EVOLUTIONARY ECONOMICS & ENVIRONMENTAL IMPERATIVES

ABSTRACT

The long-range biological imperative for survival has its economic counterpart. The present techno-economic system, with its heavy dependence on exhaustible stocks of natural resources – including environmental waste assimilative capacity – is unsustainable. The stocks of high quality raw materials, such as fuels and metal ores, are being drawn down rapidly, but this is the least of the problems because of possible technical "fixes". More ominous, there is an irreversible disappearance of tropical rainforests and other valuable and irreplaceable ecosystems, erosion of topsoil, a buildup of toxic heavy metals in soils and sediments, an accumulation of "greenhouse gases" in the atmosphere, and a catastrophic loss of biological diversity. None of these trends is reversible by any known or plausible technological intervention. Long-run human survival therefore requires that the use of the environment as a "sink" for waste residuals, especially from fossil fuel combustion and dissipative uses of heavy metals, must be slowed down drastically in the near future.

The paper examines the relevant economic adjustment mechanisms in terms of both "standard" neo-classical and evolutionary theories. It concludes that a policy based on reliance on market signals (i.e. prices) alone to induce change is likely to be ineffective. Even if the polluter-pays-principle (PPP) were fully implemented, market mechanisms would not suffice. The problem is that existing large-scale systems evolved during a period when environmental concerns were not serious, and now retain their economic dominance partly due to economies of scale and partly through influence over the political system.

INTRODUCTION: IDEAS OF EQUILIBRIUM IN ECONOMICS

The modern notion of *evolution* as a process began with the geologists and was taken up by the biologists. Darwin's main concern was to discover mechanisms to account for the historical fossil record. Since the late 19th century evolution has been, in some sense, the most important "fact of life" for much of science. Curiously, despite the fact that evolutionary ideas were well developed in the social sphere – and even by early economists like Adam Smith – long before they were adopted by the physical sciences, and geological and biological evolution are relatively slow by comparison with technological evolution (for instance), most theoretical economists in the late 19th century adopted a static or quasi-static worldview. Economists have only recently begun, in a systematic way, to consider the economic system once again as an evolutionary system.

The reasons for this peculiar blind spot probably have their origin in the so-called "marginalist revolution" of the mid-19th century, and its fascination for general equilibrium models. This fascination seems to have been based on a somewhat distorted analogy with the physics of energy. To summarize briefly, physicists had discovered the applicability of extremum principles (notably the principle of least action, and the Hamilton and Lagrange formulations) in classical mechanics. A number of economists of that period, notably Dupuit, Gossen, Cournot, Jevons, Walras, Edgeworth and Pareto, explicitly sought to develop economics along similar lines, substituting "utility" (or "pleasure") for potential energy[1].

The problems of the energy metaphor need not concern us here. Suffice it to say that Walras, in

[1] For a fascinating account of this history, see Philip Mirowski's article "Physics and the Marginalist Revolution" [Mirowski 84], and a subsequent debate in the literature [Hollander 89], [Mirowski 89].

particular, succeeded in formulating economics as a static "balance of forces" between supply and demand, and focussed attention on the question of whether (and under what conditions) a set of unique prices can exist that "clears" the market. The first existence proof for the static case was given in the 1930's by Abraham Wald. Simpler and more powerful proofs, using the Kakutani fixed-point theorem, appeared in the 1950's [Arrow & Debreu 54], [McKenzie 54].

For historical reasons, it seems, the phenomenon of economic growth has been studied primarily as a very special case (*homotheticity*) in which all structural detail remains unchanged (growth in all sectors is proportional). This is essentially indistinguishable from static Walrasian equilibrium for short periods. It consists of a steady, smooth, monotonic "quasi-static" expansion. The famous homothetic growth model of John von Neumann, first presented in a German version at a mathematics colloquium in the early 1930's and later published in English [von Neumann 45], was very influential. It led to an enormous mathematical literature. Unfortunately, such models do not at all reflect the sort of dynamic technology-driven growth that actually occurs in the real world.

The situation was nicely summarized by Mark Blaug:

> "In view of the enormous difficulties in handling anything but steady-state growth ..... the literature has been almost solely taken up with arid brain twisters about `golden rules' of capital accumulation" [Blaug 80].

In the view of some economists, at least, the static (and quasi-static) equilibrium paradigm seems to have exhausted its explanatory power. Evidently *evolutionary* models must be *non-equilibrium* and *non-homothetic,* in nature. Clearly, Walrasian static or quasi-static equilibrium is not the condition we live in. The real world is characterized by continuous (and unpredictable) structural changes. Moreover, the standard conditions for static equilibrium (perfect competition, perfect information, perfect rationality, etc.) do not exist and cannot exist.

Furthermore, it appears that the essential features of evolutionary growth and change are essentially characterized by *non-linear* dynamic behavior. This encompasses such phenomena as quasi-stability, quasi-cyclicity, morphogenesis, and "deterministic chaos". An important phenomenon of non-linear dynamics is the so-called "butterfly effect", meaning that the slight motion of air induced by the flapping of butterflies wings may be sufficient to differentiate two long-term weather patterns from each other. It is characteristic of such systems that dynamic trajectories are much more sensitive to initial conditions than to long-range "equilibrating" forces.

Another key characteristic of evolutionary behavior is **hyperselection** or **path dependence** or **self-organization**. Whereas the "Butterfly effect" refers to the exponential divergences of trajectories in the neighborhood of a single "strange attractor", hyperselection refers to the transient stage of evolution when it is possible for a system to "choose" between disjoint attractors. Still another name for the phenomenon, which is more evocative, is "lock-in/lockout". Thus, the selection of one evolutionary path or another may be largely accidental, and yet that path may be dominant for a long time (in evolutionary terms). This happens because – in the real world – there are feedback effects ("returns to adoption") that favor the established choice over most competitors [e.g. Arthur 88; Arthur *et al* 87].

