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The Microeconomics of Waste and Entropy

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Abstract

The increasingly relevant problem of natural resource use and waste production, disposal, and reuse is examined from several viewpoints: economic, technical, and thermodynamic. Alternative economies are studied, with emphasis on recycling of waste to close the natural resource cycle. The physical nature of human economies and constraints on recycling and energy efficiency are stated in terms of entropy and complexity.

What is a cynic? A man who knows the price of everything, and the value of nothing.

Oscar Wilde [1]

Our planet is finite in size and, except for a few energy and matter flows, its biosphere forms a closed system. The envelope that makes life possible extends a small distance below the surface of the Earth and less than a hundred miles into the atmosphere. While almost closed, the biosphere is not static, but is constantly changing, moving flows of energy, air, water, soil, and life around in a shifting, never-repeating pattern. The combination of general physical laws and the specific properties of the Earth places important constraints on the activities of life, some embodied in the metabolism and forms of living creatures, others imprinted into their genes by selective effects. All life needs sources of energy for sustenance and imposes a burden of waste on its environment. Since this waste is usually harmful to the creatures emitting it, the environment must, if these creatures are to continue living, break the waste down into less toxic forms and possibly reuse it.

The growing dominance of humankind over the planet, both by technological power and by numbers, imposes certain costs on the biosphere, sometimes a result of conscious attempts at controlling Nature, but more frequently by unwitting influence. Moreover, the burden of carrying the activities of human sustenance, unlike that of other animals, cannot be understood by considering the physical and biological activities of each person in isolation. Because of their unique position at the top of the food chain, their tool-making abilities, and the co-operative character of human activities (the division of labor or specialization), the physical and biological aspects must be considered together in the context of the peculiarities of economic life [2]. The economic aspects take on an independent importance because of the modification of individual or family subsistence by tool-making, surplus production, and trading [3]. This point of view is necessary for comprehending the ecological significance of all economies more elaborate than the simplest subsistence or household economies, up to and including the most sophisticated systems of technology and trade. On the other hand, the formulation of economic theory has generally taken place, apart from a few outstanding exceptions [4], with scant attention paid to how physical and biological laws make their appearance in the course of humanity's reshaping of its environment [5]. This article explores human economics as a special branch of ecology, with particular regard to the production, disposal, and possible reuse of waste.

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Natural Resources and Rents

To begin investigating the problem that the waste produced by our economic system poses, we consider, in simplified diagrammatic form, the streams of economic activity that make up a conventional economy (Figure 1) [6]. We ignore complications such as hoarding, credit and debt, and unemployment of resources, as they do not change the essentials. One set of streams is made up by various flows of matter and energy in the form of goods and services, a collection usually called the *real* economy. The inputs of the real economy are natural resources, labor, and capital (tools) [7]. The outputs are consumption goods, capital goods, and waste. Two of the output streams are tied back to the input streams to form a closed system, the consumption goods used by labor to sustain and reproduce life and the capital goods added to the previously existing stock of capital. The third output stream is waste, discharged into the environment, but not tied back to the input stream of natural resources, which are taken from the environment. Since a functioning economy is never exactly in an equilibrium of steady flows, but always expanding or contracting, diagrams such as Figure 1 are only instantaneous snapshots.

Counter to the flow of matter and energy, in an exchange system, is the *money* or *information* economy of income streams. The income flow corresponding to a particular item is the product of the physical flow of an item and its price: prices are information [8]. To the inputs are paid three types of income: wages to labor, profit to capital, and *rents* to the owners of natural resources [3]. The term "rent" should not be confused with its common usage; in technical economic usage, "rent" refers to the monopoly incomes received by the owners of scarce and non-substitutable natural resources — such as land, in the common meaning. Two of these incomes go to pay for two of the outputs, wages to pay for consumption goods (consumption spending), profits to pay for capital goods (investment spending). The rent incomes are simply *gratis* and pay for nothing. In fact, rents are extracted from the flow of wages and profits as a tax and necessarily diminish the level of consumption and investment, as first pointed out by David Ricardo [9,10].

The scarcity of land and of the food produced on it led to the first crisis of the infant industrial system in England in the early nineteenth century, a crisis that played a prominent role in the works of Ricardo and his fellow economist, Thomas Malthus [9,10,11,12]. As the industrial system and the population of workers expanded, it ran into the fixed amount of land in England and the relatively fixed level of food production possible on that land. The rent on scarce land threatened to destroy the profits on capital and halt investment; rising food prices apparently condemned the workers to a chronically low level of subsistence. The inability of England to feed itself beyond a certain limit formed the centerpiece of a powerful argument for free trade in agriculture; what food England could not produce, it would import and pay for with manufactured goods. Eventually, the arguments of Ricardo and others won out, and England adopted free trade in food in 1846. Other factors also prevailed to prevent a fatal crisis. Population growth in England was slowed by delayed marriages, urbanization, and, later, by the introduction of artificial birth control methods. Improved agricultural methods made much higher levels of production possible on a given amount of land. A larger population had the advantage of greater diversity, specialization, and productivity, given enough freedom to make economic improvements. A final factor of great importance in preventing a crisis of resource exhaustion has been the substitution of more common inputs for scarcer ones [13]. Few famines, at least in recorded history, seem to be due to overpopulation, but rather are caused by warfare, panic hoarding, and criminal or misguided governments. However, it is misleading to concentrate only on food production, as overpopulation in localized ecosystems is responsible for other environmental problems, such as deforestation, soil erosion, and drastic changes in rain cycles.

Later in the nineteenth century, the American amateur economist and crusader Henry George rediscovered the importance of rents on land and launched an attack on them as the source of society's economic ills in his once-famous work, *Progress and Poverty* [10,14]. Although George exaggerated the evil of rents, he performed a public service by raising the issue of unearned rent incomes and by emphasizing the difference between unearned monopoly rents on fixed land and profit on competitive capital, which the common use of the term "profit" confuses. His cure for the unearned incomes derived from monopoly control of fixed natural resources was to introduce a single tax that would absorb all rents.

Although the monopoly rent incomes received by natural resource owners seem like an unjust burden on the rest of society, rents cannot be condemned out of hand as serving no function. In particular, in an ecologically conscious age, we should recognize rents and private ownership of resources as brakes on the overexploitation of Nature. If people have to pay for resources, they will use less of them. This is all the more true if the resource owners impose extra charges, *reservation prices,* to cover not only the current cost of resource extraction but also to prevent future depletion [6]. The charging of interest on credit (future discounting) has the same effect. Many of the most prominent examples of the overuse of resources today — overlogging in the Pacific Northwest, overgrazing on the Great Plains, wasteful water usage in California, suburban overdevelopment, overuse of chemicals in agriculture, urban overconsumption of food and discouragement of agriculture in the Third World, destruction of the topical rainforests, environmental devastation in the Communist countries — are supported by public subsidies designed to keep raw materials cheap to their users [15]. The result is the *tragedy of the commons:* if everyone is supposed to take care of something, no one takes care of it [16]. Furthermore, by shielding the users of a particular resource from the full cost of their exploitation, these subsidies not only encourage present overuse of resources, but also discourage the search for cheaper (less scarce) substitutes and thereby exacerbate future shortages. Although environmentalists are not usually thought of as friends of private property, private ownership of a resource provides a powerful motive to bar others from its overuse and is usually the best way to protect wilderness areas [17]. Private property allows, while limiting, the individual exploitation of Nature by separating ownership from political power. Of course, private ownership is not a panacea; some owners are as shortsighted as anyone and can strip their property for quick benefit. Nonetheless, if societies are interested in protecting the environment, they could do worse than refrain from these subsidies. Such discriminatory intervention subsidizes select groups of raw materials users at the expense of everyone else and of the environment. Natural resource use is always subject to diminishing returns and thus has no economic justification for subsidy, unlike knowledge- or technology-based sectors of an economy that sometimes exhibit increasing returns to scale spread out over time [18]. Unfortunately, these subsidies are usually of great benefit to select, politically powerful groups whose influence over governments is difficult to remove. The subsidies result from the the conversion of the profit motive, the basis of any functioning economic system, into the power motive characteristic of politics [19].

