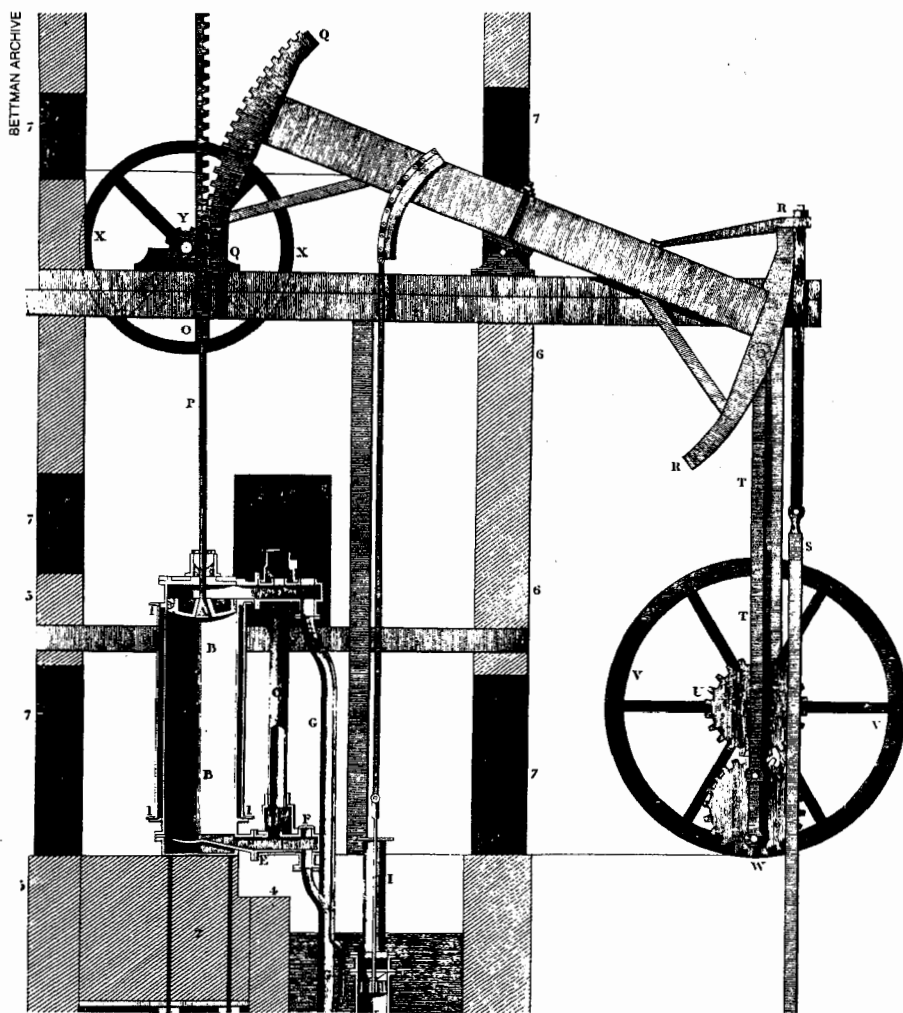


Thermodynamics and economics

The laws of the conservation of energy and of the increase of entropy constrain the processes by which raw materials are transformed into consumable goods, and therefore have implications for the way economists model these processes.

Robert U. Ayres and Indira Nair



James Watt's steam engine. The conversion of coal to mechanical power for lifting water out of mines was the first practical application of thermodynamics. An investigation of the efficiency of such engines (in a sense, a problem in economics) led to the formal development of thermodynamics.

Figure 1

While physical sciences deal with the interactions of matter and energy, economics can be said to deal with the production and exchange of goods and services. Because goods and services incorporate matter and energy, the physical sciences are clearly relevant to economics. In particular, one can expect the laws of thermodynamics to impose constraints on economic processes as they do on physical processes (figure 1). It is clear that the laws of conservation—of matter and energy, for example—have implications for the use of resources and for the generation and treatment of wastes. The law of the increase of entropy—the second law of thermodynamics—constrains economic processes to those that reduce available work, increasing the entropy of the Universe.

The fact that these connections between physics and economics are not trivial was perhaps first taken seriously¹ in the 1960s. In this article we will focus on the second law of thermodynamics. We hope to demonstrate that it has significant—if not world-shaking—implications for economic theory, especially as applied to resource, environment and technology policy. We begin with a review of the basic assumptions and concepts of economics, giving particular attention to their consistency with physical laws. We then discuss several examples where physical considerations—in particular the increase of entropy—are of critical

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importance both to economic theory and to policy.

Economics

We have said that economics deals with the social production, exchange and consumption of goods and services. Economists themselves customarily refer to their field as the science of the allocation of scarce resources.

The term "scarce" in the economists' definition is important: Conventional economics has nothing to say about the allocation of "non-scarce" resources. A resource is scarce if it cannot be used or acquired except by exchanging another scarce resource for it. In practice, money is usually the medium of exchange; the amount of money exchanged for a unit of the resource—its price—in a free market is considered an economic measure of its value. A resource may also be scarce if by having or using it one thereby deprives other potential users—even if one does not have to give up anything in exchange for it. (Fresh air and water fall under this definition of "scarce" in some regions.) Such situations are difficult for economists to deal with, because of the absence of a market price for the resources.

The term "resource" as used in economics is very slippery: It may refer to land, labor, energy, materials, capital, or all of these. Sometimes what is considered to be a "resource" is not made explicit, and resources that are not "scarce" are generally not considered in economics. Because a scarce resource normally has a price—its value in exchange—economists are able to express both the inputs (scarce

resources) and outputs (socially valued products) of the production process in monetary terms. The advantage of this device is obvious: It permits straightforward aggregation of fundamentally different quantities such as labor and capital. Land, labor, energy, materials, and capital can thus all be referred to as "factors of production," and aggregated or disaggregated into arbitrarily many sectors to match the requirements of the economic model.

