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FROM THE BIG BANG TO SUSTAINABLE SOCIETIES

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Abstract

A series of events in the history of cosmos has created the prerequisites for life on Earth. With respect to matter, the earth is a closed system. However, it receives light from the sun and emits infrared radiation into space. The difference in thermodynamic potential between these two flows has provided the physical conditions for self-organization. The transformation of lifeless matter into modern life forms, with their high degree of order and complexity, has occurred in the context of the earth's natural cycles, including the water cycle and the biochemical cycles between plants and animals. Primary production units, the cells of green plants, can use the thermodynamic potential of the energy balance in a very direct way, i.e. in photosynthesis. Plant cells are unique in their ability to synthesize more structure than is broken down elsewhere in the biosphere. The perpetuation of this process requires the recycling of wastes. However, modern industrial societies are obsessed with the supply side, ignoring the principle of matter's conservation and neglecting to plan for the entire material flow. As a result there has been an accumulation of both visible and invisible garbage (pollution), which disturbs the biosphere and reduces stocks of natural resources. Furthermore, due to complexity and delay mechanisms, we usually cannot predict time parameters for the resulting socio-economic consequences or the development of disease. To continue along this path of folly is not compatible with the maintenance of wealth, nor with the health of humans or the biosphere. Rather than address the millions of environmental problems one at a time, we need to approach them at the systemic level. It is essential to convert to human life-styles and forms of societal organization that are based on cyclic processes compatible with the earth's natural cycles. The challenge to the developed countries is not only to decrease their own emissions of pollutants but to develop the cyclic technology and life styles needed by the entire human community.

Key words: Cosmology, thermodynamics, evolution, linear processes, cyclic processes, self-organization, information theory, pollution.

By human standards, our solar system is a big place. For instance, it took the Voyager 2 spacecraft twelve years to travel to Neptune. The orbit of that planet has an average radius 30 times that of the earth and a year (orbital period) of 165 earth-years. Beyond Neptune is Pluto, which remains unexplored.

In our solar system, only the earth has conditions suitable for life forms based on the complex chemistry of carbon. Of the neighbouring planets, Venus is too hot and Mars is too cold. There have been speculations about the possibility of establishing an oxygen-rich atmosphere on Mars in order to make it habitable, at least as a colony of some sort, but that is a rather doubtful prospect.

In science fiction, interstellar travels are commonplace. In the world that we live in, such travels are not easy to perform within human time frames. To send a one-kilogram space probe the 4.2 light-years to the sun's nearest neighbouring system, Centauri, and back again within the lifetime of a research group would require relativistic speeds (i.e. comparable to the speed of light). Even under ideal technological assumptions, the project would require an energy input comparable to humans' annual global energy use. A reply to a message sent to the probe at its destination would require a wait of 8.4 years. In short, apart from limited excursions, practical considerations restrict human society to the solar system in which it arose and further, to the earth.

Thus, we are restricted for the foreseeable future to the planet which is our home in the solar system. We are even further restricted to the biosphere—the thin surface layer which lies in the path of the sun's energy flow, and in which all the necessary ingredients for life are mingled.

One of the earth's animal species, *Homo sapiens sapiens*, has formed societies that are spreading over the entire planet at the expense of other species. To a large extent, those societies have a metabolism of their own, which is based not only on solar energy flows and cyclic material flows but also on one-way flows of energy and materials from the earth's interior to its surface. The industrialization that has made it possible to support a large human population has, to date, been characterized by this linear processing of energy and materials. But that process has also become a geophysical force in itself, causing profound changes in the biosphere, some of them irreversible. We shall return to this problem later.

Cosmos, life, and the evolution of science

The fact that we are restricted to the biosphere does not mean that the universe at large is irrelevant to life on earth. As we shall see, the evolution of life, and the resources that it depends on, are intimately related to the dynamics of the cosmos. Before addressing that question, however, we will note that the heavenly bodies—the sun, the moon, the planets, and the stars—have had a decisive influence on the development of human science. In attempting to understand the regular patterns of the year, of night and day, of the phases of the moon and the motions of the planets, generations of human observers developed the ideas of science. The notion developed that simple natural laws govern the complex dynamics of cosmic objects. One may speculate on the fate of science had the night sky always been covered with clouds, or had Jupiter been a small star that prevented the night sky from getting dark.

The motion of celestial bodies finally led Galilei and Newton to the formulation of classical mechanics, and thus began the development of modern physics. That development was very dramatic, as most tragically demonstrated in the 1945 tragedies of Hiroshima and Nagasaki. The rapid evolution of physics led to a physical/mechanical way of looking even at phenomena far outside the area of application. A mechanical world view, based on the description of deterministic systems, became dominant even in areas of societal planning, particularly in economics.