In a conventional economy, no money exchange is associated with the other end of the resources flow, the production of waste. The waste flow is discharged into the environment with no cost or payment. In short, the price of waste is zero.

The Pay-for-Trash-Removal Economy

The conventional economy is not the only possible one: waste in many cases is not dumped for free into the environment. Instead, the waste producers pay someone else to remove their trash and to dispose of it in some fashion (in a landfill, for example) that often involves an additional charge. This type of economy is diagrammed in Figure 2. Money payments accompany the waste outward to pay for its disposal.

But the trash-removal economy is odd, since the waste producers pay *twice* for their use of natural resources, once for the inputs and once again for waste removal. So there are now *two* rents extracted from the economy, both rents being subtracted from the flow of wages and profits. Such a system will eventually press up against a new Ricardian barrier, because the *producers* of waste, unlike producers of consumption and capital goods, pay the *consumers* of waste for its removal, rather than the other way around. Waste has a negative price in this type of economy.

Of course, from a more limited point of view, this arrangement makes sense to the parties involved. The waste removers receive a rent income, while the waste producers have their trash removed. But as the level of waste production rises with economic growth, and the free space for waste disposal declines, the rent charges for waste removal must necessarily rise and put a larger and larger burden on the rest of the economy, wages and profits. If the natural resource inputs also become scarce, then the economy is caught in an even worse squeeze, with rent being extracted from both ends. The desire of select producers for cheap input resources and enlarged export markets has already inspired one form of imperialism at various periods in economic history [3,20]; the frequent absence of a price system for waste is now prompting a new "garbage imperialism", the search for cheap places to dump trash [15].

Unfortunately, the pay-for-trash-removal transaction has become the paradigm for many other kinds of pollution control. For example, the control of air pollution is accomplished typically by direct regulation of pollution sources with limits on emission. The cost for the "trash removal" is necessarily borne by wages and profits, either directly or indirectly, in a clumsy way. A simpler solution, where the polluted resource is privately owned, is for its owner to bear the cost, or its polluter to recompense the owner. For a polluted commons, such as the air or water, that cannot be privatized, the *legal right* to pollute it can be, such as in a market for pollution shares, where polluters can trade rights to emission with an overall fixed number of pollution shares. But all of these schemes share the same feature: paying for trash removal.

There is a broad justification for the pay-for-removal approach found in the economics literature on pollution which rests on the proposition that by paying for trash removal, a society is "buying" a clean environment [6,21]. People are behaving "as if" there is a market for "cleanness", with so much clean environment available at different costs and varying levels of social preference for cleanness at different prices. The difficulty with this justification is that the pollution of the environment is a product of human activity in the first place; the environment is not a manufactured commodity, and Nature is not subject to any but superficial and temporary human control, nor does it exist only for our use, nor can it in general be priced by us (except for those parts that we do use and trade with one another), because we did not make it. Furthermore, waste disposal is not subject to substitution the way inputs are, except for the possibility of finding less wasteful production techniques that do not reduce useful output.

The Recycling Economy

The way out of this conundrum is to make the natural resources cycle closed like the two other economic cycles (Figure 3). A partial solution is to use the rent income from natural resources, which pays for nothing now, to pay for the trash removal. Since there would be no direct physical flow from outputs (trash) to inputs (natural resources), there would be no market to guide the necessary counterflow of money, and the payment for trash removal would have to be implemented by a tax on natural resource income. Such a tax would be an updated ecological version of Henry George's universal land tax, instead levied on the resources that contribute to the production of waste.

The full solution, however, is to start the physical flow of trash output back to natural resource input — that is, to recycle. There would then be a market for trash, and the counterflow of money to pay for it, derived from natural resource rents, would be automatic. Waste output would be treated like the other outputs, consumption and capital goods, in that the *consumers* of waste (the recyclers) would pay the *producers* of waste for the trash. The availability of recycled materials for input would subtract from the income of virgin natural resource owners, and the natural resource rents would in effect pay for the recycling, establishing full closure (both physical and monetary) of the resource cycle.

The economics of waste can be restated in Marshall's graphical formulation [22], with supply and demand curves for waste, as in Figure 4. The supply curve is the marginal cost of each additional unit of waste as a function of waste flow (the partial derivative of the cost function with respect to waste flow). Typically, the marginal cost for waste production is *negative,* at least to start with; that is, the producers of waste find their costs *decreasing* as they produce more waste associated with the making of their useful outputs. Eventually, with high enough waste output, the production process becomes increasingly inefficient, the cost function starts to *rise* as a function of waste flow, and the marginal cost of waste becomes positive. We assume, as is always the case with natural resource costs, that the waste supply curve is subject to diminishing returns and therefore always rises with quantity. In the absence of a market for waste (zero utility of waste), the producers generate waste up to the point where the marginal cost of waste is zero. This fact explains why, even when unregulated, producers in a market system do not produce an infinite amount of waste. Such behavior serves as an illuminating counterexample to the usual pattern in command economies, which, lacking a price system, generally have no sensible way to account for costs. Natural resource exploitation consequently is often subsidized to extreme levels, and the result is an almost infinite production of waste and pollution, as reported in great detail by a number of visitors to Eastern Europe and the former Soviet Union [23,24].

The demand curve for waste is the marginal utility to the consumers of waste; that is, the partial derivative of the consumers' utility (reflected by what they are willing pay for the waste) with respect to waste flow. As shown in Figure 4, the marginal utility might be positive for small waste flows — in that case, consumers can find some use for the waste — but the curve usually becomes negative for large enough waste flows; that is, the curve is really a marginal *dis*utility for waste. Or, if the waste has no use at all, the demand curve is always negative (not shown; in that case, the points E and F coincide). Figure 4 shows the typical result in this situation. The market equilibrium for waste — point of maximum benefit (utility less cost) to society — occurs at *negative* marginal cost and utility, so that waste has a *negative* price. Thus, Figure 4 displays in graphical form our earlier example of the pay-for-trash-removal economy. Such a result might be embodied in real markets, as it is with trash collection services and landfills, or implemented by direct regulation, as when the government makes known through legislation or administrative ruling the putative social disutility of waste. The question of which approach to use reduces to the question of creating, wherever possible, markets for the waste.

Careful examination of the market equilibrium reveals the mutually beneficial nature of the transaction to both producers and consumers of waste, even with negative prices. Referring to Figure 4, the area FDCB is what producers pay consumers to take the waste. On the other hand, the producers save the area FDCA in costs by producing the waste; it is clear that this cost saved is greater than or equal to what the producers pay for waste removal. Similarly for the consumers of waste, the income they receive for removing the waste is greater than or equal to their total disutility for the waste, the area EDC, and they may also receive positive utility from the waste, the area EFG.

The long-term difficulties with waste production discussed earlier can be restated in this graphical language. As ecological niches for waste run out and a society's tolerance for rising cumulative waste declines, its utility for waste becomes increasingly negative. That is, the demand for waste moves down and to the left in the figure. This change forces producers to produce less waste, which can have one of two impacts, or a combination of both: Either the producers produce less waste by also producing less useful output, reducing the society's standard of living and capital accumulation; or the producers continue to produce the same useful output as before with less waste by adopting less wasteful techniques.