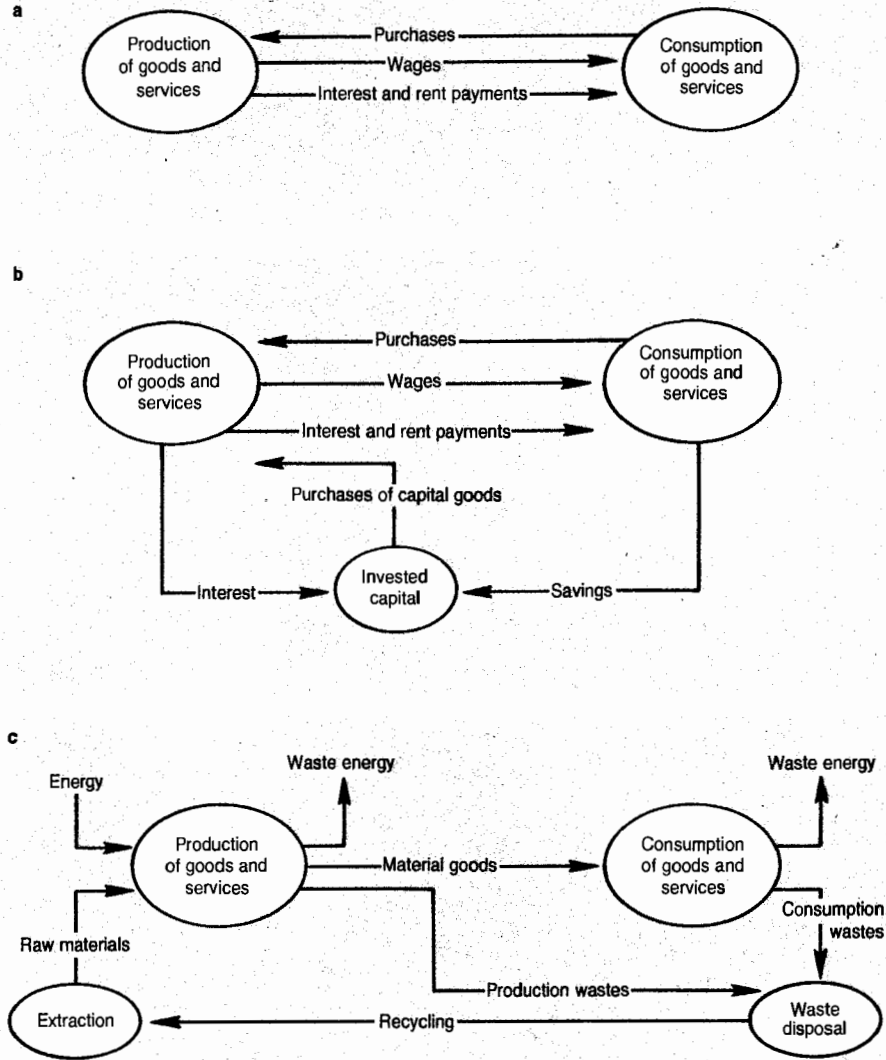
The notion of the exchange of goods and services is central to economics. In fact, most of economic theory is built on a very simple but powerful model of behavior: that rational "agents" (individuals or firms) seek to maximize their own utility by exchanging—buying and selling—goods or services in a free competitive market. This model is so pervasive that most economists today fail to recognize either its origins in 19th century political philosophy or the fact that this simplistic form of utilitarianism conspicuously fails to explain social phenomena such as the existence of etiquette, fashion or government regulation. Aggregating all the factors of production, economists represent the production-consumption system by a simple, abstract model (figure 2a) in which consumers receive payments for their labor or the resources they control and, in turn, pay for goods and services they require. This abstract model clearly reflects the fact that payments by consumers for goods and services must be balanced by payments to consumers (as workers) in the form of wages, and to consumers (as owners of land or capital) in the form of

interest and rents. As we have said, both the production and consumption activities can be disaggregated into arbitrarily many sectors—including government—without altering the model's basic character. Under "reasonable" assumptions it can be shown that there exists a price that simultaneously maximizes utility for both buyers and sellers. On this simple theorem, much depends.

One of the major achievements of 19th century economic theory was the mathematical proof that a stable equilibrium exists for the sort of closed production-consumption system shown in figure 2a—at least under special conditions.² Leon Walras, the French economist, originally proved it in the 1860s; his work was extended by Gustav Cassel in Sweden in the early part of this century. The model of figure 2a is highly simplified and restrictive: Resources are fixed (and given), individual preferences are invariable (and determined), technology is unchanging, and all relationships between economic variables are linear. The model represented in figure 2a also does not allow for economic growth; however, a closely related model developed by John von Neumann in 1945 and by Piero Sraffa in 1960 (illustrated in figure 2b) allows for investment and technological change within the general equilibrium framework.³

The closed Walras-Cassel allocation model, however, departs from physical reality in another fundamental way, which can be seen as soon as the underlying physical mass-energy flows are added to the picture. Figure 2c adds the flow of matter and energy

Economic systems. The simple, closed, static production-consumption model (a) dates from the mid 19th century; it does not allow for changes in technology or economic growth. A model that includes investment (b) allows for changes in the same equilibrium framework. Neither model is consistent with the flows of matter and energy through the system (c). Figure 2



involved in the static economic model of figure 2a. Any goods—capital goods or consumption goods—embody both materials and energy; similarly, most services in an economy require some input of materials or energy. The economic model (figure 2a) has a source (production) and a sink (consumption) of economic goods. But real materials are not really consumed, of course: They are merely returned to the environment as waste. The economic system cannot be a closed system, even if one includes the extraction and disposal of materials—unless one includes within the system the global environment and the Sun itself. However, even if one does consider such a large closed system, it cannot be in thermodynamic equilibrium: A closed system in thermodynamic equilibrium is necessarily passive and inert, without flows of matter or energy. The flow of matter and energy through the system, in turn, precludes the existence of an economic equilibrium except in the special case of zero growth.

It is clearly more realistic to regard the economy, like the Earth itself, as an open system through which materials and energy continuously flow. The laws of thermodynamics now assert themselves. One immediate consequence is that the mass and energy in the waste flow must equal the mass and energy extracted from the environment. Moreover, the waste flows are obviously proportional to the amount of mass and energy processed into material goods and, hence, to the size of the

economy. In other words, the bigger the GNP, the greater the aggregate quantity of waste residuals that will be generated.¹ It follows that the notion of equilibrium growth, as conceived³ by von Neumann, is also inconsistent with a closed system. (It does not follow that the amount of damage to the environment, or to human health, caused by waste residuals is proportional to the size of the economy. Many kinds of waste residuals, especially the bulkier ones, are either inherently harmless or can be rendered harmless. The most toxic residuals, such as pesticides, heavy metals, radioactive wastes and some chemical wastes, involve insignificant amounts of mass. It is plausible that these dangerous wastes could be either eliminated at the source—by finding safer substitute materials—or safely encapsulated, transformed chemically into harmless forms or fully recycled, for a relatively minor additional expenditure of energy.)

