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Economics, entropy and sustainability

GEORGE F. McMAHON
Camp Dresser and McKee, Inc., 2100 RiverEdge Parkway, Suite 500, Atlanta, Georgia 30328, USA

JANUSZ R. MROZEK
Georgia Institute of Technology, Atlanta, Georgia 30332-0615, USA

Abstract Neoclassical economics has only recently considered the problem of sustainability—how to provide for the well-being of future generations given ecological constraints. In general, the neoclassical economist perceives physical and ecological constraints on economy-environment interactions as inconveniences that will inevitably be overcome by substitution—the discovery of new economic resources or technologies allowing the conversion of noneconomic materials to economic goods. Ecologists and ecological economists, however, argue that the constraints will bind. The debate centres on the relevance of entropy to the economics of resource use: irrelevant in the neoclassical view, relevant in the ecological. This paper places entropy, within the context of neoclassical economic thought, as a limit to economic growth. The paper rigorously argues the existence of limits to knowledge and consequently to technology and substitution, undermining a basic assumption of neoclassical economics and establishing the relevance of entropy to economic theories of resource use.

Economie, entropie et durabilité

Résumé Ce n'est que récemment que l'économie néo-classique s'est intéressée au problème de la durabilité, à savoir assurer le bien-être des générations futures en présence de contraintes écologiques. En général, l'économiste néo-classique considère les contraintes physiques et écologiques auxquelles sont soumises les interactions entre l'environnement et l'économie comme des inconvénients qui seront nécessairement surmontés par substitution, c'est à dire par la découverte de nouvelles technologies ou ressources économiques permettant la transformation d'objets non-économiques en biens économiques. Les écologistes et les économistes écologiques soutiennent par contre que ces contraintes finiront par prévaloir. La discussion tourne autour de la pertinence du concept d'entropie en économie de l'utilisation des ressources: hors de propos selon la vision néo-classique, appropriée selon celle de l'écologie. Cette étude identifie, dans le contexte de la pensée économique néo-classique, l'entropie comme une limite à la croissance économique. Cette étude argumente rigoureusement l'existence de limites aux connaissances et par conséquent à la technologie et à la substitution, réfutant ainsi une hypothèse fondamentale de l'économie néo-classique et établissant la pertinence de l'entropie dans le domaine de l'économie de l'utilisation des ressources.

INTRODUCTION

Economics is the science traditionally dealing with questions of scarcity. The allocation of scarce resources (natural and human) involves broad philosophical issues—questions of values, preferences, efficiency, and equity. Advances in the physical and ecological sciences in recent years have led to the notion of *sustainability*, and with it a new problem that has not historically been of great concern to mainstream

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economists. Daly (1992a) describes the problem of macroeconomic scale, or how large the economy should be relative to the environment, as the "glittering anomaly" of neoclassical economics, because whereas the optimal scale of a single economic activity may be defined as the point at which net benefits are greatest, there is no agreed-upon metric for optimal macroeconomic scale. This anomaly is reflected in conflicting opinions among mainstream economists on the approaches to achieving an optimal intertemporal allocation of resources, the principal problem of sustainability. The debate raises fundamental questions as to whether the problem of scale might already be adequately considered in neoclassical theory, and whether it needs to be considered at all.

A central issue to this debate (Burness *et al.*, 1980; Ranson, 1979, 1986; Swaney, 1985, 1986) is whether neoclassical theories of resource use should be modified to incorporate the Second Law of thermodynamics, also known as the entropy law. Neoclassical theory presently incorporates First Law principles, i.e. conservation of energy and materials, demonstrating conditions under which prices, indicating the preferences of rational economic agents, accurately reflect resource scarcity, and conditions in which markets efficiently allocate scarcity. Nonetheless, the entropy law imposes an additional constraint of directionality on all physical processes not reflected by conservation alone. Entropy then becomes relevant to the economics of resource use if First Law considerations yield significantly inaccurate measures of scarcity within the forecast horizon of economic planning and policy development.