While not strictly an example of "lockout", an established manufacturing technology will not be displaced automatically by a slightly better one. Only when the advantage of the new technology is quite large will a "rational" entrepreneur introduce a substitution. In the first place there are frictional costs. For example, the workforce may need retraining. In the second place, old manufacturing technology in existing plants has the advantage of variable costing with fully depreciated capital equipment, whereas new technology must compete on the basis of full cost[2] [Salter 60]. But even in new facilities, the higher risks of unproven technologies have to be weighed against expected but uncertain gains in performance.

An example which illustrates the point that a small improvement is not sufficient to induce a change, is the familiar QWERTY typewriter keyboard [David 85]. This keyboard is not optimal from an ergonomic point of view. (In fact, it was introduced originally to show down typists, because early typewriters had a tendency for keys to stick). But the cost of change – replacement of all keyboards and retraining of all typists – is not justified by the marginal benefits of the improved keyboards.

A second example of hyperselection might be found in the history of urban transportation. In the U.S. electric tramways were once as widespread and heavily travelled as they are today in Europe. But in the 1930's through the 1950's conditions in the U.S. – notably lower fuel prices and less restrictive land-use policies which favored expansion of the suburbs – were somewhat more favorable for diesel buses than was the case in Europe. Bus interests were supported by the powerful automotive and petroleum industries. By the 1960's trolleys and trams were obsolescent in the U.S. and the tracks were being removed from most cities. This did not happen in Europe. Today, curiously enough, the virtues of trams ("light rail systems") are being rediscovered in some U.S. cities, but once the tracks are gone it is prohibitively expensive to replace them in most instances.

An example of lock-in that is much more relevant to current environmental concerns is the likely future dependence of the economy (for many decades to come) on automotive vehicles depending, in turn, on liquid hydrocarbon fuels. Here the initial determining factor was probably the availability of low priced gasoline. Prior to 1905, when the competition between rudimentary gasoline engines and electric cars was basically settled in favor of the former, gasoline was a very cheap by-product of petroleum refining, the primary product of which was kerosine ("illuminating oil") for lighting purposes [Ayres & Ezekoye 90]. Later, when gasoline became the primary product of refineries, the price was kept low by subsidies to producers, notably the "depletion allowance". At the present time, fossil fuel prices are still effectively subsidized by the lack of any charge on consumers of petroleum products to reflect the environmental damages caused by fossil fuel use. From this perspective, it has been estimated that fossil fuels, in general, are probably underpriced by a factor of 3 or more [e.g. Chizov & Styrikovich 88;].

In contradiction to this view, it may be argued that the technology of electric automobiles was certainly very primitive at the beginning of the century, whence the internal combustion engine might well have prevailed on its merits, even if gasoline (or diesel oil) had been much more expensive. On the other hand, electric car technology – and supporting infrastructure – would have developed much faster than they did, whereas the ICE (and associated petroleum refining) technology would certainly have evolved more slowly. The outcome in this hypothetical case is unknowable. However, a much stronger argument can be made that electric propulsion would win out over gasoline engines if a fair competition between the two technologies were held today (or, better still, in the year 200). The comparative benefits of electric drive for urban use – no air pollution, no smells, no noise – appear likely to grow still further over time. These benefits would be compounded if electricity can be produced at reasonable cost in the next century by means of photovoltaic cells[3].

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[2] This is a consequence of the in-built specialization or "clay-like" characteristic of most kinds of capital equipment.

[3] A recently completed study suggests that power can be generated by large-scale PV "farms" on the surface of the moon (manufactured by automated factories on-site) and transmitted to earth very efficiently by phased-array microwave beams, at a total cost to the user in the neighborhood of one or two percent of current costs for electric power generated

(continued...)

In any case, the phenomenon of hyperselection is quite relevant to the direction of long-run evolutionary change. I will return to this point later.

BROWNIAN MOTION OR GRAVITATIONAL ATTRACTION?

As mentioned above, economic growth is difficult to accommodate in neo-classical economics. Most of the early growth models tried to explain aggregate growth in terms of capital accumulation and increasing labor force. This simplistic view became untenable after the empirical studies in the mid-50's by Fabricant [Fabricant 54], Abramovitz [Abramovitz 56], Solow [Solow 57] and others, which established that other factors – lumped under the general heading `technology' – have been responsible for most of the per capita economic growth that has occurred.

Theory tried to cope with this by introducing technological change (in the guise of increasing productivity) as an *exogenous* driving factor. But this is clearly unsatisfactory, inasmuch as technological change is anything but exogenous in reality. The fact that the rate and direction of inventive activity are inherently difficult to forecast does not alter the fact that R&D and innovation are themselves economic activities, and occur to a large extent in response to other economic conditions.

There are two theoretical possibilities, representing extreme cases. The first is that evolutionary progress is stochastic: it occurs entirely as a result of short-range, localized events and decisions or "collisions". This notion can be characterized as "drunkard's walk", or deterministic chaos. The analog in physics is "Brownian motion". The opposite extreme case is that evolution is guided by a long-range force, analogous to gravity. The analogy might be to an intergalactic spaceship drifting through a stellar cluster.