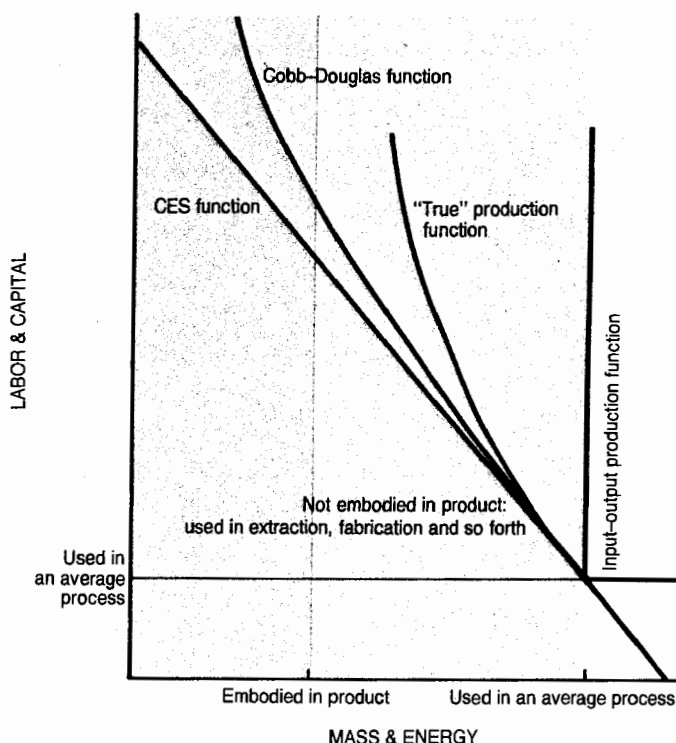
Another immediate consequence—of the second rather than the first law—is that the available energy in the total output of any sector of the economy

must be less than the available energy in the input. This is a direct consequence of the increase in global entropy associated with any irreversible process. Materials tend to be entropically degraded at every stage from extraction to final consumption. The wastes, from both the production and the consumption sectors, shown in figure 1c, contain little or no available energy.

The wastes that result from an economic process can, in many cases, be recycled. However, because of the second law, the degraded materials in general cannot be returned to productive use without expenditures of additional available energy, which must, in turn, be extracted from the environment. The recycling itself thus necessarily results in additional waste—if only in the form of waste heat to be radiated into outer space.

We should emphasize that the increase in global entropy required by the second law does not prevent one from decreasing the entropy of a part of the environment. Thus, for example, extracting metal from an ore decreases the entropy of the metal; but the

Production functions. The curves show relative amounts of labor-capital and mass-energy required to produce the same amount of final goods. Different production functions represent different assumptions concerning the substitutability of labor and capital for mass and energy. The "true" function cannot cross into the region of embodied mass-energy, because labor and capital can only substitute for nonembodied mass and energy. Figure 3



extraction process also increases the entropy of all the material that remains and of any fuel that was used by an even larger amount. Likewise, living organisms maintain their states of low entropy with respect to their surroundings, in spite of dissipative processes, by consuming materials (as food or photons) that contain far more available energy than the organisms actually convert to mechanical work or biomass.

Efficiency

The notion of efficiency was first used in thermodynamics in the context of heat engines: engines that used (costly) fuel to produce (valuable) mechanical work (figure 1). The early steam engines were more efficient if they could raise more water from a mine with the same consumption of coal. (Note that a link between economics and thermodynamics is already implicit in this definition: thermodynamics provides the limits, but economics determines what are the "valuable" inputs and "desirable" outputs.) In this context, the efficiency is simply defined as the ratio of output work W to input heat Q

$$\epsilon = \frac{W_{\text{out}}}{Q_{\text{in}}} = \frac{(Q_{\text{in}} - Q_{\text{out}})}{Q_{\text{in}}}$$

The output heat is simply waste. This efficiency is often called the first-law efficiency, because it takes into account only the limits imposed by energy conservation. As is well known, no engine that operates in a cycle can

convert all its input heat into work: The efficiency ϵ is further limited by the second law of thermodynamics. It is therefore often useful to define another kind of efficiency that measures how nearly a process approaches the limits imposed by the second law. For example, one such "second-law efficiency" is

$$\eta = A_{\text{out}} / A_{\text{in}}$$

where A is a measure of the "available energy" embodied in the inputs and outputs. (The most general measure of the available energy is the "availability." For a system with an internal energy U , volume V , entropy S , and N_i moles of substance i that is relaxing to an ambient temperature T_0 , pressure p_0 and chemical potentials μ_{i0} , the availability is $U + P_0 V - T_0 S - \sum \mu_{i0} N_i$. It is related to the Gibbs free energy $U + PV - TS - \sum \mu_i N_i$.)

For the usual sort of reversible heat engine operating between heat reservoirs at temperatures T and T_0 , both efficiencies reduce to the Carnot limit:

$$\epsilon = \eta = 1 - T/T_0$$

However, for systems that are not closed-cycle engines, such as Rankine or Stirling cycle engines, the two efficiencies need not be the same. Thus, for example, in open-cycle engines (Otto cycle internal-combustion engines or gas turbines), the efficiencies ϵ and η differ somewhat. And in some cases they can be substantially different, as in the case of a space-heating system where a fuel with a great deal of

available energy (low entropy) is burned to provide heat at temperatures only slightly warmer than the environment. A typical gas-fired home furnace may have a first-law efficiency ϵ (proudly advertised by the manufacturer) of 70%, meaning that only 30% of the heat goes up the chimney. Its second-law efficiency, η , may only be 4%; that is to say, the available energy in the fuel is almost entirely wasted instead of being turned into mechanical work. Rather than just use the heat from the very hot flame to heat up the room, one could use it, for example, to drive an absorption refrigerator acting as a heat pump; the same amount of heat could then be delivered to the room with a considerably smaller expenditure of gas or available energy—albeit with a greater expenditure of capital. The table on the next page gives other comparisons of first- and second-law efficiencies.

In economics, efficiency is normally defined in quite a different way: It is a qualitative, not a quantitative term. An "ideal" economic system (analogous, say, to the Carnot cycle heat engine) is a competitive, free market consisting of rational, well-informed consumers and producers, and involving none of what economists call indivisibilities or externalities. The 19th century Italian economist Vilfredo Pareto suggested that the equilibrium state achieved by this system is an optimal one in the following sense: Resources are allocated in such a way that no person in the economy can be made better off with-