In recent decades, a reconciliation has taken place between physics and biology. The mechanisms of life can be understood in biochemical, i.e. ultimately in physical, terms; but physics has had to widen its perspective. In the words of Ilya Prigogine (1), physics has had to shift 'from being to becoming', from studying deterministic systems to studying evolutionary systems. Georg Henrik von Wright (2) has called this process a 'biologization' of physics, and it has been facilitated by the modern computer, which has made a wide range of physical models accessible for simulation. A system which amplifies minute disturbances exponentially cannot be adequately described by a unique deterministic time evolution. Thermodynamics, which aims at probabilistic rather than detailed descriptions, has become an important basis for this understanding.

Thermodynamics: energy/materials balances

The first law of thermodynamics states that energy cannot be created or destroyed. A similar law holds for matter. Thus, stable atomic nuclei not involved in nuclear reactions, including most matter on Earth, cannot be created nor destroyed; this principle is known as the conservation of matter. (Exceptions involve the decay chains of heavy elements used as fuel in nuclear reactors, and radioactivity induced by cosmic radiation, such as C^{14}.)

Since neither energy nor matter can be destroyed, it is possible to set up an account for the turnover of energy and chemical elements in nature. (In fact, such an account can easily be generalized to include nuclear decays and nuclear reactions.) The same can also be done for human societies.

In order to understand how matter and energy pass through a complex open system such as the biosphere, an electrical analogy may be useful. Electric current is electric charge in motion; and electric charge is conserved, i.e. it can neither be created nor destroyed. Mutual repulsion of electric charges of the same sign makes their local accumulation improbable; but it is comparatively easy to achieve local separation between positive and negative electric charges (regions with deficit of electrons or excess of electrons respectively), as in a battery. One battery can be partly discharged while charging another; the electric current passes from a higher voltage to a lower voltage. Since electric charge cannot be accumulated when electricity is being used (i.e. when the charge is in motion), the same amount of electric charge is exported as is imported.

The situation is similar for matter and energy passing through an *open system*: They pass from higher to lower thermodynamic potential. If we consider the biosphere as an open system, it is driven by an energy flow passing through it on its way from the hot sun (high potential) into cold interstellar space (low potential). There is virtually no accumulation in the system, i.e. the same amount of energy that enters also goes out and matter circulates, all in a complex network of flows. In the process, new 'batteries' may be charged, such as the atmospheric gradients that make the winds blow and lift water to high-altitude positions, and the *photosynthesis* that provides a chemical 'battery' of carbohydrates-atmospheric oxygen.

Thermodynamics: entropy and exergy

In this discussion, the term 'thermodynamic potential' has been used in a somewhat vague way as analogous to electric potential. However, thermodynamics and its underlying theory, statistical mechanics, have very precise concepts for this. The key concept in thermodynamics is entropy. The entropy of a physical system is a measure of internal disorder, indicating the degrees of freedom (range of motion) in which the energy is distributed in a system. Maximal entropy occurs when a system is in a state of thermodynamic equilibrium, which means total random distribution of the energy over the available degrees of freedom.

The second law of thermodynamics states that there is always an impetus towards equilibrium: The entropy of an isolated system always increases. This means that the energy tends to distribute itself over as many degrees of freedom as possible. Heat flows spontaneously from hot to cold, from a concentrated to a less concentrated state of energy; but not in the opposite direction. A similar relation holds for materials: The spontaneous flow in a diffusion process is from higher to lower concentration.

The two forms of mechanical energy in macroscopic objects, potential and kinetic, are concentrated and limited to one or only a few degrees of freedom. Thus, these forms of energy are completely ordered, which means that they have zero entropy and are of highest quality. On the other hand, heat (random molecular motion) is a disordered form of energy with a higher degree of entropy. Through friction, mechanical energy can be completely converted into ambient heat. This conversion is irreversible: The energy cannot be refocused into a few degrees of freedom.

Mechanical energy can be used to concentrate energy or material in a system. With a refrigerator or a heat pump, an input of mechanical work can be used to move heat from a cold region to a warm one, and thereby increase the temperature difference. Conversely, with a heat engine it is possible to extract mechanical work from a system containing temperature differences. In similar fashion, pressure differences can be used in a turbine.

Exergy as a measure of resources

Since energy can be of variable quality, i.e. concentrated or dispersed, it is of little value as a measure of resource supply unless its quality is specified. The heat content of the oceans is enormous, but that heat is not included in any resource accounting, due to its lack of quality. (What is included, however, is the mechanical work that can be extracted from temperature differences resulting from the absorption of solar heat in the surface layer.)

These considerations lead to a unique, useful measure of resources in any system: the amount of mechanical energy that could be extracted from it in given surroundings, assuming an ideal (thermodynamically reversible) process to be available. This quantity, which was referred to by one of the pioneers of statistical mechanics, J.W. Gibbs (3), has been given many names over the years. Now, an international consensus seems to be forming that it should be called exergy (German: Exergie) (4). Exergy is simply ordered energy, or energy weighed by a quality factor. For the highest quality energy such as mechanical energy and electricity, this quality factor is unity. No work can be extracted from waste heat at ambient temperature; hence, the quality of this energy is zero. Solar radiation has a quality factor of 0.95. For the contents of a refrigerator, the energy quality factor is not zero; it is negative, since cold (low energy) is valuable.