Or (a subtler idea) evolution may be subject to both short-range random collisions and a very general long-range directional constraint. Such a directional constraint is not quite equivalent to a long-range attractive force like gravitation. For one thing, it is not sufficient (by itself) to determine the trajectory of motion. It merely excludes some possibilities. It implies that evolutionary progress is *irreversible,* without specifying its actual direction or rate. The second law of thermodynamics (entropy law) is an example of just such a directional constraint in physics: it states that all physical processes must *approach* thermal equilibrium. (They cannot move away from equilibrium). It is also true that in some generalized sense the distance from equilibrium is a measure of the "force" operating. But the actual rate of approach to equilibrium is not determined by the second law. It depends on the detailed characteristics of the system in question.

It is noteworthy that this irreversibility in physics is what guarantees the existence of a non-decreasing function, which we call **entropy**. It follows, incidentally, from the existence of such a function, that the dynamics of a system can be described by an extremum principle. For instance, in thermodynamics, systems tend toward states of (locally) maximum entropy or minimum free-energy.

Evolutionary biologists have postulated both irreversibilities and extremum principles. For instance, Dollo's "law of irreversibility" (1893) postulated an irreversible trend toward increasing complexity or organisms. Dollo's law was reformulated by Julian Huxley [Huxley 56]. Ludwig Boltzmann saw biological evolution in terms of a competitive struggle to capture free-energy. This notion was restated as an extremum principle by A.J. Lotka [Lotka 22].

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[3](...continued)
by conventional means [Criswell 90; Criswell & Waldron 90]. Even if this analysis is too optimistic by an order of magnitude, the option is worth considering very seriously. It scarcely needs to be said that the petroleum and utility sectors would oppose this scheme vehemently.

Recently, Prigogine and his colleagues have applied ideas from non-equilibrium thermodynamics to biological evolution [Prigogine *et al* 72; Prigogine & Stengers 84]. Some of these ideas have also been reformulated in terms of extremum principles [Ebeling & Feistel 82,84], although it is too early to judge whether these principles explain observed phenomena satisfactorily. Brooks & Wiley have attempted to apply similar ideas at the ecosystem level [Brooks & Wiley 86]. In some sense, all of the above are attempts to show that biological evolution is not only compatible with the laws of thermodynamics (increasing entropy), but a direct consequence of them.

In micro-economics, too, there is a fundamental irreversibility phenomenon. To state it briefly: if a pairwise exchange transaction can proceed in one direction under bounded rationality – A is willing to buy X and B is willing to sell X – then it cannot proceed in the reverse direction[4]. This sort of irreversibility is implicit in Walras' law and the *tâtonnement* process for price determination. It was later articulated by Ville [Ville 51].

It should be pointed out that the approach to Walrasian static equilibrium has nothing (other than irreversibility) in common with the approach to thermal equilibrium in physics. Nor does it reflect economic or technological "progress" in any sense whatever. It is simply a conceptual device to explain how pure exchange markets might converge to a set of unique market-clearing prices[5].

In the economic case, as in the biological case, no satisfactory extremum principle has been formulated to explain economic (or technological) evolution at the macro-level. In the real economic system two kinds of evolutionary progress do seem to occur. That is, there are clear indications of stochastic or chaotic processes analogous to Brownian motion [e.g. Chen 89]. But there are also hints at the existence of "long range forces" or, at least, directional constraints, as noted above.

Traditionally, in the sciences one tries to explain, and then predict, macro-level phenomena in terms of micro-level behavior. Economists have not, up to now, been very successful in this endeavor. One of the few areas where some success can be claimed is the proof that "self-organization" of markets follows from micro-level behavioral axioms. The existence of a non-decreasing "progress function" is a consequence of transactional irreversibility on the micro-scale.
One of the questions I am raising in this paper is whether one can identify a directional constraint on the macro-scale and work back to infer the corresponding micro-mechanisms. If the *real* economic system is subject to apparent directional constraints at the macro-level, how might those constraints be characterized? And, are there plausible mechanisms at the micro-level that might give rise to the appearance of such macro-constraints? These questions reverse the usual "bottom up" (micro-to macro) logical order of causation imposed by traditional scientific reductionism.

In the discussion that follows I use the phrase "dynamic equilibrium" in an essentially metaphoric sense. It refers to evolutionary "motion" around a "strange attractor" whose existence is, however, merely postulated. There is an obvious analogy with the motion of planets or asteroids in the gravitational field of an invisible object (e.g. a "black hole"). The analogy of "approach to

[4] It can be shown that transactional irreversibility also implies the existence of a non-decreasing function in economics [Ayres & Martinàs 90a]. This function is analogous to the entropy function only in the sense that it is non-decreasing. However, it is not a consequence of thermodynamics. It can be thought of as a "progress function". In general terms, the progress function can be interpreted as a growing stock of useful information.

[5] The *tâtonnement* process described by Walras is not implementable in real markets because no actual exchanges can occur until the market-clearing price is determined. Implementable price-adjustment processes have been described by Smale [Smale 76] and Aubin [Aubin 81], but in Smale's case an active `auctioneer' is postulated. while Aubin requires a passive mechanism for publishing information on prices. Both assume that there exists a unique money price, known to all parties, for the good(s) being exchanged at every instant of time. More recently a decentralized convergence process has been described, involving only pair-wise transactions in which the exchange price is not unique and is known only to the parties [Ayres & Martinàs 90b].

equilibrium" in classical thermodynamics is also relevant, although in that case the equilibrium is static. However, modern non-equilibrium thermodynamics also allows the possibility of "self-organizing" stationary states far from equilibrium [Prigogine *et al* 72], [Nicolis & Prigogine 77]. Organic life exemplifies such self-organized states. It is evident from the biological case that, if the system is sufficiently complex and non-linear, a self-organizing stationary state far from (thermodynamic) equilibrium is capable of evolutionary change. It is a natural assumption that a self-organized economic system should also be capable of evolutionary change [Ebeling & Feistel 82,84].