Thermodynamic efficiencies

Energy conversion processes	ϵ	η
	First Law	Second Law
Burner to steam-electric generator	0.33	0.33
Burner to process heat, 1000 °F	0.8	0.65
Burner to process steam, 250 °F	0.8	0.225
Electric heater to hot water, 120 °F	0.75	0.045
Burner to hot water, 120 °F	0.50	0.029
Burner to space heat, 70 °F (room)	0.60	0.028
Burner to space heat, 110 °F (at the register)	0.60	0.074
Burner to space heat, 160 °F (at the furnace plenum)	0.75	0.145
Otto cycle engine, constant speed	0.32	0.32
Engine driven heat pump to steam 250 °F	1.18*	0.299
Engine driven heat pump to space heat, 110 °F	2.45*	0.202
Industrial electric drive	0.90	0.90
Automobile engine to rear wheels, 60 mph	0.14	0.14
Automobile, federal urban driving cycle	0.09	0.09
Materials Transformation Process		
Coke oven	—	0.88
Pig iron, blast furnace	—	0.77
Steel, open hearth furnace	—	0.66
Steel, electric arc furnace	—	0.80
Steel, basic oxygen furnace	—	0.93
Iron and steel finishing	—	0.415
Aluminum, Bayer-Hall process	—	0.45
Aluminum, ALCOA process	—	0.59
Chlorine manufacturing	—	0.40
Ammonia manufacturing	—	0.50
Pulp and paper	—	0.29
Cement	—	0.25
Glass manufacturing	—	0.22

*Coefficient of performance
From R. Ayres, *Resource, Environment and Economics*, Wiley, New York (1978).

out making at least one other person worse off. The existence of such a Pareto optimum depends on each person having a well-defined set of preferences that depends only on his income. However, real people do not simply maximize a well-defined individual utility function (for example, they subordinate personal interests to the interests of larger groups, they submit to customs and laws and they engage in altruistic behavior), so the Pareto optimum is a very remote abstraction indeed. Nonetheless, economists find it useful to define the efficiency of an economic system by how closely it approaches the Pareto optimum.

Economic efficiency, as thus conceived, involves an array of variables including incomes and prices of all goods and services—capital, labor, land and resources of materials and energy. Because of this complexity, most economists have rejected the notion that there might be any particular relationship between economic and thermodynamic efficiency. On the other hand, some physical scientists have argued that a link should exist—at least via the prices charged for goods and services. In particular, as long ago as 1922, Frederick Soddy suggested⁴ that the price of a commodity should reflect the energy used directly or indirectly to produce it. (Actually, because energy as such is not used up, free energy or available work would be the more appropriate measure). In the 1930s, the idea of energy-pricing was espoused

by a technocratic political movement, under the leadership of Howard Scott, as a notional panacea for the economic ills of the Great Depression. The idea popped up again in the 1960s, with its impetus deriving mainly from environmental and resource concerns—prompted, for example, by the suspicion that some large-scale energy projects (such as solar satellites or gasohol) might require more energy to implement than they could hope to produce. For a few years a number of physical scientists and engineers were involved in various forms of “net energy” analysis.⁵

But there was and is no consensus on the appropriate use of net-energy analysis in practical decision-making. What is unambiguously clear, however, is that economic optima and thermodynamic optima do not coincide except under extraordinary and unrealistic conditions. The proof is straightforward, though not worth recapitulating here. Let us only remark that the two optima coincide in a free market if, and only if, free energy or available work is the only scarce factor of production—that is, if the “shadow prices” of labor, capital and so forth are zero.⁶

Production functions

In considering economic efficiency, we have already seen that economists tend to be more concerned with relations either among the inputs or among the outputs of a process than they are in the relations between inputs and

outputs. In general, the interesting questions in economics concern the substitution or variation of inputs of different kinds: the effects, for example, of substituting machines (capital) for labor, of substituting energy (via intensive cultivation) for land, of increasing the relative cost of labor (wages) or of fuel. Particularly interesting are questions that deal with the margin (or differentials, in the physicist's language): How much does an increase in the cost of phosphate fertilizer decrease wheat production and increase its market price? How will a wage increase for auto workers be reflected in the prices of domestic cars and the demand for imports?

The marginal questions can be separated into two varieties:

► If one of the inputs to a process is increased or decreased by a small amount, how much does the output increase or decrease?

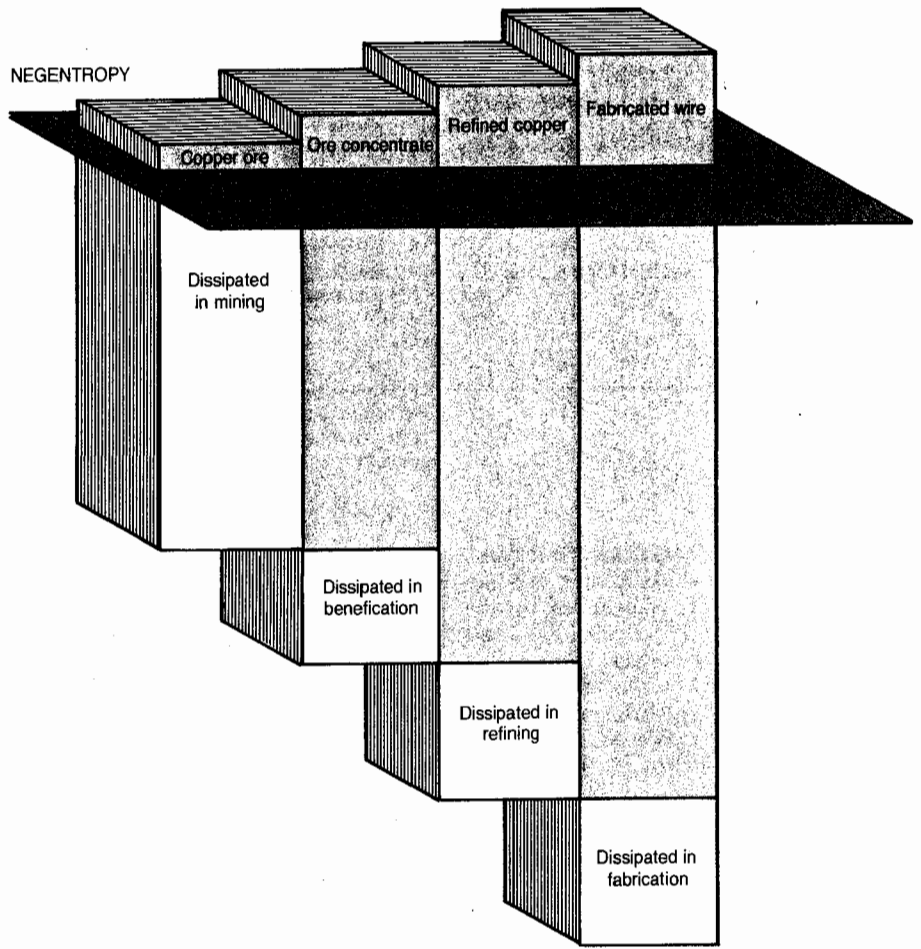
► If one of the inputs to a process is increased or decreased, can one keep the output constant by a marginal increase or decrease in another input?

The economic significance of the first type of question has to do with the nature of the equilibrium allocation of marginal payments for land, labor, capital, energy and so forth. In other words, if an incremental gain in output is achieved, how should the corresponding gains in income be distributed among landowners, workers, owners of capital and owners of resources?