Exergy is thus a measure of deviation from equilibrium with these surroundings. In a state of thermodynamic equilibrium, entropy reaches its maximum and exergy is zero. Any increase of entropy is accompanied by a loss of exergy. Since, according to the second law, entropy always increases, some exergy is lost in all processes. However, neither the second law nor any other general physical law, tells how large the system's entropy increase/exergy loss must be. In human societies, that is largely determined by the availability and choice of suitable technology. Much technology is very inefficient when compared with the natural techniques that have resulted from biological evolution. There is great potential for improvement in human technology; it is at the beginning of technical development.

Exergy implies a state of disequilibrium. The predominant source of exergy on the earth's surface is the disequilibrium between incoming solar radiation and outgoing heat radiation, which is in turn derived from the disequilibrium between the hot sun and cold interstellar space. We shall see below that the origin of this disequilibrium is the expansion of the universe.

Entropy, exergy, and structure formation

Open systems located within a thermodynamic potential through which an energy flow passes—i.e. systems receiving exergy—may have complicated non-linear dynamics that allow formation of structure. In physical and chemical systems, there are many known instances of spontaneous structure formation. In living organisms and societies, structure formation is guided by steering mechanisms, which partially determine the outcome by issuing orders in the form of enzymatic and genetic codes, or operational plans and blueprints.

When structure is formed—whether it is the formation of new cells in an animal or a tree, or the construction of a machine, house, or bird's nest—exergy is used up. But some exergy, usually a very small fraction, also goes into the structure.

Closed thermodynamic systems inevitably increase their entropy and approach an equilibrium, the state of maximum entropy. Open systems within a *small* thermodynamic potential approach a stationary state, characterized by minimum entropy production.

However, open systems with complex dynamics within a sufficiently *large* potential may start a process of spontaneous self-organization or structure formation (1, 5). Due to the thermodynamic potential, the outgoing entropy flow is larger than the incoming entropy flow. Thus, there is a net export of entropy from the system and, if its entropy production does not exceed this export, the system decreases its entropy, i.e. its order increases. (In terms of exergy, the energy flow through the thermodynamic potential results in an exergy inflow to the system. Some of this is consumed in the process, but part of it may accumulate as order in the system.) This is the basic thermo-dynamics of structure formation. However, the formation process itself is often so rich in possibilities, and so open to the influence of random perturbations, that the evolution is open-ended and impossible to predict. It is thus very difficult to formulate any concise physical laws governing self-organization; but many different kinds of behaviour are known for self-organizing systems.

Exergy and information

To describe any structure, information is a useful concept. Information theory evolved from the study of messages, e.g. sequences of zeroes and ones in a computer (6, 4). The theory is easily extended to written messages with any number of signs, including the four-letter alphabet of the genetic information, the approximately 30 signs of the ordinary Indo-European alphabet, or the 2 000 basic characters of modern Chinese. It may also be extended to include two-dimensional objects (necessary for the blueprint mentioned above), like the pixels of a television screen or a photograph, as well as three-dimensional objects.

To analyze structures of various sizes and resolutions with varying internal correlations, a general mathematical information theory has been developed. In fact, this theory is sufficiently general so that statistical mechanics, the theory underlying thermodynamics, can be derived from it. Thus, it is not surprising to find that the physical concept corresponding to the mathematical concept of information is exergy. In fact,

$$E = (k \ln 2) T_0 I$$

where E is the exergy (in joule, J) of a system, and I is its information content (in bits) (7, 4). T_0 is the ambient temperature (in Kelvin, K) and k is the Boltzmann constant. Then

$$k \ln 2 = 1.0 \cdot 10^{-23} \mathrm{J/(K \cdot bit)}.$$

The small size of this constant means that, in principle, transfer of information can take place with very little energy dissipation or exergy loss at ordinary temperatures (a few hundred Kelvin) on the order of 10^{-20}J/bit. In practice, most everyday processes spend exergy amounts far beyond this limit. However, some biological information processing, such as the registration of light on our retinas or the synthesis of proteins in our cells according to the genetic information in t-RNA, is not very far from this limit. Therefore, there is a great room for improvements in technological systems, as evidenced by developments in microelectronics, the efficiency of which is not far from the theoretical limit.

In physics, information theory is now used to analyze complex systems, such as chaotic systems or self-organizing systems. In information theory, therefore, measures of the complexity of various systems have been developed (4, 8). The exergy stored in a hydropower dam is totally lacking in complexity, since its state can be described with just one number, the water level. But at a given moment on one winter evening, for example, some of that exergy is converted—via turbine, electric generator, transmission lines and lamps—into light quanta (photons) that carry fleeting images of myriad household interiors, along with all the activities going on there. Some of these photons stimulate visual impressions on people's retinas. Finally, the photons' energy is converted into heat which leaks out to the surroundings. That which is complex and interesting is thus present only for a very brief instant, as the simple but ordered energy in the dam is converted into the equally simple but *disordered* energy of ambient heat.