In short, I suggest that the economic system must eventually evolve in accordance with certain macro-directional constraints and that this motion can also be characterized as a kind of approach to (dynamic) equilibrium. The equilibrium in question, of course, concerns the interaction between human agricultural, industrial and consumptive activity and the physical and biological environment. An equilibrium interaction, in these terms, is one that is indefinitely *sustainable*, albeit *not* necessarily static[6].

THE ECONOMIC SYSTEM AND THE ENVIRONMENT

The dissipative character of the real economy, and its dependence on large quantities of physical materials and fuels, has two important consequences. First, since matter is conserved, all materials that are extracted from the environment as crops, fossil fuels, metal ores or other minerals must eventually return to the environment as waste residuals. (See Figure 1). The material cycle is closed in a very short time (weeks or months) for most organic materials, and a somewhat longer time for some metals and minerals. But the time between extraction and return is extremely short by geological standards.

The second consequence follows from the first, plus a massive market failure: the indivisibility and non-exchangeability of environmental "goods" and "bads" and our consequent inability to attach meaningful prices to them, or to the consumptive uses of raw materials and goods that are exchangeable. Because of this market-failure, most of the environmental costs noted above are *externalities* in the sense that they result from economic transactions but are imposed on "third parties". Large environmental damages (hence costs, whether paid or unpaid) are imposed on the environment and, indirectly, on society. These damages and damage costs include environmental health problems such as cancer, cardio-bronchial problems (e.g. emphysema and asthma), climate-warming, corrosion of metals and building materials due to acid rain, acidification, erosion, and salt buildup in the soil, eutrophication of lakes, accumulations of toxic metals in soils and waterways, growing solid waste mountains, and a host of other problems. To the extent that these damages are not being compensated or repaired today, they are simply accumulating for the next generation to deal with.

In short, human economic (industrial and agricultural) activity is based on the consumptive use of non-renewable and irreplaceable resources, from fossil energy to topsoil. Having introduced the notion of long-term sustainability as a criterion of economic-environmental equilibrium, it must be said that the human economic system – at present – is far away from such an equilibrium.

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[6] The definition of sustainability has attracted considerable attention in the economics literature in recent years (see, for instance [Pezzey 90]). Pezzey's definition of sustainability is, essentially, "non-decreasing utility", on the standard assumption of unlimited substitutability between economic and environmental factors, both in production and consumption. A more "radical" definition (which I subscribe to) takes it for granted, both that substitutability is quite limited – there is no technological substitute for air or water, for instance – and that some degradation processes are irreversible, which implies that some environmental assets, once lost, may not ever be replaceable. It follows that sustainability implies that irreversible processes, such as the accumulation of greenhouse gases in the atmosphere, or the buildup of toxics in soil and groundwater, must not be allowed to continue. This definition essentially amounts to a set of constraints on economic activities.

The question now arises: what (if any) relationship exists between the above notion of equilibrium with the environment and the traditional Walrasian equilibrium? The former is related to materials and energy flows and accumulations; the latter is defined in terms of prices that "clear" the market, i.e. match supply and demand. At first sight, static market equilibrium does not necessarily have anything to do with sustainability in the physical or ecological sense.

However, on deeper analysis, there should be a very close connection. A number of economists have extended the original Walrasian general equilibrium framework. By the late 1960's growing awareness of environmental problems underlined the need to correct for market failures by broadening the Walrasian definition of exchangeable goods (or services provided thereby) to include non-exchangeable "bads" (or disservices) such as waste emissions from industrial and consumption processes [Ayres & Kneese 69]; [Kneese *et al* 70]. Others, concerned with the problem of exhaustible resources, explicitly introduced the time dimension by extending the market to allow for exchange of future goods (or bads), much as the stock market buys and sells "futures" contracts [Solow 74],[Dasgupta & Heal 79].

Given these extensions of the static framework, it might be argued that, in principle, the market price system should be able to adjust for externalities – such as environmental damages – resulting from market failures, both now and in the future. In other words, a perfectly functioning market should properly balance supply and demand for both conventional "goods" and environmental "bads". In such a system, the marginal (social) cost of an incremental increase in the environmental burden of some harmful waste product should exactly balance the marginal cost of eliminating that waste residual at source or repairing the environmental damage, whichever is cheaper[7]. This, rather standard model relationship is illustrated for the static Walrasian equilibrium case by Figure 2.

It is a fundamental principle of efficient markets that externalities (third-party effects) of transactions should – if possible – be eliminated or compensated for by adjustment of the transaction price. By this mechanism all social costs are directly and explicitly included by sellers and absorbed by buyers. This is the basic condition for markets to achieve allocative efficiency. A way of approximating this condition is commonly termed the *polluter-pays* principle (*PPP).* If the polluter has to pay for all the damages, he will presumable take these downstream costs into account in his choice of technology, and his pricing policy.

Of course, there is a problem with the above theoretical prescription. While the Walrasian framework of analysis can be extended, in principle, as described above, the equilibration *process* still depends upon the existence of explicit prices for the non-exchangeable "bads", as well as the exchangeable "goods"[8]. Absent voluntary individual exchanges, we envision social choices decided by some semi-undefined (but democratic) political process, based on some undefined method of determining the willingness-to-pay (WTP) of the population. The practical difficulties in determining the shadow-prices of environmental disservices and implementing a polluter pays program are so great as to possibly constitute an objection in principle.