The economic significance of the second question is most easily grasped from an example. When one class of inputs suddenly becomes much more costly than others, as happened in 1974 with energy, the market system adjusts by seeking combinations of inputs that cost less but can yield the same outputs: During the energy crises, the system

Accumulation of local order (negentropy) in manufactured goods, accompanied by an increase in global entropy. In this example, copper ore is refined and turned into wire. While the negentropy of the copper is increased, large amounts of available energy (usually in the form of fuel to drive the processes) are dissipated, increasing the overall entropy. The dissipated energy is not recoverable from the final product.

Figure 4



thus sought to substitute labor or capital for energy. Economists raise questions⁷ such as: Given a higher price for energy, will capital (or labor) be used more or less? In other words, is capital a substitute for energy, or a complement of it? After the adjustment, what is the equilibrium mix of factors? A more difficult but related question is: How will the rate of economic growth be affected by a change in relative prices? Have higher energy prices, for example, exacted a permanent penalty in terms of slower economic growth and less wealth per capital than otherwise would have been achieved?

A similar kind of question arises with respect to the substitution of robots for human workers in manufacturing plants. In this case, the recent advent of ever less expensive microprocessors and their application to machine controls, as contrasted with ever more expensive labor in manufacturing industries, appears to be shifting the historical relationship between labor and capital in many industries. This, of course, raises the question, what will the optimum mix be in the future? Advanced automation and robotics should result in an economic growth bonus, in contrast to the growth penalty imposed by the 1974-81 energy-price escalation. This means that while some jobs may be lost in the factories, others could be gained in the economy as a whole. The question is: how much gain in exchange for how much loss?

Questions like these are easier to pose than to answer. Truly useful answers often require quantitative models of production processes. Probably the first attempt⁸ in this direction was made by Philip Wicksteed almost a century ago; he postulated that the

output P ("production") of an economic process is a function of the inputs x_i ("factors of production"):

$$P = \Pi(x_1, x_2, \dots)$$

Wicksteed had no qualms about this statement, even though it is full of conceptual difficulties—such as whether the factors x_i are to be regarded as discrete quantities, as in a batch process, or flow rates, as in a continuous process. Both types of process exist, of course. Unfortunately, each interpretation precludes the other, as Nicholas Georgescu-Roegen has pointed out.⁹

Nonetheless, the function Π was immediately assumed to be differentiable, homogeneous and of the first degree—not because of any empirical evidence, but for mathematical convenience. With these assumptions, Euler's theorem applies, and

$$P = x_1 \partial \Pi / \partial x_1 + x_2 \partial \Pi / \partial x_2 + \dots$$

Here the terms $\partial \Pi / \partial x_i$ are the marginal products of the various factors and the x_i are payments to them. Euler's theorem thus implies that the total product is precisely exhausted when

the factor inputs x_i (land, labor, capital and so forth) are paid according to their marginal products. This neat and simple but powerful relationship has kept macroeconomists from using anything but homogeneous production functions of the first degree, although such a function also implies something rather curious: Namely, that if all the inputs x_i are increased by a factor z , the output also increases by exactly a factor z . This property, the homogeneity of the function Π , is known as "constant returns to scale" in economics. However, it is obvious that if not most, real industries do not exhibit constant returns to scale. In general, manufacturing processes become more efficient, both financially and thermodynamically, as the scale of production increases. That is, they have "positive returns to scale": A large electric power plant not only burns coal more efficiently than a small one, producing more electric power per unit input fuel, but it can also make more efficient use of labor and machines through specialization.

To take into account these positive returns to scale while maintaining

Information Inputs to Production

Source	Thermodynamic information	
	Embodied in product	Not embodied in product
Raw materials plus primary energy	Materials from which the product is made	Fuel, electricity, lubricants, solvents, surfactants, abrasives, bleaches, worn and broken parts, and so forth
Labor	Design of product and system; composition of the material	Layout, setup, control monitoring, inspection, assembly and overhead functions in manufacturing
Capital goods (that is, information embodied in machines)	Shape and finish of parts	Materials, handling, storage, environmental modification and protection

homogeneous production functions, economists argue that changes of scale actually represent differences in the technology of production. For any state of the technology there is a maximum product consistent with the state of the art; the (homogeneous) production function represents the economic factors involved in the state of the art. A technological improvement that allows a larger scale of production then corresponds to a different (homogeneous) production function.

At present, economists generally argue that the Wicksteed type of production function—a homogeneous function of the first degree—is applicable only to the economy as a whole, and only when factors of production are expressed in strictly monetary terms, but that such functions are not applicable to specific processes or plants. On the small scale, economists do acknowledge, in principle, a need for explicit process analysis based on engineering data and principles. The incompatibility between the global and particular analyses, or macro- and micro-scales, is a continuing source of embarrassment.

What has all this to do with the two laws of thermodynamics? On the micro-scale, where positive returns to scale are admitted, it is clear that a characterization of thermodynamic efficiency is necessary (though not sufficient)¹⁰ for any adequate description of the production process. On the macro-scale, as we have said, the choice of production function is typically guided by mathematical convenience. The popular choice for several decades was the famous Cobb–Douglas function:

$$\Pi(x_1, x_2, \dots) = x_1^{\alpha_1} x_2^{\alpha_2} \dots$$

To make the function homogeneous, the sum of the exponents is

$$\alpha_1 + \alpha_2 + \dots = 1$$

In the past decade or so the Cobb–Douglas function has been supplanted

by the constant elasticity of substitution function:

$$\begin{aligned} \Pi(x_1, x_2, \dots) \\ = [A_1 x_1^\rho + A_2 x_2^\rho + \dots]^{1/\rho} \end{aligned}$$

where

$$A_1 + A_2 + \dots = 1$$

(The Cobb–Douglas function is actually a special case, $\rho \rightarrow 0$.) The quantity $\sigma = 1/(1 - \rho)$ is called the elasticity of factor substitution.

In view of their ancient lineage and common use, it is somewhat surprising to note that not only do these functions fail to allow for economies of scale in the use of capital or labor, they are also not compatible with the simple materials-balance models illustrated in figure 2. One can define mass and energy as explicit factors of production, but this does not eliminate the difficulty. The problem is that any of these production functions has the mathematical property that the process represented by Π can produce a given output even in the limit as any one input vanishes if it is supplied with sufficient quantities of other factors. Thus, for example, one could reduce the input of materials to zero, substitute sufficient capital and labor, and still produce the same amount of goods. Clearly this is physically impossible: Both the final goods produced by the economy and the capital stock used to produce them necessarily embody a certain amount of mass and energy. Mass and energy cannot be created by labor or capital. The realm of substitutability of labor or capital for mass or energy is, at best, limited to the non embodied uses of mass and energy, as shown in figure 3.