The recycling economy is illustrated in Figure 4 by the alternative demand curve for waste, which is always positive, or at least positive for the waste flows relevant to this discussion. That is, in a recycling economy, the waste is useful and its marginal utility positive. In this case, the price of waste is *positive*. As explained earlier, the income flow to pay for this transaction is ultimately extracted from the rent incomes of virgin natural resource owners. Curiously, the amount of "waste" produced in the recycling economy is higher than it is in the pay-for-trash-removal economy, as Figure 4 shows, simply because the "waste" is more useful and so there is a demand for it. The waste transaction in this case is also mutually beneficial to both parties; the graphical proof follows the same steps as in the case of negative prices above.

Limits to Recycling

The recycling economy already exists in embryonic form [15]. Some recycling takes place of metals, paper, glass and oil. Certain automobile manufacturers are planning the reusable car, to end the abandonment of autos in junkyards. Junkyards already pay for old cars and cannibalize them for spare parts. But the full impact of natural resource scarcity and limits to waste removal has not yet been felt in advanced economies. The logical ideal for the development of a "green" (ecologically correct) economy is: as much recycling as possible and zero production of non-recyclable wastes. The "green" economy must move as close as possible to zero waste production without reducing useful output and to the complete recycling of what waste *is* produced. The key to recycling is obviously finding ways to make waste useful.

The immediate limits to recycling are institutional. Almost all producers have set up their production processes so as to use virgin natural resources only. They are not organized to recycle internally their own waste or recycle other producers' waste. The ideal of complete recycling would be implemented, either by each production facility forming a closed system or by many facilities forming a symbiotic "food chain" of producers and recyclers of waste. Internal recycling of waste already exists for some extraordinarily valuable inputs, such as catalysts in chemical reactions that can be used an indefinite number of times. An example of external recycling by a consumer-producer loop is the venerable milk bottle [25]. A large potential recycling loop exists with aluminum cans, since the trucks that deliver the filled cans usually drive back to the producer without any used cans. Recycling "food chains" are less common. Cogeneration of heat by burning trash is a primitive example, although the burning itself pollutes. The change necessary to implement such schemes mostly involves a change of mentality, a more accurate recognition of the efficiencies to be gained by internal recycling and recycling chains. For the latter, markets would have to be created to trade the waste.

The technological limits to recycling form a more basic obstacle. The limits have two interrelated components: design of original products to facilitate their later recycling, and development of efficient recycling techniques [15]. The "green" design of original products requires the foresight and incentive to anticipate recyclers' needs and limitations and to incorporate these into the product from the start. The establishment of stable and mutually beneficial relationships between producers and recyclers (or better, producers becoming their own recyclers) would make this process much easier. Some soft drink companies already buy back their own aluminum cans after use by consumers to be recycled for iterated use. A well-known example of a recycling bottleneck created by poor design is the glossy finish used on some types of newsprint that prevents their reprocessing. Efficient recycling techniques have already been developed for aluminum, steel, glass, and some types of paper and plastic. Many more materials could be recycled.

Even after institutional and technical obstacles are overcome, however, there is an ultimate physical limit to recycling, the limit posed by the second law of thermodynamics, which requires the total entropy of the universe never to decrease [26]. Entropy admits of precise definition, either in statistical, microscopic form or thermodynamic, macroscopic form, but in either case, is a measure of disorder. A process of maximal thermodynamic efficiency is *adiabatic* or *reversible,* with no net entropy production. A less-than-ideal process is irreversible and involves a net increase in disorder, which typically appears as waste heat unusable for work; the increment of entropy is the increment of waste heat divided by the absolute temperature (in degrees Kelvin) at which is produced. However, although total entropy never decreases, it can be moved around in space and time so as to create regions and periods of greater order, but only by creating at least an equal amount of *dis*order in other places and times. Useful goods and activities are fashioned from raw materials into a more organized form, requiring the expulsion of entropy in time and/or space that reappears as waste heat and junk. To make the growth of organization [27] more precise, we distinguish two kinds of entropy, the *maximal* entropy or disorder a given macroscopic object or process *could* have, depending only on its size or duration, parts, and energy; and the *actual* entropy or disorder the object or process *actually* possesses. The former is fixed for a given system, while the second law requires the latter never to decrease. The generalized *complexity* or *thermodynamic depth* is the former less the latter [28]. Highly regular systems or those in thermal equilibrium have low or zero complexity: the former, because both the maximal and actual disorder are small; the latter, because both are large but equal. Highly complex systems have large maximal but small actual entropies (much possible, but little actual, disorder). The negative of actual entropy is often called *negentropy* and is equivalent to *information* [29]. Thus, for a fixed maximal entropy, complexity and information are equivalent.

Care must be taken in applying the second law to the biosphere; because it is not a closed system, its entropy *can* decrease. Biological, and in particular, economic, activity acts as a limited Maxwell demon in decreasing local entropy as the Universe's entropy rises [30]. Physical processes inject or remove entropy in four ways: (1) sunlight received; (2) heat released from the Earth's interior; (3) radiation re-emitted into space; and (4) material and heat subducted into the Earth's crust on the ocean floors [31]. These four, like all manifestations of spontaneous self-organization through feedback, are consequences of the universal struggle of gravity and entropy. The second and fourth are minor components of the Earth's heat balance; with a small but important corrections from the second, the first and third account for almost all of the Earth's heat budget [32]. There is one further avenue for entropy flow: life stores, rearranges and releases entropy. Inasmuch as the complexity of life on Earth has increased over its three-and-a-half billion year history, information stored in genes, metabolism, form, and, more recently, in culture, life has expelled entropy from its domain, in addition to changing the chemistry of the atmosphere. This highlights the fact that, over long periods, the biosphere is not at all in equilibrium, with occasional large departures from stasis occurring against a background of steady, smaller changes [33,34]. For metabolism to occur, however, entropy also has to be released, as with the consumption of food or the burning of hydrocarbon fuels. The instantaneous effect on the Earth's gross heat balance is small, a slight Gaian fever of global warming, although the consequences over long times may be substantial.

In examining the entropy produced by humans, we can distinguish two broad classes of economic activity, one involving the withdrawal, the other the release, of entropy. The latter class I call *consumables* or *fuels,* such as food, hydrocarbons, etc., that are taken from a state of greater complexity and subject to chemical reactions that release energy and entropy, bringing them closer to thermodynamic equilibrium. Consumption, the goal of all economic activity, is the destruction of value and demand. The energy released heats or performs work. The possibilities of recycling for this class are quite limited, so that reduction of the associated pollution requires greater efficiencies of production and use to minimize entropy production. The former class I call *durables.* These include packaging — containers, newspapers, clothing, housing, etc. — as well as all manner of activities and machines that extend human powers, both for consumption purposes

— cars, newspapers, etc. — and capital purposes — tools. Capital investment constitutes a special kind of durable, the economic analogue of catalysis, goods that produce other goods or services yet themselves not consumed. The creation of durables, like the evolution of life on the planet, requires a large *increase* in complexity to create the prototypes, which can then be copied (mass production or reproduction) with only small additional increments of complexity (due to the copying process itself, not to the copies [28]). Production is the creation of value and demand. Because they degrade slowly, durables are recyclable, although their use requires fuels. The major limitation is design, embodied in the original of the item and reflected in its mass copies. Of course, some durables we already recycle; we use houses, clothing, and cars over and over, rather than produce new ones for each use. The initial rarity of complex objects and processes creates opportunities for profit and economic growth, which proceeds by the exploitation of new and generally temporary relative scarcities. The scarcities usually disappear because competition and/or mass production (if increasing returns appear [22]) turns the rare into the commonplace, eliminating the relative advantage of scarcity and its above-normal profits. A new cycle of growth can then begin only with the discovery of another rarity. Economic equilibrium is a thermodynamic non-equilibrium steady state (steady flows of matter and energy), while economic growth departs further from thermodynamic equilibrium into non-steady states of matter and energy flow [35].

