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Because the manufacture of goods and services incorporates matter and energy, the physical sciences are clearly relevant to economics. In particular, the laws of thermodynamics can be expected to impose constraints on economic processes just as they do on physical processes. The Second Law of Thermodynamics - the law of increasing entropy - constrains economic processes to those that increase the entropy of the universe. This fact has significant, even world-shaking implications for economic theory, especially as it is applied to resource, environmental and technology policy.

ECONOMICS

Many economists regard their field as the science of the allocation of scarce resources. The economists' definition of scarcity is important: a resource is considered scarce if it cannot be acquired or used without exchanging another scarce resource for it, i.e., if the available quantity of the resource is insufficient to satisfy all demand for it at a price of zero. As a consequence, it will command a money price in the market place that reflects both its value and scarcity. In addition, some resources may command no market price, but still be considered scarce, as their use by one person deprives other potential users of their benefits. However, such situations are difficult for economists to handle because of the absence of a market price.

The term "resources" as used in economics is a slippery one. It refers variously to land, labor, capital, materials, energy, or all of these simultaneously under the non-specific rubric of "factors of production." If the resource in question is not "scarce" as defined above, it will not be considered at all. Since scarce resources command a market price, economists can express all inputs and outputs of a productive process in monetary terms, allowing a straightforward aggregation of these fundamentally different quantities.

Much of economic theory is built upon the simple but powerful notion that economic agents seek to maximize their utility through the buying and selling of economic goods in a free and competitive market. Thus, under a specific set of assumptions, it can be shown that a unique price exists in all markets that will simultaneously maximize the utility of both producer and consumer. Much depends on this simple contention; for example, in the 19th century Walras provided mathematical proof that a general equilibrium exists under these assumptions. However, many economists fail to recognize either the 19th century roots of this philosophy or that this simplistic form of utilitarianism conspicuously fails to account for much observable phenomena. While this original model has been made more sophisticated with respect to technology and growth in the 20th century, despite all the embellishments the economy continues to be viewed and modeled as a closed system with a circular flow of money and goods.

However, this view is fundamentally flawed, as the closed system model departs from physical reality in important ways that are apparent once the underlying physical mass and energy flows are considered. All goods, capital and consumer, embody both materials and energy, as do most services. The standard circular flow model has a source of goods (production) and a sink for goods (consumption). However, real materials are not actually consumed, they are returned to the environment as wastes. Thus the economic system cannot be closed if one includes the extraction and disposal of materials, since a closed system in thermodynamic equilibrium is necessarily passive and inert, without flows of matter or energy. The flows of matter and energy through a system also preclude the existence of an economic equilibrium, except in the special case of zero growth.

It is clearly more realistic to regard the economy as an open system through which materials and energy continuously flow. Once this is recognized, the laws of thermodynamics assert themselves and have significant implications for economic theory. The first of these, derived from the First Law of Thermodynamics, is that the output flow of matter and energy into wastes must be matched by the input flow, i.e., that which was extracted from the earth. The second implication of physical laws, derived from the Second Law of Thermodynamics, is that the available energy contained in the output is less than that contained in the original inputs. In other words, materials tend to be entropically degraded during each stage of the production process, so there is a global increase in entropy as economic production proceeds.

EFFICIENCY

The concept of thermodynamic efficiency was first developed in connection with steam engines: an engine was more efficient if it could pump more water while using the same quantity of coal. This is considered first-law efficiency, and is concerned with the quantity of work generated from a given volume of heat input. A process that is more efficient requires (or wastes) less heat and thus uses less energy to accomplish a particular task. Second-law efficiency is measured by taking the ratio of available energy contained in the output to that contained in the input. A process that is second-law efficient generates outputs with available energy levels that are not substantially less than those of the inputs. Thus a simple heating system may be considered first-law efficient if only 30% of the heat goes up the chimney to heat a space, but may be second-law inefficient in that a large volume of low-entropy matter is used to warm a room to a few degrees above the natural environment, while producing a large volume of high-entropy waste in the process.

However, in economics, efficiency tends to be conceptualized qualitatively rather than quantitatively, and derives from a competitive free market. In this free market, rational maximizing economic agents will generate a Pareto optimal equilibrium if no possible reallocation could be effected that would make one person better off without making another worse off. This implies that the output has been maximized for the economy given well-defined preferences and the available inputs (resources). However, in reality this is a remote abstraction - one that denies any relationship between economic and thermodynamic efficiency.

PRODUCTION FUNCTIONS

The divergence between these two concepts becomes clearer when production processes are considered. Economics uses production functions to describe mathematically the relationships between various inputs and the volume of outputs. These functions, subject to a strict set of assumptions, presumably reveal the substitutability between various factors of production, and also measure the maximum potential output given a particular technology set. As one resource becomes more costly, perhaps reflecting greater economic scarcity, it may be replaced by other factors of production at precise, measurable rates derived from the production functions. This approach may be valid when measuring small substitutions at or near the current market equilibrium, but it is clearly problematic when used - as it often is - to draw conclusions about more remote situations involving the entire system over longer time horizons.

This flaw is particularly evident when it comes to resource economics. In spite of the physical impossibility of indefinitely substituting labor and capital for matter and energy, economists have continued to insist on using production functions for this purpose, thereby basing policy analysis on the flawed supposition that constant levels of output can be maintained through input substitution. For example, much of the economic analysis done during the energy crisis was inconsistent with the known laws of physics, making it a kind of reinvention of the perpetual motion machine.

NEGENTROPY

For some time a connection has been seen between entropy and information: the greater the knowledge about the microscopic state of a thermodynamic system, the lower is the entropy of the system. Knowledge or information (orderliness) tend to increase the available energy in a given quantity of matter, and are thus the negative of entropy, or negentropy. A production process may therefore result in decreasing entropy locally even as global entropy is increasing due to the generation of waste material and heat. As nonrenewable resources are used up, it is necessary for technical knowledge and capital to accumulate at a sufficient pace to provide a steady increase in negentropy to offset the rise in entropy. For example, in this fashion it is possible, through knowledge, to substitute types of matter (e.g., plastic for aluminum) within the production process. However, these observations do not remove the central limit imposed by the Second Law; no amount of knowledge will enable us to substitute labor and capital for all matter and energy.

RESOURCE DEPLETION

While the technologies of resource exploration and extraction have become more sophisticated over the past several centuries, it is equally clear that the highest quality and most readily available of those resources have already been discovered. What remains is less pure and less accessible, and will consume more available work or energy to retrieve it. At present, a large proportion of the world's energy comes from fossil fuels, a resource that is necessarily finite.

The economic system as a whole may be considered a stable, dissipative system that functions far from a thermodynamic equilibrium, and it cannot be sustained in its present form.

It is possible to avoid a resource-depletion catastrophe, but only through an enormous, conscious effort to do so. The inevitable alternative is a bleak future. Massive R and D efforts can increase the negentropy embodied in knowledge - the orderliness of our system - to increase the available matter and work, and to increase the thermodynamic efficiencies of processes to offset the catastrophic rise in entropy associated with our present system. But higher energy prices or other decentralized market forces will not automatically induce these investments, and there is a significant danger that we may not react in time; the necessary investments will become increasingly expensive and the available energy increasingly scarce as we delay. We may find ourselves on a downward escalator from which a democratic, free-enterprise society could find it impossible to disembark.