However, skating lightly over this conceptual thin ice, it seems evident that most raw materials are drastically under-priced (and, as a further consequence), over-used. To achieve allocative efficiency the environmental damage costs *should* be paid by the polluters (namely us), but not directly. The efficient way to accomplish this is to transfer the extra costs not to final consumers – who can only decide whether and how much to consume – but by a tax or other charge on primary producers. The

[7] Of course, some kinds of damage are inherently irreversible and unrepairable. This is probably true of climate change and certainly true of loss of species diversity or of mature Redwood forests. Lacking the possibility of damage repair, the market should balance marginal damages with marginal costs of source reduction.

[8] Admittedly, in a decentralized pure exchange market the actual transaction prices need not be published to ensure convergence; nor do they need to be unique [Ayres & Martinàs 90b].

latter will take these costs into account in making technology choices. They will also pass their added costs along to the next tier of customers, who will also make choices between alternative materials and between raw and recycled materials. (For instance, if fossil fuels were much more expensive than they actually are, energy conserving technologies and solar energy technologies would be selected much more often than they are now). The chain continues until the consumer is presented with choices that better reflect all these costs.

Unfortunately, the polluter pays principle is seldom adhered to in practice or enforced by governments. (In a sense, this *is* the market failure). From a physical perspective, the basic problem is that most pollution is ultimately due to the extraction and primary processing processes, on the one hand, and the consumption processes, notably burning of fossil fuels and the dissipative uses of materials, on the other hand. When the user-polluter is an industry (an intermediate), it is sometimes possible to apply the principle. But when the polluter is the government or the final consumer – increasingly the case – the polluter (so far) simply refuses to pay. If preferences are judged by behavior, consumers seem to prefer cheap energy and cheap materials to a clean environment. Loss of jobs is feared more, by most people, than loss of environmental amenities.

The use of taxes or emission charges, often advocated by economists, can also be faulted, on the grounds that it is difficult (or impossible) to calculate the "correct" tax rates, or to allocate the burden equitably. This reflects, in part, the conceptual problems noted earlier. On the other hand, it might be argues with some force that the present system of taxation for the purpose of raising revenues for the government is so regressive and counter-productive that almost any tax on exhaustible resource use or pollution would be an improvement, as long as it is simply used for revenue and substituted for some existing tax on labor, income or final consumption. In short, the present tax system is far from optimal, so why worry unduly about optimizing a system of resource/environmental taxes?

In summary, it is unclear whether an economic system satisfying the polluter-pays principle (PPP) PPP is implementable, even in principle. If such a system could be designed and implemented, a second question arises, namely whether its application would suffice to make the economic system ecologically sustainable in the long run. Doubts arise because of the prevalence of hyperselection or "lock-in" phenomena, which drastically interfere with – or totally prevent – the convergence of the real economy to its theoretical static or quasi-static equilibrium state. A further question that arises, and which deserves deeper study, is the extent to which market failures and externalities are, themselves, major causes of hyperselection (as already suggested in the case of automotive vehicles dependence on liquid hydrocarbon fuels).

Whether convergence to a sustainable equilibrium state can be expected to occur spontaneously on the basis of market (or quasi-market) price signals alone, it is quite evident that the present economic system is far away from either equilibrium or sustainability. It is also clear that a significant reduction in the degree of environmental market failure would result in a radical improvement in the degree of ecological sustainability.

TECHNOLOGICAL AND ECONOMIC EVOLUTION IN LONG TERM PERSPECTIVE

I commented earlier that I want to examine technological and economic evolution as an example of a dynamic process subject to a directional constraint. The constraint I have in mind, obviously, is the requirement of long-term environmental sustainability, already discussed (in footnote). The full range of implications of sustainability need not be spelled out in detail (even if this were possible). However, I take it that necessary, if not sufficient, conditions for sustainability include the following: energy must be taken only from renewable sources, greenhouse gases must not be allowed to accumulate in the atmosphere, and non-biodegradable toxic materials must not be allowed to accumulate in soils or sediments. It follows that combustion of fossil fuels and dissipative uses of toxic heavy metals – among other things – must be phased out. In fact, all use of exhaustible stocks of materials will eventually have to cease. Long term sustainability also implies that in future centuries materials recycling will have to be very nearly total in the coming "spaceship Earth" [Boulding 66].

Biological evolution was subject to similar sustainability requirements. The biosphere today is a nearly perfect materials recycling system, but this was the result of billions of years of natural selection. The earliest organisms simply exploited (by fermentation) a stock of organic materials that had accumulated in the oceans prior to the appearance of organic life. Photosynthesis was an evolutionary "invention", using the energy of sunlight to convert carbon-dioxide into glucose to replace the exhausted resource stock. But photosynthesis yields a toxic by-product, oxygen. At first, the oxygen was used up as fast as it was produced in the formation of iron oxide (now iron ore), but when the dissolved iron – essentially, the "waste assimilative capacity" of the early ocean – was exhausted, the level of molecular oxygen in the oceans began to rise. But oxygen was toxic to all existing (anaerobic) forms of life.

Another evolutionary "invention" was necessary to solve this problem. It was a new metabolic process based on oxygen respiration (essentially, catalytic partial oxidation) in place of the older fermentation process. The newer aerobic process was more energy efficient (by a factor of 18) and so, began to replace the old one. Thus, to simplify a very complex story, the fundamental carbon cycle came into being. (Other natural cycles also evolved subsequently, to recapture nitrogen, phosphorus, and other minerals).

Evolutionary biologists tend to concentrate their attention on the micro-mechanisms of natural selection. At this level, the influence of the long-term imperative to recycle is difficult to see. It is like a very faint signal in a very noisy background. But, looking at the biosphere from a holistic perspective, it is clear at least in retrospect that the carbon cycle was an essential feature of organic evolution. The details might have evolved differently, but the result was inescapable. Both a photosynthesis process based on carbon dioxide (CO2) and a metabolic process to utilize molecular oxygen "had to" evolve.