Similary, the solar radiation falling on a landscape on a beautiful spring day has a rather simple thermal composition. (Here, we disregard the information that it carries about the state of the solar surface as of limited interest except to scientists studying the sun.) Upon its arrival on the earth's surface, this radiation is immediately coded with detailed information from all the structures of reawakening life—to which the radiation also contributes with exergy supply. Blueprints for the emerging structures are already present, in the physical conditions of the landscape and in the genetic information of existing organisms. Still, the resulting development is indeterminate and involves a lot of freedom. All of evolution, from the dawn of life on Earth, is a long history of building up new complexity through the creation and reformulation of information.

Information is a very flexible concept which can be used on different levels. The ongoing theoretical development of information theory and the theory of computation can provide new methods for better understanding complex systems in nature and society. Any guess as to which final form this knowledge will take would be premature, but scientific developments are very promising.

Exergy creation in the early universe

The glimpse into space at the beginning of this paper was intended as a reminder that we are tied to this earth and are responsible for how we handle our inheritance of both life, itself, and the geophysical conditions for life. Furthermore, cosmic and stellar evolution was a prerequisite for the evolution of life. The chemical elements were formed in the early generations of burning stars, some of which have exploded as supernovae. Also, the formation of exergy, the separation of hot and dense matter from cold and thin matter, was a process inherent in cosmic evolution. Clearly, the gravitational force has an inherent tendency to accentuate density fluctuations and thus to achieve such a separation. What we shall consider now is the process by which nuclear matter ceased to be in equilibrium and became the fuel of the hot stars.

According to what is regarded as the standard theory of cosmology (9, 10), the primeval universe started out as very dense and hot and space was expanding (Big Bang). The hot matter was in a highly dissociated state, and cosmologists' hypotheses about this early stage are therefore based on particle physics. Their speculations go all the way back to the age of 10^{-43} s, to the point at which the constants of nature set up a theoretical 'horizon'.

For present purposes, we may begin with the situation at 0.01 s. At that point in time, the present constituents of matter were already formed; neutrons, protons and electrons were suspended in a sea of radiation, photons, which spent part of their time as electron-position pairs. Other particles, such as gravitons and neutrinos, were almost totally decoupled from matter and radiation, which were in a thermal equilibrium state of 10^{11} K (Kelvin). Entropy was thus at its maximum, given those circumstances, and exergy was zero. How then could the present disequilibrium between hot stars and a cold interstellar space arise? Does this not contradict the second law of thermodynamics?

The answer is very simple and is to be found in the dynamics of the Big Bang (9, 10). As the universe expanded, its temperature and pressure dropped, and the conditions for equilibrium changed. But the conditions for equilibration processes were not present, and were therefore delayed. In fact, order and entropy increased at the same time. Thus, the equilibrium entropy (for the actual temperature and pressure) simply increased faster than the actual entropy (11–13). During the first few minutes, however, nuclear reactions did take place to some extent. Neutrons and protons fused into deutorns, and further into helium, in such a way that roughly one-fourth of nuclear matter was in the form He_4, and three-fourths in the form of protons, i.e. hydrogen nuclei (10). If equilibrium had been maintained, the nuclear reactions would have gone further and stopped only with the formation of the most tightly bound nuclear matter, that of iron. However, this did not occur, because the temperature had fallen below ignition temperature and the necessary nuclear reactors, the stars, had not yet formed. The formation of stars and galaxies could only begin much later, after several hundred thousand years, when the temperature had dropped below the ionization temperature and neutral atoms could form, no longer prevented by radiation from coalescing into protogalaxies and protostars.

The fact that condensation into iron nuclei, the 'ashes' of stellar nuclear burning, was thus delayed, means that the universe was in this sense 'supercooled' (14, 4). The nuclear fusion ('condensation') which now takes place in the sun is a slow process—slow enough to allow time for the evolution of life.

The first organisms and their preparatory work

Having thus established the connection with our cosmic roots in the early universe, we will now take a giant leap forward in the history of evolution. We pass over the formation of stars and galaxies, the creation of the chemical elements in stellar nuclear burning and supernova explosions, and the formation of planets, which took up the angular momentum of the cloud of matter that contracted into our sun. We also pass over the earliest geological history of our planet.

We continue from the point at which the planet has a gravity and mean temperature capable of maintaining an atmosphere. At this stage, the earth's atmosphere contains several chemical elements and small inorganic compounds, and there are also a few organic compounds created by non-biological processes. These had the potential to become building blocks of living organisms.