The purposes of this discussion are to develop a vocabulary for framing the issue of the relevance of entropy to economics, primarily by exploring the role of technology in economy-environment interactions, and to establish formally the limits of technology in overcoming entropic constraints to economic growth. The broader objective in resolving the relevancy issue is to remove the principal obstacles to the assimilation of ecological economics into the mainstream of neoclassical economic thought. These obstacles are the beliefs that scarcity is accurately reflected in price, and that markets will always respond to acute scarcity by spawning backstop technologies or natural-capital substitutes. In this view, markets perpetuate themselves, circumventing entropic constraints to growth by continuous technological improvement, and existing neoclassical theory adequately deals with scarcity. If these beliefs are true, then entropy is not relevant to economics, and sustainability can be defined merely in terms of technological capability. If they are false, however, then entropy does constrain economic growth and would therefore be relevant to economic theory; theories of sustainability framed entirely in terms of technological improvement must then be false. It follows that neoclassical corrections to market behaviour cannot overcome the constraint that entropy places on sustainability.

SUSTAINABILITY OF ECONOMIC SYSTEMS

In contrast to the well-known Brundtland definition (WCED, 1987), widely seen as a call for continued economic expansion without environmental degradation, "sustainability" for the purposes of this discussion is more broadly defined as the

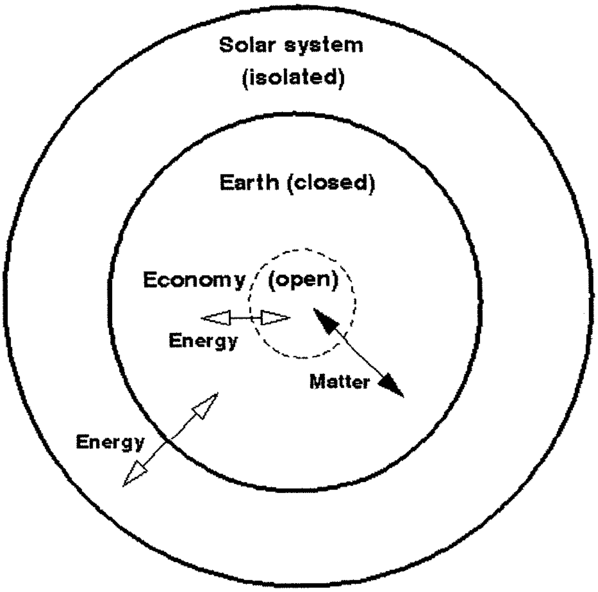

Fig. 1 Hierarchy of physical and economic systems.

ability to maintain or increase well-being over time. Exploration of the axiomatic bases of economic models, in terms of how they interpret the hierarchy of systems in which economy- environment interactions occur, frames the debate on the relevance of entropy to economics.

The hierarchy of physical systems affecting the economy is shown in Fig. 1. The economy is an open system, extracting usable energy and matter from, and returning unusable wastes to, the surrounding environment. Its boundary is movable (represented by a dotted line), because it shifts as economic activity adds to and removes materials from the economy. The global environment, upon which the economy depends for life support, for supplies of raw materials for production, and for the assimilation of wastes, can be considered to be a closed system, because while it receives solar energy and radiates heat, it receives relatively insignificant amounts of matter from the surrounding space. Finally, the solar system, relatively insulated by enormous interstellar distances, receives comparatively little energy or matter from its surroundings, and so can be considered for practical purposes to be an isolated system. Much of the sustainability debate can be cast as determining how large the economy system is relative to the earth system.

First and Second Law considerations in economics

Broad definitions of the First and Second Laws of thermodynamics allow their incorporation into a vocabulary suitable for framing and discussing the issue of relevance of entropy to economic processes. The First Law requires that matter and energy be conserved, i.e. matter-energy can neither be created nor destroyed. The consequences of the First Law to physical systems are that the total content of matter and energy in an isolated system is fixed, and that the total matter in a closed system is fixed. The First Law is implicit in, if not axiomatic to, most commonly-accepted economic theories of resource use.

The First Law fails to describe irreversibility, however. The original inputs may never be recovered from the outputs of real or [more precisely] finite-time processes, and in some cases from mathematical or infinitesimal-time processes as well. Thus, while the quantity of energy and materials is conserved as predicted by the First Law, their quality or availability is not—all physical processes convert low-entropy energy and materials to high-entropy wastes, from which the original low-entropy inputs cannot be recovered without the conversion of still more low-entropy resources to high-entropy wastes. This irreversibility is governed by the Second Law; entropy is defined here as the degree to which finite-time processes are irreversible.