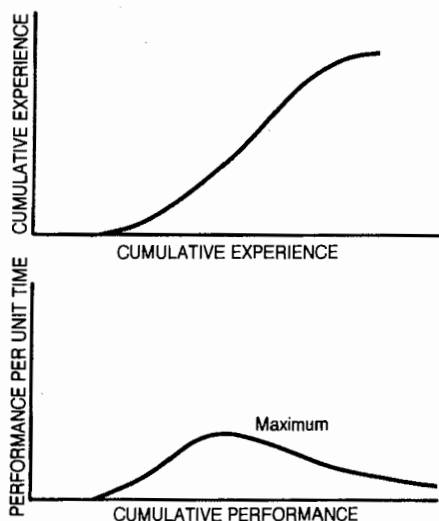
This objection is probably academic when such production functions are used only to analyze economic problems involving marginal substitutions near the current point of market equilibrium. But economists occasionally also use simple models such as these to

draw conclusions about more remote situations. A case in point is the classical problem of resource economics, namely: What is the optimal policy for extraction of an exhaustible resource? Despite the physical impossibility of substituting labor or capital for all materials, a number of economic theorists have used production functions, such as the constant-elasticity function, to analyze this problem. Indeed, in the midst of the energy crisis of 1974, Robert Solow presented¹¹ a model suggesting that a constant level of economic output could be sustained indefinitely, in principle, provided that the elasticity of substitution of capital and labor (taken together) for exhaustible resources is greater than unity. In effect, the model allows capital and labor to substitute for exhaustible resources such as fossil fuels. In fact, most of the theoretical work¹² being done by economists at the time ignored the implications of the basic laws of thermodynamics. Economic theorists, at least briefly, seem to have reinvented the perpetual motion machine, an idea that seems very hard to kill. It was, of course, the consequence of using a production function that is inconsistent with the known laws of physics, as Ronald Cummings and William Shulze, among others, have pointed out.¹³

Incidentally, macro-economic theory does not escape from difficulties by discarding aggregate production functions and retreating to a sectoral, static, equilibrium model of the Walras type, as Cambridge capital theorists tried to do. As we pointed out earlier, the closed static Walras model itself is inconsistent with the real world because of its failure to acknowledge the critical role of exogenous inputs of available work.

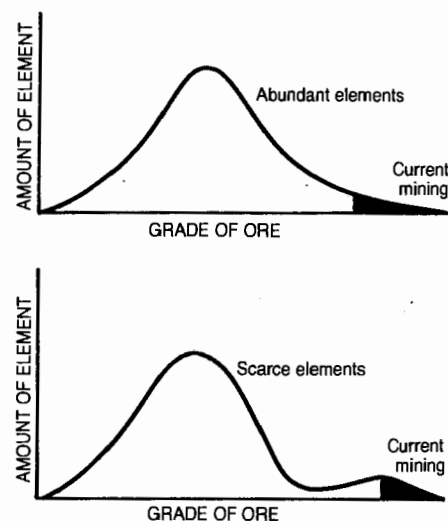
Negentropy

The existence of a connection between entropy and information has



Technological progress. As experience accumulates, performance improves; but as the technology matures, the rate of improvement diminishes. The easy discoveries are made early. Figure 5

Distribution of ores. The graphs show possible distributions¹⁶ of abundant and scarce elements in the Earth's crust: While for common elements there is a steady increase in the reserves (unmined ores) as we accept lower-grade (less concentrated) ores, the scarce elements appear in highly concentrated ores as well as "average" concentrations. Once the high-grade ores are exhausted, drastic changes of technology will be needed to mine scarce elements, while only evolutionary changes are required in the case of abundant elements. Figure 6



been at least highly plausible since the work of Gibbs and Ludwig Boltzmann around the turn of the century. Thus, for example, Maxwell postulated a demon who can segregate fast and slow molecules into different containers; starting from an equilibrium state, the demon generates a temperature difference between the containers, producing an apparent violation of the second law of thermodynamics. To make the separation, however, the demon requires precise information about the speeds of the molecules in the containers—information that can only be obtained by expending available energy from an outside source. The decrease in the entropy of the gas in the containers is necessarily associated with an increase in the information about the state of the system; in this case, on the part of the demon.

The connection can be made general: The more we know about the microscopic state of a thermodynamic system, the lower is the entropy of the system. Information is the negative of entropy. To make this notion more precise, we can paraphrase the statistical definition of entropy as

$$S = k \log \Omega + \text{const}$$

with Ω the maximum volume in the phase space of the system that is consistent with the information we have about its state. (More or less equivalently, one can take Ω to be the probability that the system takes on the thermodynamic state, assuming that it may take on *all* microscopic states with equal probability.) In this view, then, thermodynamic states of low entropy carry a great deal of information about the microscopic state of the systems; states of high entropy, represented by a large number of microstates in the statistical ensemble or a large volume in phase space, convey little information. Ordered states—for which there are few

alternatives—have low entropy; disordered states—where many alternatives look the same—have high entropy.

The concept of information is, of course, far more general than the notion of information about microscopic states of a thermodynamic system. In his investigation¹⁴ of the capacity of communications channels, Claude Shannon showed that one could define a general measure of information conveyed by a message consisting of "symbols" E_i :

$$I = - \sum p_i \log p_i$$

where p_i is the inherent probability of recording E_i . Consider an experimenter recording microstates of a thermodynamic system—using them as the symbols E_i ; specifying a macroscopic state then conveys an amount of information I . Shannon and, later, Leon Brillouin¹⁵ and E. T. Jaynes¹⁶ showed that the information and entropy are equivalent

$$S = - kI$$

and that one can, in fact, base much of thermodynamics on information theory. Information, of course, has much the same meaning in economics as it does in physics or engineering—a point we propose to elaborate.

Consider, as an example, the process of converting a set of raw materials, such as iron ore, coke, limestone and so forth, into a finished product—a piece of machinery of some kind. At each stage the organization (information content) of the materials embodied in the product is increased (the entropy is decreased), while global entropy is increased through the production of waste materials and heat. For example:

► Extraction activities start with the mining of ores, followed by concentration or beneficiation. All of these steps increase local order in the material being processed, but only by using (dissipating) large quantities of avail-

able work derived from burning fuel, wearing out machines and discarding gauge and tailings.

► Metallurgical reduction processes mostly involve the endothermic chemical reactions to separate minerals into the desired element and unwanted impurities such as slag, CO_2 and sulfur oxides. Again, available work in the form of coal, oil or natural gas is used up to a much greater extent than is embodied in metal, and there is a physical wear and tear on machines, furnaces and so forth, which must be discarded eventually.