There is also a steady stream of energy passing in and out of the surface layer of the planet; and, as explained above, there is a net inflow of exergy, due to the temperature difference between incoming and outgoing radiation, There must have been many possibilites for self-organization through hydrodynamic and chemical processes, leading to the formation of structure and local concentrations of molecules that could serve as constituents of the first life forms. The details of this chemical evolution are not known, and may be difficult to trace but, drawing on basic principles, it has been possible to devise models of what could have happened (15, 16).

The first cells were *prokaryotic*, i.e they had no nucleus (17, 18). These primitive cells, which first appeared 3.5 billion (3 500 million) years ago, acquired the exergy essential to their metabolism by fermenting the small supply of non-biological organic compounds then available. At the same time, inorganic molecules were incorporated into the first biomass. Thus, the biosphere was 'detoxified' of compounds—such as hydrogen sulfide, carbon monoxide and hydrogen cyanide—that would have proven toxic to *eukaryotic* cells at a later stage of evolution.

Detoxification of the biosphere has not occurred entirely by converting 'disorganized' material into building blocks for the creation of natural resources. Cells have also contributed to detoxification, using other, much slower, processes. Heavy metals such as lead, mercury and cadmium were removed from the biomass by the comparatively slow process of biomineralization, and through passive accumulation in cells. Subsequently, the metals were trapped in sediments and fossil deposits. These processes also led to local decreases in entropy, as the metals became concentrated (19).

In addition to this 'cleaning up', the atmosphere was gradually enriched with oxygen as a by-product from the production of organic molecules (17, 18). This resulted from the evolution of cyanobacteria (blue-green algae), prokaryotic cells that employ a photosynthetic mechanism. Additional quantities of oxygen have also been released through the deposit of carbon, originating from CO_2, into sediments (20). This oxygen was first tied up in new chemical bonds, such as the oxidation of iron and other metals. Only after these 'oxygen sites' had been saturated could the concentration of oxygen in the atmosphere increase. As the amount of oxygen increased, the ozone layer in the stratosphere was established. It protected the earth's surface from ultraviolet radiation, and made it possible for eukaryotic life forms to survive and, eventually to emerge from the seas and colonize land.

The biochemical cycles

After some two billion years of these preparations, cells with nuclei and respiration appeared on the scene—eukaryotes. First came the green plants, about 1.5 billion years ago, and then the first animal cell about 0.7–1 billion years ago. Photosynthesis, or primary production, was thus initiated by blue-green algae and further developed by the green plants. The capture of solar exergy and its conversion into chemical exergy by plants is the foundation on which all life rests. Some of the exergy provided by the green plants is subsequently consumed by animal cells in increasingly intricate food chains and food webs.

During the past 500 million years, the two main families of eukaryotic organisms, plants and animals, have exchanged matter in growing biochemical cycles, giving rise to the enormous diversity and complexity of the biosphere. The green plants capture solar exergy in the process of photosynthesis and make it available to all forms of life. The plants, themselves, do not take up more matter from their environment than they need for their work of construction.

Animal wastes are broken down into new building blocks by decomposers such as fungi and protozoa, rendering the matter available for another cycle of photosynthesis. In this way, the basic components of life—water, carbon, oxygen, nitrogen, sulphur and phosphorous, etc.—all take part in huge material cycles, powered by the sun via the water cycle and photosynthesis. Animal waste has not exceeded the reconstruction capacity of these cycles. In fact, the degradation of structure in respiration has been *overcompensated* by photosynthesis during evolution, leading to an apparent 'upstream' flow against the second law of thermodynamics. Biochemical cycles have thus mediated the transformation of disorganized and dispersed matter into the highly organized complexity of the biosphere (Fig. 1). During the past 500 million years, the interchange of matter between plants and animals has formed the basis of an accelerating evolution that has led to the rich natural diversity of which humans are a part.

Thermodynamics of the biosphere

Following the analogy used earlier in this paper, the sun and the surrounding interstellar space can be conceptualized as the poles of a giant battery. The earth's surface is connected to this battery through an energy flow—the 'electric current' of our analogy (21). There is an incoming current of solar radiation at a temperature of 5 800 K (absolute temperature) with an average power of 175 PW ($P = \text{peta} = 10^{15}$), of which 39% is immediately reflected.