I believe a similar teleological imperative will drive future technological and economic evolution in the direction of lower energy and materials intensity, use of solar energy, and materials recycling. There is virtually no evidence for this statement in past trends. In fact, most of the trends are still going in the wrong direction. Again, the signal that determines the direction is (currently) almost drowned out by the noise of competing shorter-term imperatives. In effect, the direction of evolution in this case is almost impossible to infer from an analysis of the details of the economic selection processes, insofar as we understand them.

It is now assumed that the primary mechanism that drives the evolution of technology is a combination of "Schumpeterian" (radical) innovation and "Usherian" incremental improvements (e.g. "learning"). The latter process is perhaps consistent with a quasi-static paradigm, but the radical innovations are not. Schumpeterian innovations are generally quite risky. The motivation for taking the major risks associated with innovation is assumed to be the additional profit available to an innovator by virtue of having a (temporary) monopoly.

But the Schumpeterian mechanism (as described above) is directionally neutral. It implies only a search for profit opportunities, but implies absolutely nothing about where they will be found. It is the external environment that defines the *direction* of technological progress or innovation. The prevailing macro-economic theory for explaining the direction of change (the theory of "induced innovation") is driven by factor price differentials[9]. The idea is that if energy prices are higher relative to labor costs in country A than in country B, country A will be a relatively more favorable environment for energy-saving innovations, while country B will be relatively more favorable for labor-saving innovations. This difference in outcome would presumably result even if the *a priori* probability of basic inventions in each field were the same in each country.

Social needs are presumed (by economic theory) to express themselves through the price system. In simple terms, a rising price suggests increasing scarcity: demand increasing faster than supply (or supply falling faster than demand). A rising price suggests an inadequately filled or unfilled need, and should "signal" a suitable response by technology adopters and/or by the technology creation sector. For example, it can be argued that the rising price of whale oil in the mid-19th century "called forth" developments in petroleum refining technology and led to the commercialization of kerosine and the development of the petroleum industry. Similarly, it can be argued that the growing demand for automobiles after 1908 called forth the petroleum refining innovations that have allowed that industry to make gasoline its primary product. (Recall, however, the counter-argument presented earlier, to the effect that it was the availability of natural gasoline, a cheap by-product of kerosine, that enabled the gasoline engine to achieve an insurmountable lead in the competition with electric cars).

Evidently the induced demand hypothesis cannot be the whole story. Wrong price signals can also induce inappropriate technological responses, which in turn may be locked in by economies of scale or other increasing returns to adoption. Moreover, there are needs that are not clearly reflected by a rising commodity price. While prices are signals of social need, they are not the only such signals. More to the point, in some circumstances, at least, prices are evidently no longer an effective signal. In the previous section, I have suggested that environmental degradation itself is *ipso* facto evidence of disequilibrium. However, there are other kinds of evidence of disequilibrium that may be more persuasive to a neo-classical economist.

To explain this, let me revert to the neo-classical framework. Suppose, to begin with, that there are no externalities and the real economy reflects a utility-maximizing quasi-static Walrasian equilibrium (as assumed by neo-classical economics). In this case, it would automatically have selected the optimum (lowest private cost) production technologies. Now suppose that environmental externalities (damages) are suddenly discovered. If an appropriate tax system (based on PPP) were then introduced to correct for the distortions due to environmental externalities, the choice of technology would – in a Walrasian world – automatically shift to minimize the sum of private and social costs. Both total costs and social costs would fall.

However, this shift would involve some increase in private costs (or decrease in gross national income), as suggested by Figure 2. Under these assumptions, it would be correct to assert that there must be some money cost (or loss of money income) to reduce pollution. The same logic applies to saving energy. That is, if the economy were in a Walrasian equilibrium, and if adjustments to price signals were `automatic', our economy would already be using the most cost-efficient technologies. In this case, it would surely cost money to save energy. This is the situation that is almost universally assumed by economists (if not engineers) to exist in the real economy.

I have argued on the contrary, however, that the economy is not in Walrasian equilibrium, due to a

[9] Of course, inventors and investors seldom track the price indices of aggregate factors of production. They read the newspapers. There is a close connection between the intensity of public interest in a subject and the intensity of interest on the part of would-be technology creators. This link has been expressed as a societal response to social "needs" [Ogburn & Thomas 22].

combination of uncompensated externalities and hyperselection (lock-in) phenomena[10]. I argue, further, that the postulated price adjustment and convergence mechanism (*tatonnement* and its modern variants) is relatively (though not altogether) ineffective. In short, the standard assumptions do not hold for the real economy. In fact, the existence of major opportunities to reduce pollution or save energy, while saving money at the same time, would constitute compelling evidence of the non-equilibrium character of the economy [Ayres 90]. Evidence compiled from many engineering studies suggests that such opportunities are widespread. If so, the true picture is more like Figure 3, which illustrates the case (which I believe to be realistic) where it is possible to reduce emissions – or save energy and/or material inputs – while simultaneously saving money. This situation could not exist if the economy were truly in an equilibrium state, because entrepreneurs would, presumably, have found and exploited any such opportunities.

The best evidence of disequilibrium can therefore be derived from studies indicating the existence of major discrepancies between rates of return achievable from various sorts of investments. If the economy were in (or near) equilibrium) rates of return would be relatively comparable, regardless of field. It is economically irrational for a profit-making tax-paying enterprise to knowingly invest in anything yielding a rate of return less than the rate paid by safe government securities such as T-bills. This rate currently hovers between 8% and 9% (in the U.S.). Given an inflation rate of 4% or so, this corresponds to a real rate-of-return of around 5% and a "payback" (i.e. doubling) time of the order of 20 years, allowing for inflation.