► Petroleum refining involves fractionating the crude oil, cracking heavier fractions, and polymerizing, alkylating or reforming lighter ones. These processes require available work, typically 10% or so of the heating value of the petroleum itself. Petrochemical feedstocks such as olefins or alcohols are obtained by means of further endothermic conversion processes.

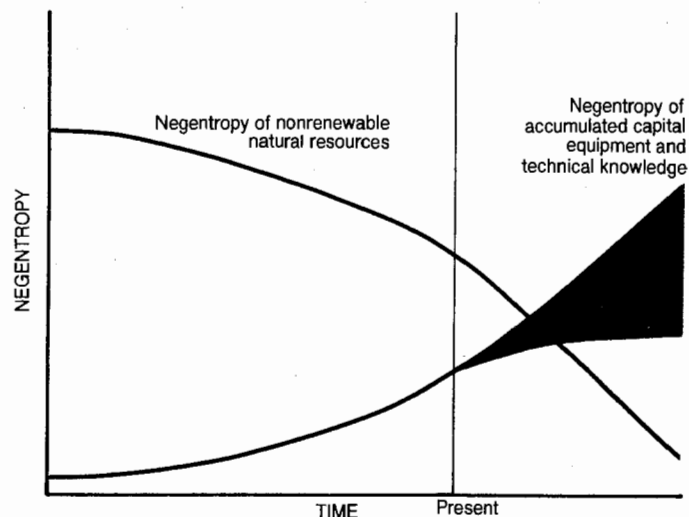
► Inorganic chemical processes begin by endothermic reduction of commonplace salts such as chlorides, fluorides or carbonates into their components. Again, available work (from electricity or fuel) is dissipated in each step.

► Fabrication involves the forming of materials into parts with desirable forms and shapes. The information content, or orderliness, of the product is increased, but only by further expending available work.

► Assembly and construction involves the linking of components into complex subsystems and systems. The orderliness of the product continues to increase, but still more available work is used up in the processes.

The simultaneous buildup of local order and global entropy during a materials processing sequence is illustrated in figure 4. Some, but not all of the orderliness of the manufactured product is recoverable as thermodynamically available work: Plastic or

The lady or the tiger? As nonrenewable resources have been used up, technical knowledge and capital equipment have accumulated at a sufficiently large rate to provide a steady increase in negentropy available to society. If future increases in accumulated negentropy continue to keep pace with the depletion of resources, we can look forward to a steady increase in the standard of living. If they do not, the future will be bleak. Figure 7



paper products, for example, can be burned as fuel in a boiler to recover their residual heating value and convert some of that to work again. Using scrap instead of iron ore in the manufacture of steel or recycled aluminum instead of bauxite makes use of some of the work expended in the initial refining of the ore.

Information content, or order, is not necessarily thermodynamically recoverable (as work), however: Order is sometimes embodied in patterns, such as material form and finish. When a DNA molecule replicates itself, embodied information (orderliness) is increased. Similarly, printing, casting, stamping, milling, forging and rolling transfer information to the workpiece and increase its orderliness. These information transfers require expenditures of available work. The order embodied in the finish and design of a final product can again be transferred or replicated, but only by still further expenditures of work—photocopying mold-making, machining, or whatever.

The increasing orderliness that characterizes the extraction, manufacture, and construction of tangible goods (as opposed to pure services) arise from information transfers of several distinct types. There are two basic categories of information input—embodied and non-embodied; and three sources—raw materials, labor and capital equipment (see the table on page 68).

An important distinction between labor and physical capital, on the one hand, and resources, on the other, is that the former play a role in production but are not physically embodied in the product. Labor and capital provide services (which generally also require inputs of material energy), but the services involved tend to be of an organizing nature: They increase local order while decreasing global order. In fact, we can argue that all economic services are essentially information transfers of some kind: One pays not only (and, in many cases, not chiefly)

for the matter and energy embodied in a product, but also for the order (information) embodied in it. Separating the informational (negentropic) contribution of an economic process from the materials and energy flows allows us to understand more clearly, in a given case, what inputs are substitutable and what inputs are complementary. Thus, while plastics may substitute for aluminum as a material input to, say, car manufacturing, one cannot replace materials (that is, plastics or aluminum) with more energy, more labor or more capital machinery. This is simply a consequence of the laws of conservation of mass and energy. The related question immediately arises: Are there comparable limits on the substitution between other factors?

Because capital equipment and human labor perform essentially similar functions in contributing embodied information, human labor and capital equipment are, in principle, mutually substitutable. The terms of competition between man and machine are dictated not by physical constraints but by their comparative economic advantage. The comparison can be made along four dimensions of capability:

- ▶ strength
- ▶ dexterity (manipulative speed and accuracy)
- ▶ perception (sensitivity to the surroundings)
- ▶ intelligence (capacity for problem-solving).

Machines easily outperform humans in strength: The days when the brawn of human workers like John Henry provided the raw power for a task are long gone from most industrial activities. Machines now perform as well as humans in terms of dexterity, depending on the specific task. However, machines at present have little or no ability to sense the outside world—with some exceptions, as in the the radar system that permits an airplane to land in fog. Industrially significant machine intelligence still lies years in the

future.

While individual processes can be characterized, in principle, by a specific combination of strength, dexterity, perception and intelligence, specific tasks can be performed by a range of processes, trading off performance in one dimension against another. It may, for example, be possible to perform a task (as a machine would) with very little sensory feedback but a high degree of mechanical dexterity. Or it may be possible to achieve the same result with less mechanical dexterity but much more sensory feedback, as a human would. The choice between a human worker and a machine thus depends on the marginal cost of substituting mechanical dexterity for perception. In both cases it is the capacity to generate information, to impose order on the workpiece, that is the criterion of performance.

Resource depletion

Because the extraction of natural resources and their conversion to raw materials is clearly a process in which the entropy reduction of some of the matter is the central part of the process, we may expect that the second law imposes economically interesting limits on this sector of the economy. Some recent economic shocks involving resource availability—such as the two energy crises of 1973–74 and 1979–80—have made resource economics a particularly lively subject for research.

It is true that the technology of exploration and extraction of resources has continuously improved over the past 200 years. But, on the other hand, the highest-quality mineral sources have mostly been discovered and extracted already, and new discoveries tend to be smaller, deeper, less accessible and generally more expensive to recover. Further technological improvements in exploration and extraction technology are also getting more costly to achieve and may become slower, as figure 5 suggests. On the

other hand, as existing reserves are consumed, the quality of replacement supplies may suddenly decline more rapidly than in the past, as in the case of the "scarce" resource of figure 6.