The optimal macroeconomic scale, then, depends on the Earth's stores of low-entropy energy and materials, and its ability to harness solar energy for economic use. While the economy may not be limited by the solar energy flux in the foreseeable future, the finite limits of materials needed to transform solar energy into economic goods are more apparent, raising serious questions as to how long the Earth's natural capital stocks can sustain present or increased future levels of throughput. Of more immediate concern than depletion of individual natural resource stocks is interdependency and complementarity, or coevolution, among natural capital sources and waste sinks, limiting or preventing substitution—the market response that alleviates scarcity. Neoclassical throughput accounting using only First Law principles can fail to account for coevolution, environmental degradation, and suffusion of high-entropy waste sinks, all of which make future consumption thermodynamically more difficult. Resolving the issue of relevancy of entropy to economics assists in determining whether current neoclassical theory can be amended to take the Second Law into account and adequately address these concerns.

As part of the relevance of entropy debate, economists have argued whether the Second Law applies strictly to energy, or whether "matter matters" as well (Georgescu-Roegen, 1971). Because the physical sciences draw no distinction between entropy of energy and entropy of matter (and in fact extend the consideration of entropy to quantum mechanics, information science, biology, cosmology, and to other fields of study as well), the distinction is viewed as purely arbitrary by the authors and not well suited to framing the issue of relevance of entropy to economics. As a result, the authors adopt the broader scientific view, that entropy is a property of matter-energy interactions and thus applies to both energy and matter.

The question of entropy's relevance to economics is the question of whether entropy is the fundamental, irreducible economic good. Arguments in favour of relevance hold that entropy is a physical law imposing an absolute constraint on economic growth—while substitution among individual resources (specific sources of low entropy) is sometimes possible, it is not always possible and will be less possible as time passes. In Daly's (1991b) words, "Substitutability among various types of low entropy does not mean there can be a substitute for low entropy itself." The opposing view is that "entropy is an anthropomorphic concept intimately associated with what is useful and, therefore, defined by current technology" (Young, 1991). Thus, in this view, new generations of technology can relax the constraint that entropy places on the economy; scarcity of low entropy can decrease or remain relatively constant over time.

Sustainability

Following Norton (1989), environmental decision making models can be characterized by the degree to which they assimilate two principles known as the *Axiom of Material Value* and the *Axiom of Abundance*. The Axiom of Material Value holds that resources have no intrinsic value apart from their economic value in markets. Thus many essential functions of the environment, though critical to the economy, may have little value because their use is not allocated through markets. The Axiom of Abundance holds that the Earth is very large in comparison to the economy, so large that for practical purposes natural capital is unlimited (cannot be significantly depleted or degraded by economic processes within meaningfully human time frames), and production need not be limited in the long run. Referring to Fig. 1, the economic open system would comprise an insignificantly small portion of the surrounding environment, and therefore cannot cause its entropy to significantly increase within an economically meaningful span of time. Entropy is then irrelevant to production, and thus to economics.

Neoclassical thought incorporates constraints on the quantity of natural capital, consistent with the First Law. However, the quality of manmade and natural capital, in terms of how they can substitute for other inputs, depends only upon knowledge, manifested as technology. Thus the Axiom of Abundance changes to an *Axiom of Technological Abundance*: technologies will always be found enabling substitution among sources of natural capital and between manmade and natural capital. This axiom, if true, means economic expansion can continue without environmental degradation as long as technological discovery continues, and entropy is again irrelevant to the economics of natural resource use. Referring to Fig. 1, the economy can expand to those of the surrounding closed system, as the economy creates manmade substitutes for environmental functions. The possibility that new technology may not be found is dismissed by rationale, anecdote, thought experiment, or by obvious apologia for technocracy (Simon, 1981; Simon & Kahn, 1984; Drexler, 1987; Myers & Simon, 1994). Carpenter (1995) classifies the neoclassical view, predicating sustainability on technological capability, as "weak sustainability".

Recently, some scientists have perceived the neoclassical tools used to measure and manage the environment to be inadequate. A new science, ecological economics, is emerging as a blend of science dealing with both economic and ecological scarcity. Ecological scarcity is seen as the result of coevolution, "...an ensemble of separate but interacting constraints" on economy-environment interactions, ultimately limiting economic growth (Ophuls & Boyan, 1992). Ecological scarcity thus limits substitution because the scarcity of one resource may create or exacerbate the scarcity of others. Increased awareness of the considerable uncertainty inherent in predicting the coevolutionary consequences of economy-environment interactions has led to the realization that the scarcity of natural resources, even those traded in markets, might not necessarily be correctly perceived or properly valued. The Axiom of Material Value is rejected in favour of a belief that parts of the environment have intrinsic value. Furthermore, markets, focusing on misperceived causes of scarcity, may sometimes produce technologies enabling economic expansion only with new or more severe environmental repercussions. Thus, from the ecological perspective defined by Carpenter (1995) as "strong sustainability", the Axioms of Material Value, Abundance, and Technological Abundance are unequivocally rejected.