The reduction of entropy production from fuel use is subject to stringent thermodynamic limits. The burning of fuel to produce heat automatically produces entropy, although the heat can be trapped and preserved for a time by insulation. The case of transforming heat into work is more subtle. As a simplified example, consider the canonical two-temperature heat engine. The ideal efficiency η of such an engine burning fuel at absolute temperature T_h and releasing heat into an environment at absolute temperature T_e, where $T_h \geq T_e$, is:

$$\eta = 1 - T_e/T_h, \tag{1}$$

where η is the fraction of heat that can be converted to useful work. Note that when the two temperatures are equal, no useful work can be extracted. The transformation of heat to work requires a temperature *difference*. Furthermore, even in the ideal case, when the *net* entropy produced is zero, a gross entropy increment is still added to the environment, taken from the fuel. For a relatively fixed environmental temperature $T_e \simeq 286$ °K (13 °C or 56 °F), the ideal efficiency of heat engines can be increased only by raising the burning temperature T_h. Thus, coal is more efficient than wood, petroleum than coal, natural gas than petroleum, and nuclear fusion than nuclear fission, under ideal conditions, each process burning at a successively higher temperature. The greater ideal efficiency of successive fuels is also demonstrated by a detailed study of their reactions; the thermodynamically more efficient burners burn further toward completion of their respective reactions. The final products of hydrocarbon burning are carbon dioxide and water; the final products of nuclear burnings are nuclei closer to the most stable nucleus, iron-56, than the reactant nuclei, uranium and plutonium splitting to lighter nuclei, and deuterium and tritium fusing to helium. The less efficient reactions not only do not move as far toward completion, they also produce unburned intermediate products that are often harmful, such as nitrogen dioxide, carbon monoxide, and unstable (radioactive) fission products. Nuclear fusion, burning at a higher temperature, produces none of the unstable isotopes that fission produces. (Carbon dioxide itself still poses the hazard of a greenhouse effect or asphyxiation, so it must be burned in a final step, to carbon and oxygen, by plants. Thus the oxygen-burners depend on the CO_2-burners to recycle their waste by fixing carbon. Natural or artificial photosynthesis could be implemented at the source of CO_2 emissions; new chain reactions could be found to burn radioactive fission products into stable isotopes.)

Apart from burning technologies with higher ideal efficiencies, any given technology as implemented is rarely close to its ideal efficiency, thus producing net entropy. The ideal functioning of a given technology is reached when it proceeds adiabatically. The Nirvana of adiabaticity is achieved by smoothing in *time* — burning as slowly as possible — and by isolating in *space* — perfect insulation between regions of differing temperature.

Final Thoughts

The concept of minimum entropy production [33] can be linked to the concept of a *sustainable economy*, a human economy with a lifetime of indefinite length [36]. The biosphere, through its leakages of entropy, is capable of eliminating entropy at no more than a certain, but unknown, rate. This putative limit is, speaking broadly, the sustainable limit to the activity of life and is sometimes called the *carrying capacity* [36] of the biosphere. The biosphere can be burdened only to a certain limit before it undergoes rapid, radical, and probably unpredictable changes [33,37]. Apart from pollution of commons and appropriation of wilderness owned by no one, the chief source of environmental degradation today, as throughout human history, is the discriminatory use of political power to lift the burden of resource cost from resource users by subsidy and political force and to place it on others, so that these users fail to register the cost of their activities and consequently overexploit the resources at their disposal. Absent such subsidy or political force and with politically guaranteed property rights of various types, ecological sustainability of the human economy is automatic, as human economic activity (making the most with the least) is only a special example of a principle universal to all organic evolution, that of minimal entropy production [33,35]: Nature is usually economical, in the sense of parsimony. With accurate (market-clearing) prices for natural resources, prices are linked directly to cost and thence to waste (entropy) production [38]. Such an economy does not need to be made part of Nature, because it already is, as the humans who make it up have always been. The great exception to this principle of "most with least" among humans is represented by war and war-like collectivist economies, such as feudalism, socialism, communism, and the various types of fascism and statism, whose participants, under the spell of the power principle or the desperation of war, register benefit without registering cost. Perhaps the major philosophical difficulty preventing us from seeing the truth about evolution and human economies are the still-common fallacies of social Darwinism and sociobiology: in fact, culture is adaptively learned, not genetically programmed, and most evolution is peaceful competition for ecological niches, analogous in every way to peaceful economic competition, contrary to the famous but misleading and bloody predator-prey picture of "Nature red in tooth and claw" [2,39]. Indeed, human history is merely organic evolution at work in culture and economy.

It may seem as if the development of modern surplus-trading economies itself has led humanity out of an idyllic relation to Nature and that the solution to our growing ecological difficulties is a return to the subsistence mode of existence that would require a far smaller and poorer population than at present [40]. However, with occasional exceptions, there has never been an innocent relation between humans and their environment, at least since the invention of agriculture: often not knowing their own strength, they have usually exploited it up to the limits of their available technology and the local carrying capacity [41]. Our present situation is a result of the cumulative inertia of thousands of years of technological progress. The difference today is that, unlike previous eras, the power of technology and human numbers has grown so great that it, like nuclear weapons, threatens the entire global ecosystem for the first time in history. But the same technology that damages the biosphere can also measure and heal that damage. Minimizing this harm requires closing the natural resource cycle of modern economies and instituting policies to extend property rights and eliminate subsidy that blocks resource cost from individual economic decisions — in short, the application of standard mechanisms to an activity never fully rationalized before in economic terms, the production, disposal, and reuse of waste.

References and Notes

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4. Historically, the most important were the ideas of Ricardo and Malthus; see below.
5. R. U. Ayres and I. Nair, *Physics Today* **37**, 62 (November 1984).
6. P. Wonnacott and R. Wonnacott, *Economics* (McGraw-Hill, New York, ed. 2, 1982).