Interestingly enough, the real rate of return for large energy supply investments (such as electric power plants) ranges between 5% and 10%, which is the absolute minimum. This very low rate of return is only possible because various government policies have made such investments virtually risk-free. (By contrast, most businesses facing market risks insist on a target rate of return for new investments of 25% or so, corresponding to a payback time of 4 years). Curiously enough, however, numerous studies have identified energy conserving investments with payback times in the range of 1-2 years [e.g. d'Errico *et al* 84]. In fact, an extended experiment by Dow Chemical Company's Louisiana Division has uncovered literally hundreds of opportunities to save energy with (post-audit) real rates of return close to 200% corresponding to payback times of six months, on the average [Nelson 89; Ayres 90].

Another approach is to look for the lowest cost way of supplying a given mix of energy services. If the economy were in a Walrasian equilibrium (or quasi-equilibrium) state, the least-cost strategy would correspond to the actual pattern of use. Such a study was carried out for the U.S. by the Mellon Institute in 1979 [Sant 79]. The conclusions were astonishing: that the least cost strategy for 1978 would have saved $43 billion in that year alone ($800 per family, or 17% of total expenditures for energy). In large part, those savings would have been achieved simply by using less energy, especially electricity. According to the study, the optimum mix would have reduced the electricity share from 30% to 17% of total energy use; the petroleum share would have fallen from 36% to 26%, while "conservation services" would have increased from 10% to 32%. In short, conservation would not have cost more, but considerably less, than the country was actually paying (see Figure 3). Again, whatever the explanation, the situation is incompatible with the economy being in a Walrasian equilibrium.

If more evidence is needed, consider the problem of waste motor oil. Approximately 2 billion gallons are generated each year in the U.S. alone, of which only 40% is collected for recycling or

[10] In fact, the two explanations are not entirely incompatible, since the continued existence of uncompensated externalities is partly due to the enormous political power of the existing techno-structure. In simple language, the auto industry, the petroleum industry, the trucking industry, the airlines and other industrial sectors whose continued prosperity is dependent on the continued use of petroleum as a primary fuel exert enormous political power and influence, especially in the U.S. These economic interests combine to effectively resist public policies – such as fuel taxes – that would discourage this dependence.

re-use. It currently costs 17 cents per gallon to collect the waste oil from service stations, of which service stations currently pay about 12 cents. Most of the waste oil collected is burned as fuel or used as road oil. Re-refining of used oil is technically and economically feasible. It can be sold at retail prices comparable to the $1 per quart ($4 per gallon) for new oil. Yet only about 10% of the collected lube oil (4% of the total) is now recycled for this purpose. The basic problem is that the large petroleum companies who dominate the marketing system have no interest in selling re-refined oil because it competes with the sale of newly refined oil[11].

Why does even private capital in our supposedly competitive free-market economy flow into projects yielding consistently low rates of return, while *not* flowing into projects with very high returns? Whatever the explanation, it is not an equilibrium phenomenon in any relevant sense of the word. Either the real economy is much slower to respond to price signals than economists have ever been willing to assume, or the Walrasian paradigm is altogether inappropriate. I suspect the latter. With respect to energy conservation (and probably other cases) the consistent neglect of economically attractive opportunities seems to me to be a case of hyperselection ("lock-in") of a non-optimal trajectory.

CONCLUSIONS

The economic incentives for technological innovation are not always effective, especially where there are massive market failures. In principle, one might expect market incentives to guarantee optimum adoption of energy-conserving technologies, given that energy is an important component of cost for both processes. In practice, market failures have kept fossil fuels far too cheap by relieving both producers and users of fossil energy from direct responsibility for paying the costs of abating or avoiding the adverse environmental and health consequences of excessive use of energy from fossil fuels. It has been estimated, for instance, that the "true" social costs of fossil energy are 3 to 4 times the current price [Chizhov & Styrikovich 88].

As noted previously, the "unpaid" environmental damage costs have been deferred and many of them will have to be paid by later generations. But as these costs become larger and more visible, one conjectures that there will be a growing political pressure to force the producers and users of fossil fuels (and other materials, such as heavy metals) to pay the costs of abating the resulting environmental damages. (At least, this is an implication of the "polluter must pay" principle). Despite resistance by energy-users, it seems inevitable that in the long run these costs will have to be added to the prices of fuels and materials. This, in turn, will create significant economic opportunities for innovators in the area of "low waste" technologies. Yet, as the energy conservation and lube oil recycling cases illustrate, rigidities in the present system operate powerfully to inhibit such innovations.

While it operates somewhat erratically, there does seem to be a long-range evolutionary imperative favoring "low energy" and "low waste" technologies for industrial metabolism, as in the biosphere. This imperative arises from the magnitude of the disequilibrium between supply and demand for environmental services (under-supplied) on the one hand, and virgin extractive raw materials (over-supplied) on the other. But, like all economic "forces", this one is subject to substantial modification – amplification or attenuation – as a result of institutional and political factors in society.

Whereas biological evolution involved accidental and unconscious selection processes, economic evolution can – and must – take place on a far shorter time scale. For this to happen, unconscious and accidental (myopic) processes must be replaced by conscious, far-sighted political-economic

[11] EPA is understandably reluctant to impose more regulations on service stations for fear that unregulated "do-it-yourselfers" (DIYers) will dump even more waste oil than they do now. The obvious solution is a returnable deposit of 50 cents per quart, or so, on all lube oil purchased by DIYers. However, strong resistance by the oil industry and its allies have prevented any such rational policy.

processes. Moreover, a conclusion that is very hard to avoid is that price signals alone cannot be relied on to trigger even economically justified investments, still less ecologically necessary innovations. This is very bad news in terms of achieving long-term sustainability. It implies that governments will have to play a more interventionist role than most economists have hitherto regarded as necessary or desirable.