Proponents of ecological economics consider the problem of sustainability to be that of sustainable macroeconomic scale, acknowledging the possibility that the economy may become or may already be so large that it places demands on the environment exceeding its carrying capacity. In terms of Fig. 1, the economy becomes too large relative to its surrounding closed system. Entropy, therefore, as a measure of irreversibility, is relevant to the economics of resource use, particularly in determining whether current or future levels of throughput threaten to overshoot environmental carrying capacity. If relevance were proven, entropy would replace Material Value and Abundance as the logical foundation of sustainability, providing a theoretical basis for the unification of economics, physics, and the ecological sciences (Odum, 1971; Georgescu-Roegen, 1971, 1976; Daly, 1980, 1981, 1991b). Theoretical and applied research has assumed relevance in creating coevolutionary models of economy-environment interactions providing physically-based metrics of sustainability (Norgaard, 1984; Meadows *et al.*, 1992; Ruth, 1993).

ENTROPY AS PHYSICAL LAW AND ORGANIZING PRINCIPLE

The essential logical argument against the economic relevance of entropy was made by Young (1991, 1993), maintaining that entropy is a physical law of limited applicability exclusively within the domain of thermodynamics (applying therein only to energy and not to matter), with the result that the environment (the closed system of Fig. 1) is really not a closed system at all because it continuously receives negentropy in the form of nearly limitless solar energy. Young poses a thought experiment to support the Axiom of Technological Abundance: limitless energy and limitless knowledge can continuously provide the tools needed to forestall natural entropic degradation, and to discover or recover negentropic (economic) resources from vast stocks of previously entropic (noneconomic) materials.

Young argues implicitly that knowledge enables a closed system to continue to perform work at a constant rate indefinitely, to which the direct response (Daly, 1992b, Townsend, 1992) is to point out the clear violation of the Second Law. Unfortunately, those responses and the more general case for the relevance of entropy to economics centre largely on anecdotal evidence of diminishing returns of technology in the face of ongoing demand (Ayres, 1978, 1994; Ayres & Miller, 1980; Georgescu-Roegen, 1976; Rifkin, 1989; Meadows *et al.*, 1992; Ophuls & Boyan, 1992). Therefore they fail to address the axiomatic basis and the underlying logic of Young's experiment. While compelling examples of ecological overshoot and collapse exist, notably that of Easter Island (Diamond, 1995), the logical case for diminishing returns is predicated on the entropy law itself and so cannot refute the teleological argument. Proof of the relevance of entropy and the limits of technology must be sufficiently rigorous to overturn the axiomatic basis on which all such thought experiments are based.

The flaw in the formulation of the thought experiment itself is the presumed abundance of economic resources as the initial condition. The Axiom of Abundance merely restates the sorites ("heap") problem of mathematics—the paradox of removing a single grain from an uncountable number (heap) of grains, leaving still a heap. Subsequent subtractions likewise leave a heap, so that unless a qualitative distinction between heap and non-heap is made after some number of subtractions (an impossibility, given the point at which the uncountable becomes countable cannot be known), the logical absurdity results of a heap remaining after all the grains have been removed. The divergence between prediction and reality produced by the sorites problem is due to the repetition of the conclusion of the previous stage serving as the initial condition for the next (Rotman, 1993). When the heap contains practically uncountable low-entropy stocks from which individual consumers remove only minute quanta, the logical appeal of the Axiom of Abundance seems compelling. From the sorites perspective, however, the reality becomes clear: resources may appear abundant until shortly before they are exhausted, belying true scarcity and impending economic collapse.