7. The most important and basic of human tools are those first evolved in hominid history, simple hand tools and language.
8. I have referred to the matter/energy flows as the "real" economy, but this should not be misunderstood to mean that information and prices are "unreal" in the sense of being unphysical, only in the sense that information, unlike matter and energy, is not conserved. All three — matter, energy, and information — are physical in the sense that the presence or absence of any one has independent causal consequences. Matter is what possesses mass or inertia; energy is the capacity to do work, force times distance; information is organization or non-randomness (see below in text). This is by way of excluding the naive scientism that regards biology and economics as merely an affair of matter and energy flows, disregarding the role of entropy, information, organization, and, most crucially, of feedback effects (see refs. [33-36] below).
9. David Ricardo, *Principles of Political Economy and Taxation* (1817) (C. E. Tuttle, Boston, Everyman's Classic Library, 1911).
10. R. L. Heilbroner, *The Worldly Philosophers: The Lives and Times of the Great Economic Thinkers* (Touchstone/Simon & Schuster, New York, ed. 6, 1987).
11. Rev. Thomas R. Malthus, *An Essay on the Principle of Population* (1798, 1803) 2 vols., P. James., Ed.; *Principles of Political Economy* (1820) 2 vols., J. Pullen, Ed. (Cambridge University Press, Cambridge, 1990). The food crisis in England in the 1790s and early 1800s was greatly exacerbated by the Napoleonic wars and the cutoff of food to England from France, and by the perversity of the English poor relief laws.
12. John Maynard Keynes, *Essays in Biography* (1937) (W. W. Norton, New York, 1963), essay on Malthus.
13. John Stuart Mill, *Principles of Political Economy* (1848) (Augustus M. Kelley, New York, 1987); *The Subjection of Women* (1869) (MIT Press, Cambridge, MA, 1970).
14. Henry George, *Progress and Poverty* (1879) (Schalkenbach Foundation, New York, 1979).
15. Sen. Albert Gore, Jr., *Earth in the Balance: Ecology and the Human Spirit* (Houghton Mifflin Co., Boston, 1992), which emphasizes recycling. The relative attractiveness of recycling depends on raw materials prices, which rise and fall as part of the fifty-to-sixty year cycle discovered by Kondratieff and extended historically by later workers. The present decade, after the collapse of raw materials prices in the 1980s, finds recycling in an economically precarious situation. On the other hand, in the 1970s, recycling and conservation were more pressing, as raw materials prices rose rapidly. The next such period, if the cycle holds (the previous three were 1790-1810, 1850-1870, and 1900-1920), will be in 2020-2040. See: N. D. Kondratieff (1926), reprinted in *Readings in Business Cycle Theory* (Blakiston Co., Philadelphia, 1944).
16. Aristotle, *The Politics*, S. Everson, Ed. (Cambridge University Press, Cambridge, 1988) book II:1-5; D. L. Soden, *Tragedy of the Commons: Twenty Years of Policy Literature, 1968-1988* (Vance Bibliographies, Monticello, IL, 1988).
17. On the conservation of African wilderness and wild animal herds through privatization, for example, see: R. Bonner, *At the Hand of Man: Peril and Hope for Africa's Wildlife* (Random House, New York, 1993). Most of the destruction of African wilderness and wildlife in historical times, and particularly within the last thirty years, is due to war, quasi-militarized economic collectivization, and their attendant famines. Much the same can be said of the disappearance of European wilderness and wildlife within the last century. A striking historical case of ecological degradation through incessant war is found in the final three centuries of the Roman empire, during which vast stretches of forest in the Mediterranean basin were rapidly destroyed.
18. W. Brian Arthur, *Sci. Am.* 262, 92 (February 1990). Increasing returns to scale spread out over time, declining marginal costs, or learning curves, justify *general* subsidy only, still subject to competitive principles, but not targeted subsidies or legal monopolies. Furthermore, marginal costs cannot decline indefinitely in any given case. Increasing returns to scale is the economic form of the thermodynamic phenomenon of autocatalysis, the repeated occurrence of which causes non-equilibrium thermodynamic systems to step down into progressively lower states of entropy production (see ref. [35] below). A familiar example is the youth and maturation (ontogenesis) of an individual requiring temporary support and education by its parents.
19. That is, the discriminatory use of political power moves a society away from the win-win, non-zero-sum,

profit-maximizing game of economics towards the win-lose, zero-sum, power-maximizing game of politics and war, the latter being zero-sum because political power is, in some sense, a conserved quantity. See: John von Neumann, Otto Morgenstern, *The Theory of Games and Economic Behavior,* ed. 3 (Princeton University Press, Princeton, NJ, 1953); also: Eugen von Böhm-Bawerk, *Capital and Interest, Vol. 2: Positive Theory of Capital,* ed. 4 (1921) (Libertarian Press, Spring Mills, PA, 1959).

20. John A. Hobson, *Imperialism* (1902) (University of Michigan Press, Ann Arbor, MI, 1965).
21. Lester C. Thurow, *The Zero-Sum Society* (Viking Penguin, New York, 1981).
22. Alfred Marshall, *Principles of Economics,* ed. 8 (1920) (Porcupine Press, Chicago, 1982).
23. It might seem that the problem with command economies is that the central authorities form a political and economic monopoly whose power can be abused. However, monopoly producers have the curious property of reducing output, of both useful product *and* waste, while raising both their prices, in comparison to the situation in competition. So the hyperpollution of Communist economies cannot be due to monopoly power. Rather, the centralized command economy, lacking a price system, has a weak or non-existent information network to make decisions and incentives to move itself toward greater efficiency, while simultaneously concentrating enormous political and technological power in the hands of central planners who cannot acquire the information required to make economic decisions in a timely way. Since prices provide information and incentive, fixed prices are *mis*information and *mis*incentive, and the absence of prices altogether is *non*-information and *non*-incentive. In other words, while the temporary failures of command economies may be due to abuse of power, the more basic failures are caused by ignorance and laziness.
24. M. Feshbach and A. Friendly, Jr., *Ecocide in the USSR: The Looming Disaster in Soviet Health and Environment* (Basic Books, New York, 1992).
25. *Garbage* **IV**, 24 (January 1993).
26. Nicholas Georgescu-Roegen, *The Entropy Law and the Economic Process* (Harvard University Press, Cambridge, MA, 1971).
27. *The Economy as an Evolving Complex System: Santa Fe Institute Studies in the Sciences of Complexity, Volume V,* P. W. Anderson *et al.*, Eds. (Addison-Wesley, Redwood City, CA, 1988). For a semi-popular account, see: M. M. Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (Simon & Schuster, New York, 1992).
28. S. Lloyd and H. R. Pagels, *Ann. Phys.* (New York) **188**, 186 (1988). See also: L. E. Reichl, *A Modern Course in Statistical Physics* (U. Texas Press, Austin, TX, 1980). The exact definition of thermodynamic depth is the difference of the coarse-grained (maximal) entropy and the fine-grained (actual) entropy. The former is the logarithm of the number of microstates available to a system with fixed macroscopic characteristics; the latter is the logarithm of the number of microstates the system actually occupies. In thermal equilibrium, the equality of the two entropies stems from ergodicity, the system spending the same time in each possible microstate; or, alternatively, from equipartition, equal probability for each microstate. Full thermodynamic equilibrium involves, besides thermal equilibrium (equal temperatures), mechanical (equal pressure) and chemical (zero affinity) equilibrium as well, complications we ignore here. The coarse-grained entropy of the Universe (local comoving volume) is itself increasing, although only logarithmically, because of the cosmic expansion. The universal fine-grained entropy is virtually fixed, with only a tiny accumulating contribution from energy sources such as stars and other non-equilibrium systems that are gravitationally bound, such as our solar system. Gravity in such systems creates spatial gradients of temperature, pressure, and chemical potential that make energy generation and heat flow possible. See: Richard C. Tolman, *Relativity, Thermodynamics, and Cosmology* (1934) (Dover Publications, New York, 1987), chapter 9.
29. C. E. Shannon, W. Weaver, *The Mathematical Theory of Communication* (U. Illinois Press, Urbana, IL, 1962); R. Shaw, *Z. Naturforsch.* **36A**, 80 (1981). A number of different quantities called "entropy", "information" and "complexity" appear in the literature on thermodynamics, information theory, and evolution, related in meaning, but not equivalent in definition.
30. J. Clerk Maxwell, letter to Lord Rayleigh (William Strutt), 6 December 1870, quoted in Emilio Segrè, *From Falling Bodies to Radio Waves: Classical Physicists and Their Discoveries* (W. H. Freeman, New York, 1984), pp. 242-243; L. Szilard, *Zeit. Phys.* **53** (1929) 840.
31. R. A. Berner and A. C. Lasaga, *Sci. Am.* **260**, 74 (March 1989).