The quality of a resource is related to its entropy: the lower the entropy (or the higher the negentropy, or information content), the higher the grade of the resource. Higher-grade resources require less available work to purify than lower-grade resources for a given level of technology. Because improvements in technology reduce the need for available work in mining, refining and so forth, the information content in extraction technology is, in some sense, equivalent to the negative entropy of the higher-grade ores. As the quality of available ores decreases, one can compensate for some of the decreased negentropy by increasing the information content of the processor.

We have noted above that the manufacturing process results in a local accumulation of negentropy in the product itself, but that this requires a (much larger) expenditure of available work—which must come from somewhere. The economic system as a whole is evidently a stable dissipative structure far from (thermodynamic) equilibrium, in much the same sense that living systems may be considered to be stable dissipative systems far from thermodynamic equilibrium.¹⁷

At present, over 95% of the world's available work comes from fossil fuels and less than 5% is derived from renewable sources, such as hydroelectricity and biomass. Because fossil fuels are necessarily finite—the Earth is finite—the production system in its present form cannot be sustained indefinitely. Solow has formulated the economic aspect of this resource-depletion problem as follows:¹¹

If it is easy to substitute other factors for (exhaustible) natural resources, then there is, in principle, no problem. The world can, in effect, get along without natural resources. Exhaustion is an event, not a catastrophe. . . . If, on the other hand, output per unit of resources is effectively bounded—cannot exceed some upper limit of productivity which is, in turn, not too far from where we are now—then catastrophe is unavoidable. . . . Fortunately, what little evidence there is suggests that there is quite a lot of substitutability between exhaustible resources and renewable or reproducible resources.

While it is not possible to substitute labor or capital, as such, for embodied material or energy resources directly, there is a more general way of looking at the problem—as a substitution of technological knowledge for raw

materials. Any increase in the thermodynamic efficiency of a machine or process is an example of such a substitution. Similarly, technical improvements can reduce requirements for materials and energy by permitting machines to be reduced in size and weight. The miniaturization trend in electronics is well known, but most people don't realize that the power-to-weight ratio of prime movers, such as steam or gasoline engines, has also improved by a factor of something like 100 000 in the 280 years since Thomas Newcomen's first steam engines. These improvements represent a major accumulation of local information, in the sense that they vastly increase the effective availability of natural resources.

That the fossil and mineral negentropy resources we now depend on are being depleted is not really arguable, though there are arguments about the length of time we have before alternatives must be found. That extraction and energy-conversion technology also constitutes a kind of stock of negentropy is also not at issue; it is clear that improvements in technology can uncover ways to utilize a resource less quickly, thereby extending its life, or lead to a more available substitute for the scarce resource. Thus if technology brings forth inexpensive solar photovoltaics or fusion power in the next 50 years, the depletion problem for oil and coal may be resolved permanently.

What are the prospects of avoiding a resource-depletion catastrophe? It will not be avoided without a major effort, we believe. Only with a sustained large-scale R&D effort and very heavy capital investment in facilities thereafter can we provide the foundation of an information resource to replace the negentropy endowment of coal and oil. We also need to overcome the inertia and institutional obstacles in the way. Both the needed R&D and the vast future investment in construction and new equipment will have to be made by utilizing conventional mineral resources—which are already getting scarce. The oil glut of the early 1980s is a very temporary phenomenon. In the long run, the price of petroleum, natural gas and electricity will continue to rise; and the longer we wait to make the heavy investments needed to bring alternative energy sources into the system, the more costly those investments will eventually be. The sharp rise in the apparent cost of oil shale recovery is, in part, attributable to this phenomenon.

Is there a change that we will fail to react in time to avoid a catastrophe, that is, to avoid a traumatic adjustment in the economy that results in considerably lower living standards for many? We think the answer is yes. Rising

energy prices may not automatically bring about the necessary economic adjustments and investments in a timely fashion. If, as seems conceivable, the cost of the necessary investments starts rising rapidly just as fuel shortages begin to choke off economic growth, industrial societies could find themselves on a downward escalator from which a democratic, free-enterprise society might find it impossible to escape.

References

1. R. U. Ayres, A. V. Kneese, *Am. Econ. Rev.*, June 1969, p. 282; N. Georgescu-Roegen, *The Entropy Law and the Economic Process*, Harvard U.P., Cambridge, Mass. (1971); H. Daly, *Toward a Steady State Economy*, Freeman, San Francisco (1973); J. Rifkin, *Entropy: A New World View*, Viking, New York (1980).
2. For a modern discussion see, R. Dorfman, P. Samuelson, R. Solow, *Linear Programming and Economic Analysis*, McGraw-Hill, New York (1958).
3. J. von Neumann, *Rev. Econ. Studies* 13, 1 (1945-46).
4. F. Soddy, *Cartesian Economics*, Hendersons, London (1922).
5. H. T. Odum, *Environment Power and Society*, Wiley, New York (1971); B. Hannon, *Ann. Am. Acad. Political Social Sci.* 410, 139 (1953); M. Gilliland, *Science* 189, 1051 (1975).
6. D. A. Huettner, *Science* 192, 101 (1976). For a more technical discussion of the relation between the two kinds of optima, see R. S. Berry, G. Heal, P. Salamon, *Resources and Energy* 1, 125 (1978).
7. A. S. Manne, R. G. Richels, J. Weyant, *ORSA Journal (ORSA/TIMS Bull.)* January-February (1979), p. 1.
8. P. Wicksteed, *An Essay on the Coordination of the Laws of Distribution*, MacMillan, London (1894).
9. N. Georgescu-Roegen, "The Economics of Production," in *Energy and Economic Myths: Institutional and Analytical Economic Essays*, Pergamon, New York (1976), p. 61.
10. E. Gyftopoulos, L. J. Lazaridis, T. Widmer, *Potential Fuel Effectiveness in Industry*, Ballinger, Cambridge, Mass. (1974); and *Proc. Nat. Mtg. Detroit*, 16-19 August 1981, *Am. Inst. Chem. Engineers* (1981).
11. R. M. Solow, *Am. Econ. Rev.* 64, 11 (1974).
12. K. Anderson, *J. Econ. Theory* 4, 251 (1972); R. M. Solow, *Rev. Econ. Studies* 41, 29 (1974); J. Stiglitz, *Rev. Econ. Studies* 41, 123 (1974).
13. R. Cummings, W. Schultze, unpublished preprint.
14. C. E. Shannon, W. Weaver, *The Mathematical Theory of Information*, U. Illinois, P., Urbana, Ill. (1949).
15. L. Brillouin, *Science and Information Theory*, Academic, New York (1956).
16. E. T. Jaynes, *Phys. Rev.* 106, 620 (1957).
17. G. Nicolis, I. Prigogine, *Self Organization in Non-Equilibrium Systems*, Wiley, New York (1977).
18. B. J. Skinner, *Am. Scientist* 64, 263 (1976). □