As a direct consequence of the undermining of the Axiom of Abundance, the sorites problem demonstrates the principal weakness of neoclassical economics: the inability of markets driven by individual preferences to measure accurately and value appropriately physical scarcity. Rational economic agents, confronted daily with countless consumer choices (each of which may present a number of sorites problems), cannot possibly ascertain true scarcity among all the "heaps" of interdependent and unmeasurable negentropy stocks, and so cannot properly or consistently value scarce resources. While occasionally perception may approximate the reality of scarcity closely enough for markets and institutions to respond appropriately, the sorites problem has implications well beyond mere uncertainty and imperfect markets. From the sorites perspective, it is unlikely that even relative scarcity among the multitude of coevolutionary resource stocks involved in economy-environment interactions (whether valued in the economy or not) can be accurately gauged in the face of complex system dynamics.

While the fallacies of resource abundance and material value are exposed by the sorites problem, the teleological arguments made by Young—on the nature of entropy itself, whether it applies to matter as well as to energy, the constraints it places on economic growth, and the ability of technology to overcome these constraints in time to prevent economic collapse—are far more difficult to dismiss. Fortunately, the entropy conundrum is partially illuminated by the sorites problem, which suggests ambiguity in perceived initial conditions as the cause of subsequent divergence of perception and reality; vagueness, divergence, disorder, and initial conditions all characterize mathematical and scientific understandings of entropy and their applications to energy, matter, and information. The scientific view is far broader than that articulated by Young's experiment, which presumes entropy to be an empirical law applicable only to things thermodynamic, an inconvenience that can be overcome by technologies improving mechanical efficiency or avoiding thermodynamic processes altogether. This is the mechanistic view of nature, a view that can only be rationalized by the Axiom of Abundance, for within a closed system, every localized decrease in entropy (in the open economic subsystem of Fig. 1, for example) must be accompanied by an overall greater increase in the entropy of the surrounding closed system. The only logical arguments for the neoclassical paradigm of sustained economic growth in a closed system are (a) the existence of unlimited (uncountable) negentropy stocks, and/or (b) the ability to recycle finite stocks with such efficiency that the rates of entropy generation and negentropy depletion are infinitesimal. The sorites problem addresses the first argument; the first step in addressing the second is taken by providing a more complete description of the mathematical and scientific understanding of entropy than presented by Young's experiment.

Entropy has been previously defined as the irreversibility of finite-time processes, but this definition admits of no explanation for the cause of irreversibility. The mathematical view of entropy extends well beyond thermodynamic empiricism, to the extent that entropy is not considered so much a natural law, nor even a law of mathematical necessity (formally deducible), as an organizing principle of knowledge. Organizing principles, in Barrow's (1991) words, "are likely to differ from conventional laws of nature because they would need to apply to systems of finite size. They will not dictate how elementary particles move. Rather, they will constrain how an entire collection of [laws] can be configured". This is because the laws of nature discovered thus far in general possess the property of time-reversibility, whereas the unmistakable predilection in nature is for history to move in one direction only (from order to disorder)—hence entropy's designation as "time's arrow". The "arrow" of entropy increase reflects the extreme improbability of the occurrence of any specific initial condition (e.g. an economically-desirable state) that sets in motion an even more improbable sequence of events in which, in sorites fashion, the entropy state of the system unfailingly continues to decrease with each subsequent event, perpetually reducing the entropy of the closed system in which these events occur. While some physicists regard entropy in this regard as a reflection of the improbability of a given initial condition, others regard it as a more fundamental idea, prior even to the laws of nature themselves (Barrow, 1991). Whether an initial condition or a paradigm for the laws of nature, entropy is clearly an *a priori* condition affecting the subsequent history of all real events (events involving both energy and matter). As such, entropy cannot be logically deduced and is therefore axiomatic to any formal system used to describe the physical universe.

LIMITS OF TECHNOLOGY

Having established entropy as an organizing principle of natural law, axiomatic to formal scientific thought, Young's conjectured ability of technology to create limitless abundance from finite resources can now be examined in the light of an area of formal mathematical conjecture known as Incompleteness.

Technology can be said to put into practice scientific principle derived from mathematics (Barrow, 1991). As such, technology developed from scientific knowledge involving the whole of mathematics is bounded by the limits of formal decidability, originally proposed in 1930 by the Czech logician Kurt Gödel (1965). These limits are known as the Incompleteness Theorems, summarized as follows:

Any formal system *T* that is:
(a) finitely describable
(b) consistent
(c) as strong (rigorous) as Peano arithmetic
is subject to two limitations:

Theorem 1: *T* is *incomplete*, i.e. there will be some statement about the addition and multiplication of natural numbers that can neither be proved nor disproved by *T*.

Theorem 2: *T* is *unable to establish its own consistency*, i.e. is unable to prove that no contradiction can be derived from *T*.