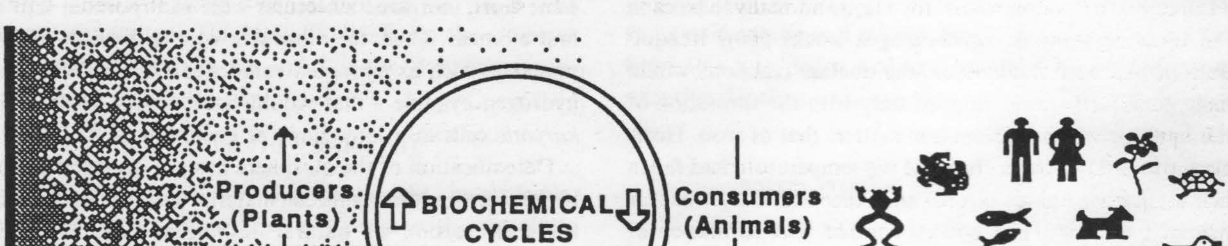

Fig. 1. Evolution from randomly distributed molecules toward a homeostatic biosphere of complex structures. During the billions of years of evolution, a mixture of widely-dispersed chemical elements has been transformed into natural resources. Their development into highly complex self-organizing structures has occurred through the processing of matter between cells in biochemical cycles. The primary producers are the green plant cells which import solar energy of low entropy and export heat radiation of high entropy back into space. The first part of evolution, 3 billion years (3 000 million), was a slow process—primitive organisms creating the prerequisites for higher life forms to appear, depositing harmful substances and providing oxygen, ozone layer and food. The explosion of diversity has taken place mainly during the last 0.5 billion years.

The rest is converted in the biosphere before it is emitted as heat radiation from the upper layers of the atmosphere at around $-20°C$ (253 K). Below this altitude, the biosphere's temperature is maintained at levels suitable to life by what is known as the greenhouse effect, which raises the earth's surface temperature to an approximate average of $+15°C$. The atmosphere is transparent to most of the incoming solar energy, but absorbs and returns a large portion of the heat radiated from the earth's surface; the most important retentive substances are water and carbon dioxide.

All natural systems on the earth's surface are characterized by internal cycles of matter, as well as external linear flows of matter passing through them. A cell may be a subsytem of a multi-cellular organism which, together with other individuals of the same population, forms a subsystem of an ecosystem, which is part of the biosphere. On all levels but one, matter moves both in cycles and in linear flows. The exception is the highest level, the biosphere itself, in which all important flows of matter are cyclic, and only energy passes through in linear fashion.

The difference in thermodynamic potential between solar radiation and the earth's heat radiation charges local 'batteries' on the earth's surface, driving the cycles of the geophysical systems. The largest material cycle, that of water, carries large quantities of heat from the equatorial to the polar areas, thus producing a levelling effect on the global climate. The exchange of water between sea/land and the atmosphere amounts to nearly 500 000 Gton ($G = \text{giga} = 10^9$, $\text{Gton} = \text{km}^3$ for water) annually. The carbon and oxygen cycles, which are part of the life processes, are next in size. For carbon, the global annual turnover is about 150 Gton.

In photosynthesis, green plants use the flow of solar energy to charge their chemical batteries, a carbohydrate pole internally and an oxygen pole externally. The aggregate of biomass thus formed, together with atmospheric oxygen, make up the huge chemical battery of the biosphere—the basis of life not only for the plants themselves but for other life forms as well. In this way, animals are supplied with the exergy required for their metabolism, which is the basis for many activities: muscular work and reproduction, as well as the information processing of sense organs and nervous systems—even the intellectual activities of scientists, philosophers and artists. The human population also uses a large quantity of biomass in household and industrial activities. After being processed by plants, animals, and people, what remains of organic matter is taken up by decomposers—such as fungi, small animals, bacteria and other microorganisms—which then complete the material cycles of living systems.

A careful study of the biosphere within the frameworks of geophysics, ecology, and physiology reveals intricate networks of cycles within cycles within cycles. Exergy is used at each step in the conversion of energy and matter. As a result of evolution, with the creation of more and more ecosystem niches, exergy has been used with increasing efficiency. Thus, an increasing complexity and quantity of life can be maintained at a given level of exergy consumption.

The crucial information governing life is carried and transmitted by the cells in a very specific way. Through the genetic code and enzymatic processes, the building blocks of life are synthesized with extraordinary precision, and the information is passed on from generation to generation. The precision of plants is such that they use exact amounts of the various chemical elements that they need, thus producing no waste.

An order-of-magnitude estimate for exergy use in human societies is 10 TW ($T = \text{tera} = 10^{12}$), or approximately 0.01% of net incoming solar radiation. If we look at industrial societies, we see that they have placed a heavy emphasis on the supply of energy and consumer goods to their populations. Little attention has been paid to the conservation of matter. Material goods are turned into garbage, and garbage collection has been introduced as a service in modern societies. But according to the law of matter conservation, garbage consists of indestructible matter that must be deposited somewhere. As long as societal turnover of material was small in comparison with natural turnover, this was not a major problem. But the consequence of extracting large quantities of material resources from under the earth's surface has been the deposit in the biosphere of matter that does not belong there.

In short, we are concerned—even obsessed—with a 'battery' process which deals only with the 'plus' pole. This process alters the physical conditions of the earth and of life. Over the years, many warnings have been raised about the consequences of ignoring the principle of matter conservation, of not planning for the entire flow of material. We shall return to this question in the concluding remarks.

The biosphere has much to teach human societies, in particular the need to maximize efficiency, so that human activities occur within the restraints established by nature. As tools for evaluating efficiency, entropy and exergy accounts are useful, since they make efficiency losses clearly visible (7, 22). No one knows how resilient the biosphere is, what will happen if it is too violently disturbed. Our neighbours in space, Venus and Mars, suggest two opposite but equally frightening alternatives—one extremely hot and sterile, the other extremely cold and sterile.