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Figure 1: Closing the materials cycle

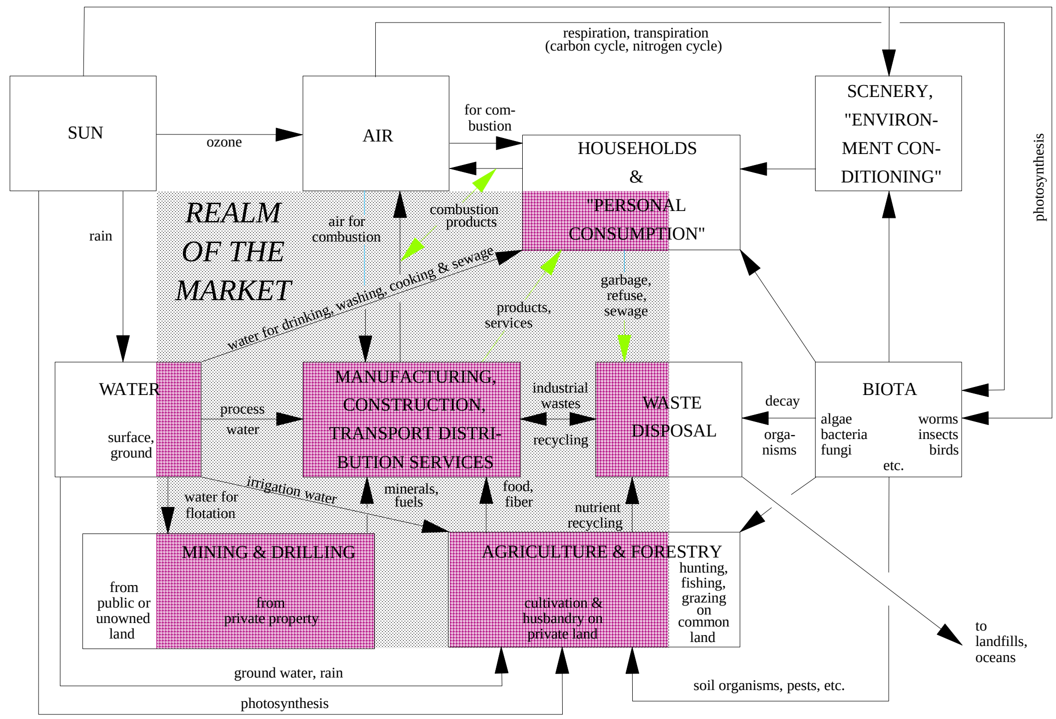

Figure 2: Optimal abatement in economic equilibrium

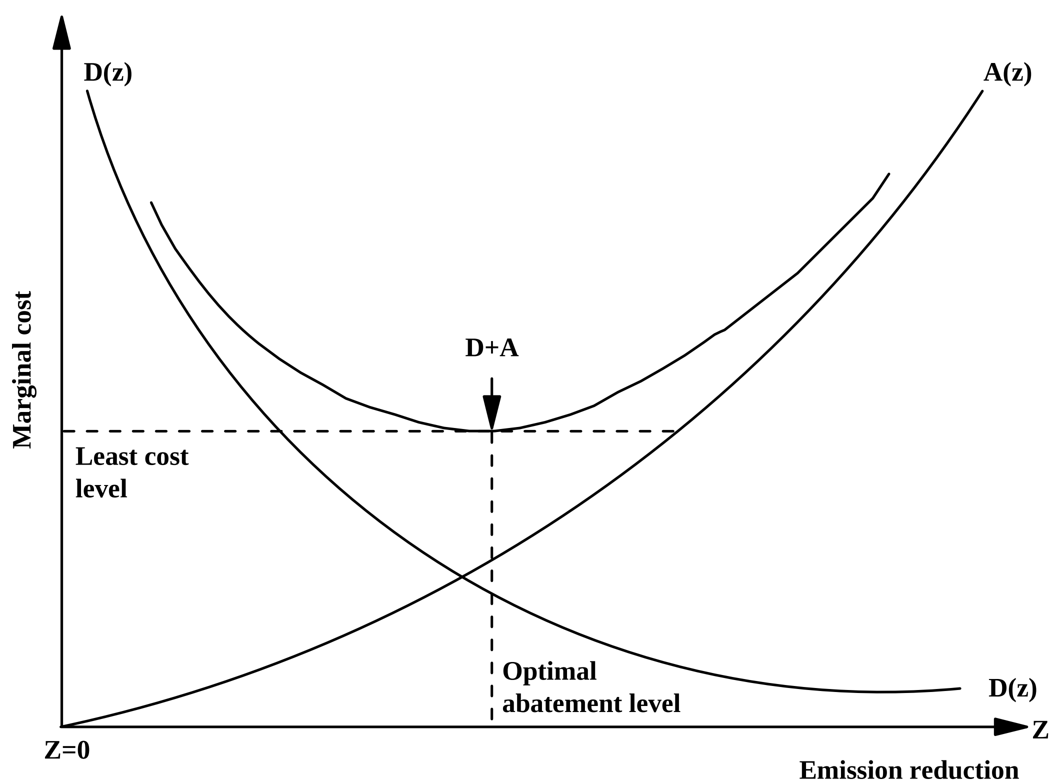

Figure 3: Optimal abatement in economic disequilibrium