But it can mislead.

However, the dangers of over-indulgence in formula spinning are avoided if mathematics is treated, wherever possible, as a language into which *thoughts may only be translated after they have first been [clearly] expressed in the language of words*. The use of mathematics in this way is indeed disciplinary, helpful, and sometimes indispensable.²

The topic of this lecture—the economics of production—presents, I believe, sufficient interest by itself. But in choosing it, I have been guided also

¹ Max Planck, *The New Science* (New York, 1959), pp. 43, 158-59; P. W. Bridgman, *The Logic of Modern Physics* (New York, 1949), p. 50.

² Reginald O. Kapp, *Towards a Unified Cosmology* (New York, 1960), p. 111. My italics.

by the fact that it may serve as a substantial illustration of the harm caused by the blind mathematics that generally characterizes a hasty mathematization.

I

What has come to be known as "the production function" is quite an old item in the economist's analytical paraphernalia. As we may recall, it was introduced in 1894 by Wicksteed with one simple remark: "the product being a function of the factors of production we have $P=f(a, b, c, \dots)$."³ This paradigm of imprecision apparently sufficed to make us accept Wicksteed's simple symbolism as an adequate analytical representation of any production process and use it indiscriminately in every kind of situation. And as the usage of the rapid terms "input" and "output" became widespread, popular manuals came to treat the subject in an even more cavalier manner than Wicksteed's. A typical presentation is that the production function expresses symbolically the fact that "the output of the firm depends on its inputs."⁴

But even consummate economists have accepted Wicksteed's formula without any ado. They only felt that the meaning of the variables involved ought to be explained. The greater number of such authors adopt the position that the formula shows the quantities of inputs (or of factors) necessary to produce a certain quantity of output (or of product). Accordingly, all symbols in a production function,

$$(1) \quad Q = F(X, Y, Z, \dots)$$

stand for quantities.⁴ Others conceive the same function as a relation between the inputs per unit

³ Philip H. Wicksteed, *The Co-ordination of the Laws of Distribution* (London, 1894), p. 4.

⁴ For a small yet representative sample, see A. L. Bowley, *The Mathematical Groundwork of Economics* (Oxford, 1924), pp. 28-29; J. R. Hicks, *The Theory of Wages* (London, 1932), p. 237; E. Schneider, *Theorie der Produktion* (Vienna, 1934), p. 1; A. C. Pigou, *The Economics of Stationary States* (London, 1935), p. 142; P. A. Samuelson, *Foundations of Economic Analysis* (Cambridge, Mass., 1948), pp. 57-58; K. E. Boulding, *Economic Analysis* (3rd ed., New York, 1955), p. 585; Sune Carlsson, *A Study on the Pure Theory of Production* (New York, 1956), p. 12; Ragnar Frisch, *Theory of Production* (Chicago, 1965), p. 41.