32. R. G. Fleagle, J. A. Businger, *An Introduction to Atmospheric Physics* (Academic Press, New York, ed. 2, 1980).

33. I. Prigogine, *Nonequilibrium Statistical Mechanics* (Wiley-Interscience, New York, 1962); I. Prigogine, *Introduction to the Thermodynamics of Irreversible Processes* (Wiley-Interscience, New York, 1967); P. Glansdorff, I. Prigogine, *Thermodynamic Theory of Structure, Stability, and Fluctuations* (Wiley-Interscience, New York, 1971); G. Nicolis, I. Prigogine, *Self-Organization in Non-equilibrium Systems* (John Wiley & Sons, New York, 1977); I. Prigogine, *From Being to Becoming: Time and Complexity in the Physical Sciences* (W. H. Freeman, New York, 1980). For semi-popular accounts, see: I. Prigogine, I. Stengers, *Order Out of Chaos: Man's New Dialogue With Nature* (Bantam, New York, 1984), and G. Nicolis, I. Prigogine, *Exploring Complexity* (W. H. Freeman, New York, 1989). A key result for our purposes is the existence and, in the close-to-thermal-equilibrium regime, uniqueness of the steady state of *minimal entropy production,* or *thermodynamic branch,* where the entropy, prevented by some given constraints (gravity, for example) from being at maximum, steadily increases toward maximum at the minimum rate possible under those constraints. The evolution of non-equilibrium thermodynamic systems along the thermodynamic branch describes, without determining, most forms of organic and non-organic growth and evolution. The general Walrasian equilibrium of microeconomics is identifiable as a particular case of this steady state of minimal entropy production and thus represents the workings of organic evolution in human economic life. Farther from thermal equilibrium exist, along with the thermodynamic, other, higher-than-minimal entropy production branches that are macroscopically more organized, but which exhibit greater microscopic disorder; unlike the thermodynamic branch, these branches have *finite* lifetimes, as they "burn themselves up" more quickly. The paradigmatic example in human affairs is war, which, in economic terms, cannot last indefinitely, as it requires overconsumption, undersaving, or dissaving of resources (people, property, environment) — excess disorder.

34. S. J. Gould, N. Eldridge, *Paleobiology* 3, 115 (1977); N. Eldridge, *Time Frames: The Rethinking of Darwinian Evolution and the Theory of Punctuated Equilibrium* (Simon & Schuster, New York, 1986). Irreversible or historical evolution occurs only because various coupled irreversible processes occur at *different* rates, the differences in such rates determining the selective forces (natural, sexual, etc.) that govern the *rate* of evolution. The *direction* of evolution, on the other hand, is set by initial conditions, not by selection. Another pair of commonly confused concepts are *function,* which is historically evolved in time, and *structure,* which is spatial and generally of no evolutionary or historical significance whatever (accidental or "just-so").

35. That is, a scarcity of scarcities slows economic growth, much as fractal diffusion requires bottlenecks as a stimulus. For relative scarcity, profit, and economic growth, see: Joseph A. Schumpeter, *The Theory of Economic Development* (1912) (Harvard University Press, Cambridge, MA, 1949). Given the general argument outlined in ref. [33] above, one can complete the thermodynamic identification of ordinary economic equilibrium via an *information theory of value* as a replacement for the defunct labor theory of value of Locke, Petty, Smith, and Marx, inasmuch as economic value or utility is tied to information content or embodied organization, not merely to work expended. Since information = negentropy = -entropy, the branch of minimal entropy production is, equivalently, the branch of maximal information or complexity production. The maximal flow of information or value is then just the maximal flow of *profit* or *net benefit* (flow of gross benefit or utility minus flow of cost) of the Walrasian equilibrium. The gross benefit or utility is the gross complexity or information, while the cost is the entropy dissipated in producing that gross benefit or utility. In the close-to-thermal-equilibrium regime, at least, the components of information production have the general form: matter/energy flow times thermodynamic force. If information is value and the matter/energy flows are identified with the flow of good and services, then prices are generalized thermodynamic forces (chemical affinities or gradients of pressure, temperature, and chemical potential). This identification should cause no surprise, inasmuch as prices usually equilibrate the flows of goods and services to maximize net benefit. The economy as a whole evolves because different goods and services flow at different rates (see ref. [34] above). Furthermore, the process of economic growth as described by Schumpeter involves the temporarily destabilizing movement from one steady state to another, which takes place by the discovery and exploitation of economic *autocatalysis,* capital goods producing more capital goods. This step transforms the thermodynamic branch to a lower-than-before entropy production state, the sudden and temporary appearance of excess

negentropy, complexity, or information identifiable with the temporary above-normal profits of new, rapidly growing economic sectors.

36. P. M. Vitousek, P. R. Ehrlich, A. H. Ehrlich, P. A. Matson, *BioScience* **36**, 368 (1986); J. MacNeill, *Sci. Am.* **261**, 154 (September 1989); W. D. Ruckelshaus, *ibid.*, 166; S. Schneider, P. Boston, Eds., *Scientists on Gaia* (Cambridge, MA: MIT Press, 1992). The lifetime of human economies on Earth is in principle very long, but still limited by the lifetime of the Sun (five to ten billion years), which in turn is set by the Sun's approach to chemical (nuclear) equilibrium. The notion of applying thermodynamic methods to the study of human economies is as old as thermodynamics itself and was first suggested by Sadi Carnot, the first thermodynamicist, in discussions with his brother Hippolyte, father Lazare, and others of Napoleon's engineers at the *École Polytechnique* of Paris (see Segrè, ref. [30] above, pp. 192-201). The use of physical concepts in economics thereafter acquired a bad reputation, in part because of their misuse in the crude militaristic and rationalist parody of the engineering mentality so powerful in the ideas of Saint-Simon and Comte, the intellectual founders of modern socialism. Among their fallacies, which are still very much in circulation, were four crucial ones: that an economy (or an ecosystem, for that matter), can be conceived of as a single, simple machine knowable, predictable, and/or controllable by any one person or a small group of persons, instead of as a composite and simplified abstraction, a mental composite photograph or collage; that an economy is the result of the deliberate design and conscious will of a single or small group of persons (a belief that might be termed *social creationism* or *anthropomorphism*); that economic evolution is mechanistic (reversible), instead of thermodynamic (irreversible), like all other organic evolution; and that economic response is linear instead of non-linear, or, equivalently, that feedback effects are unimportant. In short, they ignored the essential elements of time and entropy (or information). The relation of these pseudoscientific superstitions to centralized or command economics should be obvious (see ref. [23] above). For a presentation of and attack on this type of economic thought, see: Friedrich A. Hayek, *The Counter-Revolution of Science: Studies on the Abuse of Reason* (The Free Press, Glencoe, IL, 1952). (See also ref. [10] above, chap. V.) Most nineteenth- and twentieth-century economists have misconceived of economics as analogous to mechanics, rather than to thermodynamics and organic evolution. (Even many naturalists, such as Darwin, missed the thermodynamic nature of organic evolution; see ref. [2] above.) An exception was Marshall, who correctly saw economics as a branch of biology (see ref. [22] above).

37. An example of a carrying capacity is the infamous Laffer curve: an economy can be taxed only to a certain point before it starts to yield lower revenues, that point being apparently a tax rate of around eighty percent for closed economies, with shrinkage in total output starting at about forty percent. (The situation in an open economy is strongly influenced by the tax rate in other economies.) Isolated cases of ecological carrying capacity have been known for millenia. The growth of world population and production has brought to the fore the great variety and number of distinct ecosystems, each with its own carrying capacity.