The implications of the theorems are as devastating as they are ubiquitous; mathematics is open-ended (there will never be a final, best system of mathematics), and there will always be formally undecidable problems, so that science making use of the whole of mathematics will never have all the answers (Rucker, 1995). The situation has been characterized as a house built on sand: "...the foundations of mathematics are in doubt, and as a result all of the sciences are imperilled". (Barrow, 1993). Mathematical descriptions of physical reality using less than the whole of arithmetic, of course, could be complete (Barrow, 1991), but only if reality admitted of a finite description. This would of course require overcoming the fundamental premise of the sorites problem: knowing where the uncountable becomes countable, when "...reality is, on the deepest level, essentially infinite". (Rucker, 1995).

The most direct consequence of the first Incompleteness Theorem to a consistent economic theory of sustainability is that there will always be problems that cannot be solved. All economic activities are physical, so some of the unsolved and unsolvable problems will inevitably arise out of economy-environment interactions. A far more serious implication to technological efficacy arises out of the first Theorem: analytical and numerical representations of reality must necessarily simplify and can therefore only approximate reality. A significant probability exists that simplified models will overlook or incorrectly predict significant chaotic and/or coevolutionary responses of complex natural systems to human economic activities. In sum, technology will not solve all of the problems of resource scarcity, and in some instances will make matters worse.

Technological innovation is limited not only by Incompleteness, but also by several sources of bias that potentially shift the focus of sustainability efforts away from the true problems. The premise of technological neutrality is challenged by the commons problem (Hardin, 1968), in which agents, seeking to maximize personal profit, suboptimally deplete public goods (natural capital without property rights), thereby diminishing the common good. Economic and political institutions, reflecting the character of society as determined by market forces, dominant interest groups, and dominant technologies, give rise to "technological determinism" (Ogburn, 1933, 1934, 1964; Ogburn *et al.,* 1946; Ogburn & Nimkoff, 1955; Thurow, 1980). As long as the ecological consequences of economy-environment interactions are not fully recognized, technology will fail to accommodate ecological limits, leaving ecological scarcity either unaffected or possibly aggravated.

The second Incompleteness Theorem effectively disproves all formalist thought experiments attempting to debunk entropy, because entropy is axiomatic to the current mathematical description of the universe. For no sentence S (representing entropy) can a theory T (embodying insofar as known a correct mathematical description of the universe) prove both S and the negation of S, a contradiction represented as Con$\{T\}$ (Rucker, 1995). Thus no thought experiment nor any sequence of formal statements can decide the truth or falsity of entropy. Only the formal system Con$\{T\}$, to which entropy is not axiomatic, can do so, but then neither T nor Con$\{T\}$ can prove itself to be the final, best formal system. Young's experiment fails as must any that proposes not to establish Con$\{T\}$ as an alternative to T, but rather to disprove T from T.

THE ECONOMICS OF SUSTAINABILITY

The foregoing discussion provides a vocabulary for framing the predominant economic theories of sustainability, which is subsequently applied in formal arguments undermining the Axioms of Material Value and Abundance, the foundations of neoclassical economics. The sorites problem shows the Axiom of Abundance to be potentially illusive, and because falsely perceived scarcity cannot be appropriately valued in markets, the Axiom of Material Value is of little consequence. The hope for restoring abundance through technological innovation is shown by the Incompleteness Theorems to be false in the long run, and moreover that at least some attempts to do so will make matters worse. Because entropy is axiomatic to the mathematical system underlying technological innovation, the latter cannot cope with all problems arising from economy-environment interactions. The tragedy of the commons and technological determinism further diminish the prospects for future technological salvation.

Biases against sustainability can be overcome by recognizing and avoiding the sorites trap, by realizing that the world is being transformed in various subtle as well as obvious ways, by recognizing the passing of the historical turning point: "from empty-world to full-world economics" (Daly, 1991a). This recognition requires a judgement to be made as to when the apparently abundant stocks of natural resources have been or will be reduced to very finite size, creating physical scarcity—in effect a guess as to when the heap is no longer a heap: the only solution to the sorites problem. The issue central to the continued relevance of economics in dealing with problems of ecological scarcity is not whether entropy is relevant to economics, but how to measure and respond to entropic constraints on macroeconomic scale and sustainability, and how to structure markets to take account of the common good in balancing between present and future welfare.

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