Conditions for human productivity

Our health and wealth are completely dependent on the organized processing of matter in natural cycles. Concentrations of compounds that could become toxic to higher forms of life have been reduced, and are maintained at safe levels by homeostatic mechanisms. Furthermore, we live

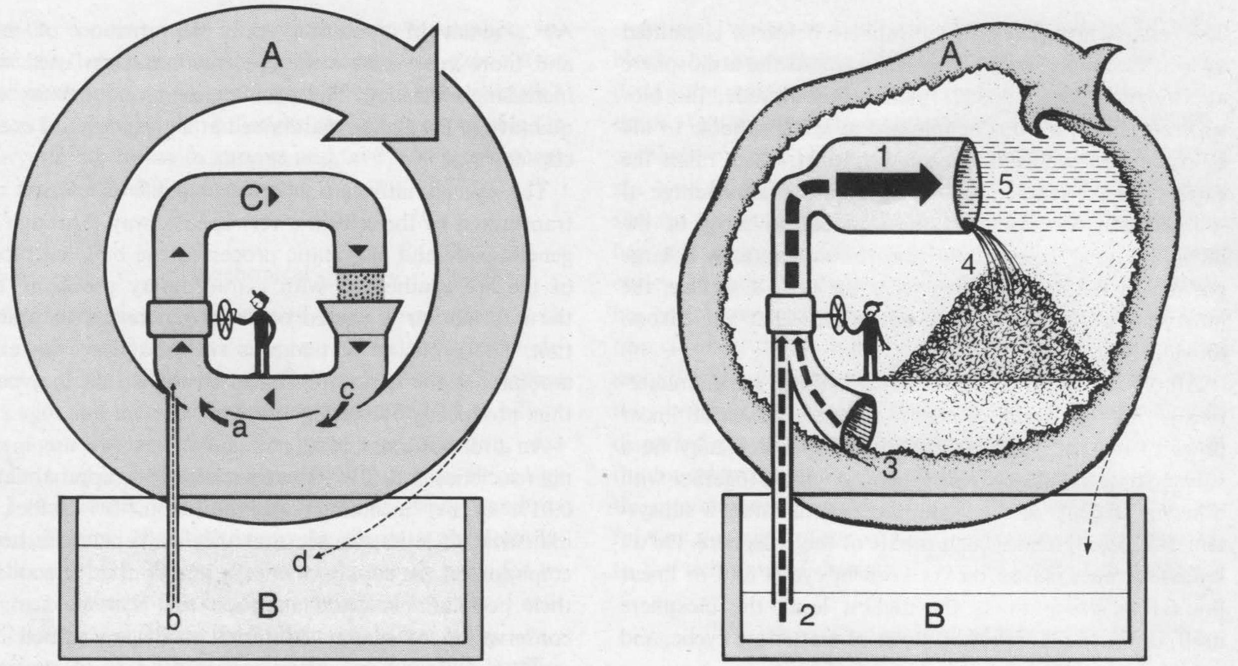

Fig. 2. A. A sustainable economy is based on the cyclic processing of material (C), and functions as an integral part of natural cycles (A). The benefits (a) derived from renewable resources, along with measured withdrawals (b) from limited deposits (B) are cycled by the economy with energy based on the steady stream of solar energy (hydroelectric, wind- and wave power, biomass, solar panels, etc.). Resource-efficient technology, durable high-quality products and recycling have the effects of decreasing demand for limited non-renewable resources, and reducing the total amount of visible and molecular garbage. Materials that " leak" out of the system (c) can be broken down and converted into resources by natural cycles. Over thousands of years, a certain portion (d) can find its way back into limited deposits. The total quantity of resources does not decline. We live on nature's 'interest'.

B. Today's non-sustainable economy is based on the linear processing of material (1). We draw from both limited deposits (2) and renewable resources (3). Primarily through the use of energy derived from limited deposits of fossil and nuclear fuels, the economy produces and consumes large quantities of basic material, which are then released in the form of visible garbage (4) or invisible molecular garbage (5). The volume of garbage is so large that it exceeds nature's capacity to recycle it. Some non-natural substances, such as persistent halogenated hydrocarbons, cannot be processed by nature at all. The conditions of living cells are not met. The 'profits' of nature are declining, and we are living off the capital. We are heading toward a state of poverty on a toxic garbage dump, and can avoid that fate only by re-establishing an economy based on natural cycles.

on the 'interest on capital' which is created by natural cycles—on fishing, hunting, forestry, agriculture, etc. But degradation of matter and energy takes place in all processes. We rely on ecosystems not only to supply us with food, drinking water and raw material for our industries, but also to receive and process our garbage and sewage. This functioned well enough, as long as we took our raw material from ecosystems. Photosynthesis more than made up for the degradation of matter caused by human activities. Now, with a large portion of our raw material extracted from mineral ores, the reconstruction capacity of the biosphere is strained. The total amount of garbage must not exceed the processing capacity of natural cycles—neither the decay process of fungi and other organisms, nor the rebuilding of energy-containing structures by plant cells. It is essential to remember that cyclic flows of material are the basis for all 'perpetual' processes (Fig. 2A). If wastes are not recycled, no process can be sustained; it will come to an end (Fig. 2B).