38. An application of entropy-based pricing is the case of energy taxes. One approach is to tax different fuels weighted by their heat content, but this approach is only half-correct, as it does not reflect the efficiency of the fuel burning. For *heating* fuels, the entropy released is proportional to heat content, but also inversely proportional to the environmental temperature, varying with time and location. For fuels producing *work* (electricity, transport), the entropy released varies as the heat content, but also inversely with the *burning* temperature, reflecting the greater efficiency of hotter fuels. *Refrigeration* requires a special kind of engine, to force heat to flow from cold to hot, and the entropy released is proportional to the heat content of the fuel *plus* the insulation-adjusted temperature difference between the inside and outside of the refrigerator and inversely proportional to the outside temperature. The entropy-based tax is a more complicated but more accurate measure of environmental damage. Yet another approach is to tax fuels in proportion to their prices, so as not to change their relative utilizations. Although the demand for fuels is related to their entropy release, proportionality of entropy release to price holds only in the overidealized case of fixed fuel supplies. Except for this qualification, price-proportional and entropy-release-proportional energy taxes are identical.

39. The "tooth and claw" phrase was popularized by Herbert Spencer. The predator-prey-vegetable food chain is unstable, because its only steady state is the extinction of both animal species. Most evolution involves peaceful competition, coexistence, or co-operation of species coevolving in a given ecosystem.

The spread in the last century of such slogans as "survival of the fittest" (another Spencerism) has done incalculable damage to the proper understanding of evolution; more accurate slogans might be "elimination or modification or departure to elsewhere of the least fit (to a given ecology)" and "survival of the at-least-adequate" — more clumsy, but much less misleading. Exposing the errors of sociobiology would require a separate paper all by itself (see ref. [2] above). Suffice it to say that humans are *not* genetically programmed to *act* in a fixed way, but rather are genetically programmed to *learn to act* in various adaptive ways (within the constraints set by previous evolution), often in response to unforeseen circumstances in the course of evolution. Genetic programming by selection is too slow a process to bear the explanatory weight that sociobiologists place on it.

40. J. Davis, Ed., *Earth First! Reader: Ten Years of Radical Environmental Journalism* (Gibbs Smith, Layton, UT, 1991). The underlying fallacy of radical environmentalism is the concept of *preservation,* as opposed to *conservation,* the false assumption that the biosphere was in idyllic stasis until disrupted by humans and can be returned to stasis: in fact, there never was any stasis, nor is it possible to achieve now. Conservation, on the other hand, correctly views ecological and human economic activity as parts of a single whole, along the lines outlined in this paper (see also ref. [2] above). A distinct but equally fallacious and dangerous idea is that individual economic activity as such is the basic threat to ecological sustainability; see, for example: G. Hardin, *Living Within Limits: Ecology, Economics, Population* and D. Worster, *Wealth of Nature* (both: Oxford University Press, Oxford, 1993). The proposed cure, ecological engineering by collectivized dictatorship, is far worse than the disease, however, being subject to the fatal flaws all such systems face (see refs. [22,36] above).
41. See, for example: B. M. Fagan, *The Great Journey: The Peopling of Ancient America* (Thames & Hudson, London, 1987), on the ancient Americans' use of slash-and-burn forest-clearing.

Acknowledgements

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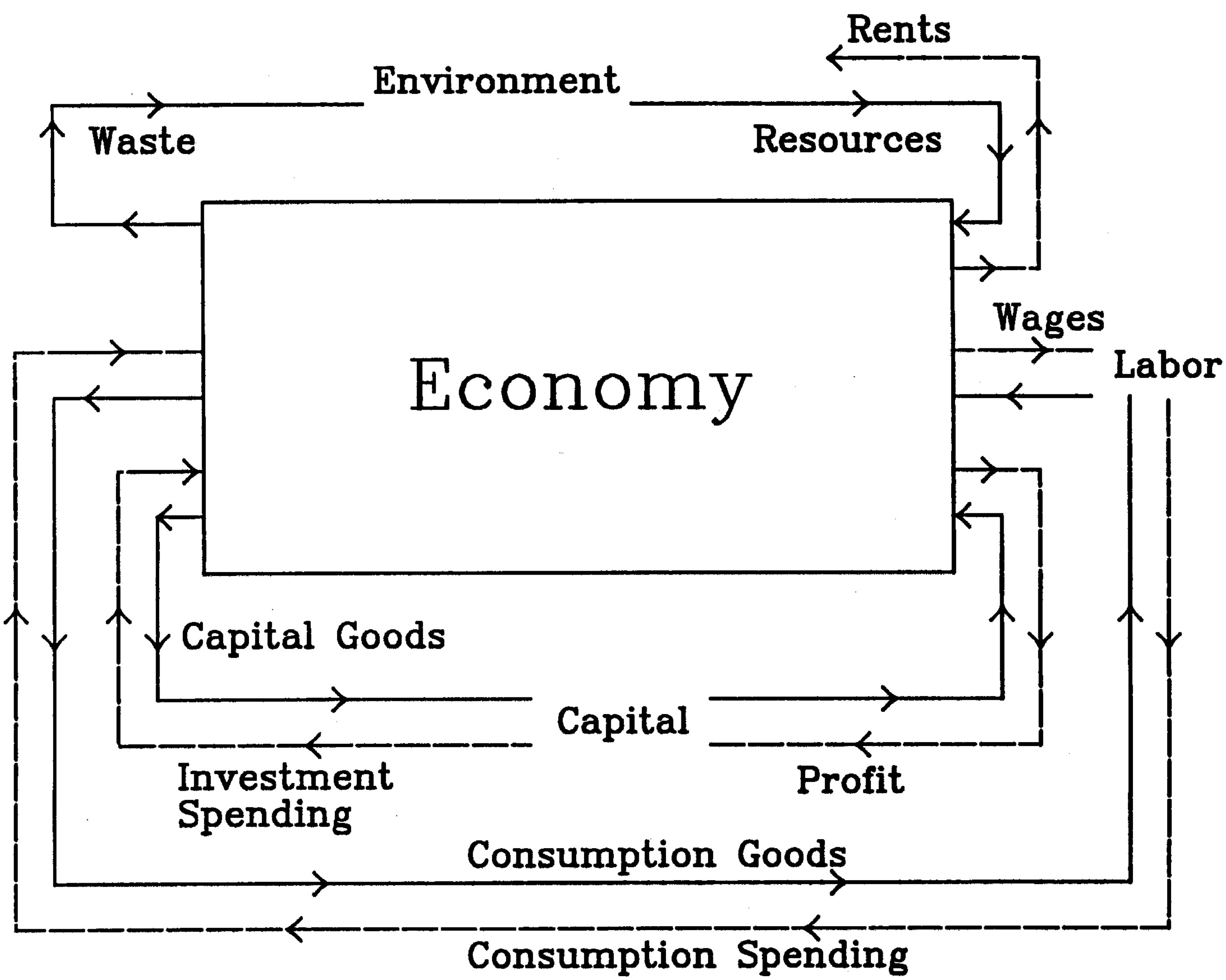
Figures

Figure 1. Conventional economy. Investment and consumption form circular flows from wages and profits, respectively; natural resource inputs purchased with rents, waste output discharged at no monetized cost or benefit. Solid lines: physical flows; dashed lines: money flows.

Figure 2. Pay-for-trash-removal economy. Same as Figure 1, but waste discharge now monetized at negative price; producers of waste pay consumers of waste to remove it.

Figure 3. Recycling economy. Same as Figure 1, but waste is now purchased by consumers from producers at positive price for recycling; cost is effectively paid by natural resource rents, and the resource-waste cycle becomes closed.

Figure 4. Instantaneous supply-demand equilibrium for waste production. Supply curve is marginal cost of waste, subject always to diminishing returns (rising marginal cost); demand curve is marginal utility of waste, typically also subject to diminishing returns (falling marginal utility). Two scenarios: pay-for-trash-removal economy, wherein marginal utility of waste is mostly or completely negative, and waste sells at a negative price; recycling economy, wherein marginal utility of waste is mostly or completely positive, and waste sells at a positive price. Marginal cost of waste is partially negative, reflecting falling total costs for moderate amounts of pollution.



Rents
Environment
Waste
Resources
Economy
Wages
Labor
Capital Goods
Capital
Investment Spending
Profit
Consumption Goods
Consumption Spending

Figure 1

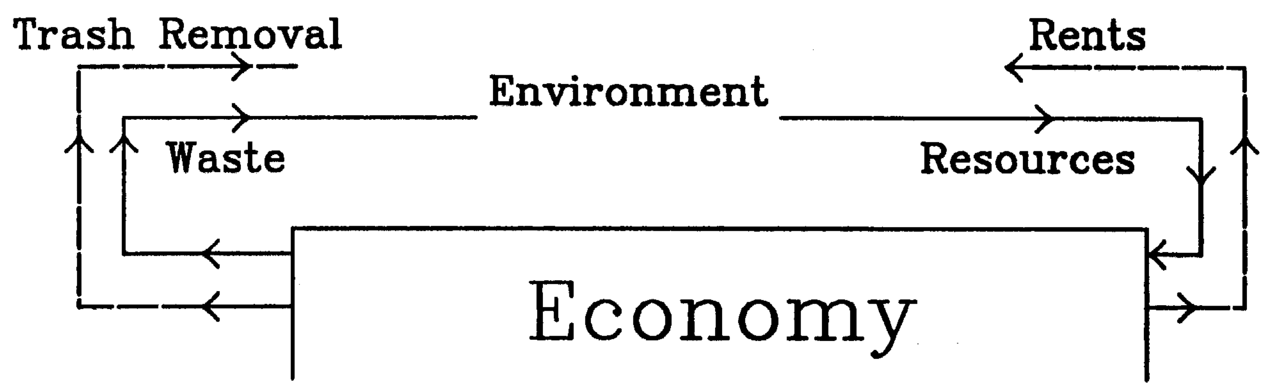


Figure 2

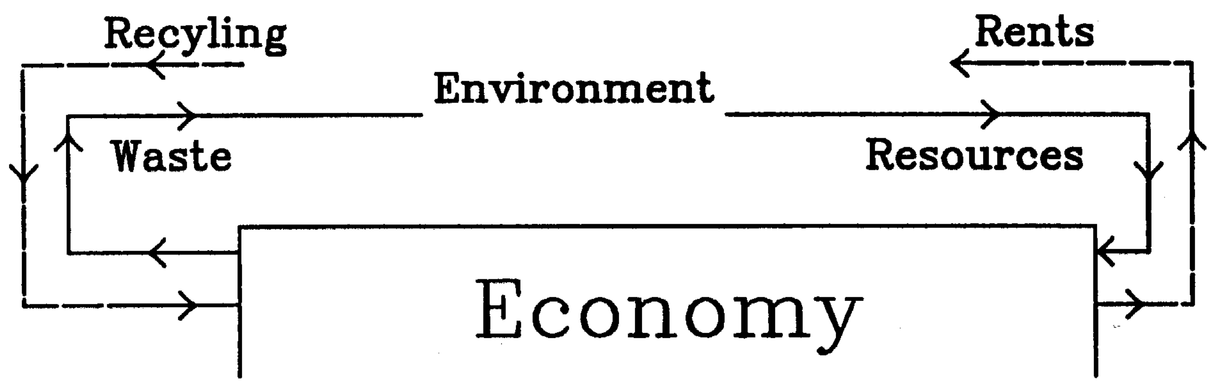


Figure 3

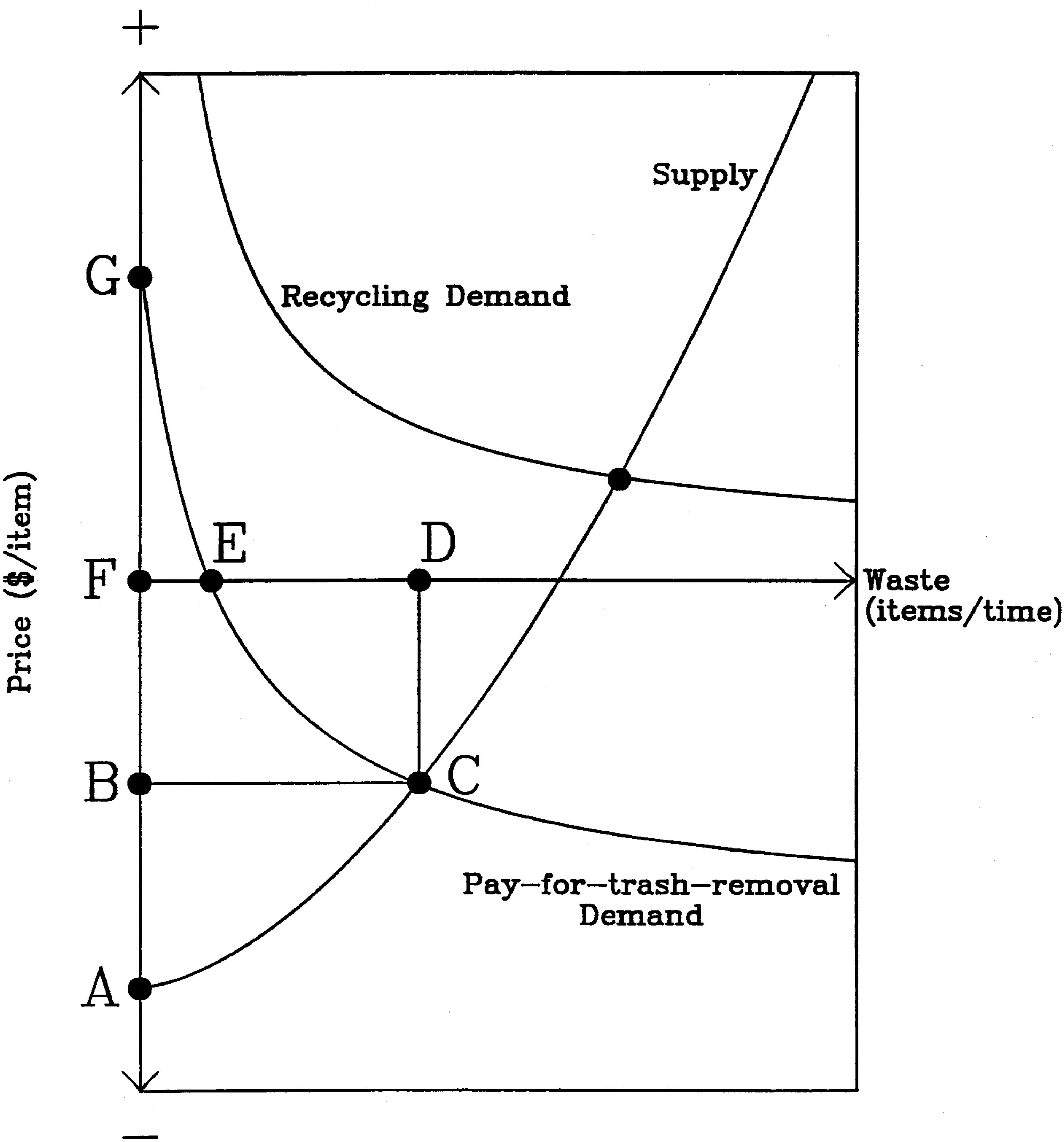

+
Supply
G
Recycling Demand
Price ($/item)
E
D
F
Waste
(items/time)
B
C
Pay–for–trash–removal
Demand
A
—

Figure 4