The preindustrial era

In early human cultures, life was based on gathering, fishing and hunting. People lived in small groups that exploited large areas. This exploitation was of a very low intensity, and the ecological impact on those areas quite small. Much later, some cultures developed slash-and-burn cultivation. A clearing was opened in the forest, an area was burned off, and crops were planted in the nutrient-rich ashes. After a few years, the farmers moved to a new clearing, and the forest returned to the abandoned area. Over time, the human population proliferated and spread over all continents; in the process, more and more land was brought under cultivation, and available space became limited. Forest were reduced to bush fallows, and then to grass fallows. Agricultural societies modified the ecosystems on which they depended. In some cases, they caused erosion damage, but for the most part their uses of energy and material were woven into natural cycles, hence ecologically sustainable.

The non-sustainable, industrial era

The sustainable pattern was broken by the industrial societies for which fossil fuels became increasingly important, to the extent that they are now totally dependent on such fuels. This dependency relates not only to industry, but also to the exploitation of ecosystems by fishing, agriculture, and forestry. Ecosystems have been subordinated, and the linear resource handling of industrial society has been allowed to determine the human relationship to the biosphere. The obsession with the supply side, i.e. the steadily increasing demand for resource inputs, has obscured the fact that even industrial societies depend on life-supporting ecosystems. The enormous output of industrial wastes—emissions from chimneys, sewage pipes, mining slag, garbage dumps, etc.—is overwhelming both the decay processes carried out by fungi and other organisms, and the rebuilding capacity of plants. At the same time, the stability of geophysical systems is threatened. To a large extent, the 'production' activities of industrial societies have become extremely destructive.

Environmental degradation has many aspects but they are all related to *one systemic error*—linear processing of natural resources. The processing capacity of natural cycles is now exceeded by both the quantity and composition of our garbage. After steadily decreasing during the past billions of years of evolution, toxic substances are again accumulating in the biosphere.

Industrial societies have 'liberated' pollutants that were previously locked up in mineral and fossil fuel deposits. Many of these are intrinsically toxic, for example mercury and cadmium, basic elements which can never be broken down into less toxic components. Other pollutants, such as oxides of sulphur and nitrogen—the key ingredients of acid rain—are products of industrial activity, including transportation. We are also producing persistent artificial compounds with which the biosphere was never confronted during billions of years of evolution. Most of them are organic compounds of chlorine, fluorine and bromine, and include many substances that are well-known from current environmental debates, e.g. PCB, DDT, dioxins, and chlorofluoro-carbons such as freon.

Natural resources are subject to extraction, manufacturing processes and use by humans before they end up as garbage that is dispersed throughout the biosphere—the linear processing of resources (Fig. 2B). Standard accounting of economic performance, often measured as 'economic growth', disregard the consequences of linear processing. Related costs, such as those for sanitation, health care and the increasing expense of natural resource extraction, are counted instead as increases in *production!* It is therefore encouraging that, following initiatives from the United Nations and other international organizations, several countries are now studying methods to include the costs of environmental degradation and depletion of natural resources as debits, not credits, in their national accounts.

Human activities not only result in the accumulation of pollutants in the biosphere, they are also devastating ecosystems which have the ability to control pollution levels. Examples include the destruction of rain forests with their rich diversity of species, the spread of deserts, and the extinction of other species. During the past couple of centuries, we have been moving towards a toxic biosphere that is becoming poorer and poorer in natural resources, information and diversity—'reverse evolution'.

The cyclic industrial era

It follows from the laws of thermodynamics that continuous linear processing of resources is compatible with neither wealth, nor with life. Furthermore, it is not possible to specify time parameters for the ultimate consequences of linear processing. This is due to the rapid expansion of the human species, the enormous complexity of the biosphere, and also to delay mechanisms such as the slow movement of pollutants, the accumulation of toxins in food chains, and interactions among artificial and natural compounds. In short, linear resource processing leads to continuous uncontrolled deterioration of socio-economic and public health conditions. The conclusion is unavoidable that we must transform our societies so that they function in harmony with the biosphere. Our flows of matter must be incorporated into those of ecosystems, so that at least as much structure is built up as is broken down. We will know that we are on the right track when the garbage mountain stops growing, and pollutants cease to accumulate in the ecosphere. At present, only a few countries have the ability to effect such a transformation. Thus, the challenge to the developed countries is not only to decrease their own emissions of pollutants, but to develop the cyclic technology and life-styles needed by the entire human community.

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