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TOWARDS AN INTEGRATED ACCOUNTING OF ENERGY AND OTHER NATURAL RESOURCES

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Abstract

The concept of exergy, the useful part of the energy, is studied in the context of thermodynamics. Its relationship to the information concept of information theory is reviewed. Efficiency concepts connected to exergy are introduced.

Energy dissipating systems are fuelled with exergy which is consumed in the process. It is then useful to keep account of how the exergy is used in such systems. This is of interest to the geophysical and biological sciences and also for the description of the "metabolic" processes of a society. Thus the exergy concept may be very useful in the accounting of natural resources. Basic conceptual problems related to such accounting are discussed at some length.

The exergy content of a system must be defined relative to some reference environment. It is therefore suggested that agreements be made on workable global and local standards to be applied in this context.

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1. Introduction

The purpose of this paper is to discuss the physical conceptual basis for resource accounting and to suggest a set of basic concepts that should be useful also in the social and economic sciences.

The ideas presented here are not original. Rather our aim has been to point to fundamental concepts and ideas and to urge scientists to adopt these and to agree on workable conventions.

The authors know from personal experience that previous discussions - at least in Sweden - concerning the use of energy and other natural resources have suffered from a lack of commonly accepted terminology based on fundamental physical knowledge. Often the terminology which is now most widely in use is directly misleading. Especially this is true of the energy and efficiency concepts.

The relationsship between the physical resource base and the social and economic structure [1, 2] is an important subject in human ecology which too often has been neglected by historians, social scientists, and economists. Natural scientists who should have provided a basic conceptual framework for this subject have usually taken a weak interest in the structures of past and present societies.

There are exceptions though. There are economists who have tried to take into account that physical resources are not only the objects of an economic game but also part of a physical reality which includes also the players of the game [3, 4]. There are natural scientists who have turned their interest into the catastrophes and threats caused by man's handling and distribution of physical resources [5]. An ecologist's point of view of society which has had a great impact on the thinking during the recent years is H.T. Odum's book, Environment, Power and Society [6].

A basic concept which we discuss here at some length is the <u>exergy</u> concept [7-10] and the <u>efficiency</u> concept related to it [11]. Exergy denotes the useful energy of a system in a certain environment, i.e. the maximal amount of work that may be extracted from the system. The basic nature of the exergy concept derives from its intimate connection to the <u>entropy</u> concept or - which is more convenient in this context - the <u>negentropy</u> (= minus the entropy) [12].

This thermodynamic basis is discussed in Section 2. (Derivations of thermodynamic relations are given in an Appendix and in "Boxes" separated from the text.) In Section 3 the relationship of the thermodynamic concepts to information theory is discussed. Section 4 deals with the efficiency concept. A brief discussion is given of the maximum efficiency in an energy conversion proceeding at a finite (= non-zero) rate.

Schrödinger [12] noted that "we feed on negentropy". He might as well have said that "we feed on exergy". Exergy is the fuel of all dissipating systems, i.e. systems with a "metabolism", the biosphere, an ecosystem, a species, or an organism. Therefore an exergy accounting should be useful in sciences which study such systems. This is discussed briefly in Section 5.

Human individuals, groups, and societies are in command of exergy flows used to accomplish certain ends. Commonly, one talks varyingly of energy resources, concentrated material resources (e. g. ores), food and other biological materials, and self-cleaning capacity of a recipient. But they are all sources of exergy flows, and can be accounted in a unified way. This is discussed in Section 6 and as an example a diagram of the exergy conversions in the Swedish society is given. A comment is made on the much discussed "energy analysis".

In Section 7, there is a discussion on how natural resources could be brought into social and economic analysis. The physical resource base is immense, but societies can still have natural resource problems, due to constraints in their technical knowledge and social structure. A society´s dependence for its exergy flow on biological systems and on "dead stocks" lika minerals and fossil fuels is discussed and the effects of environmental pollution on the resource base is reviewed in this context. The natural resource problem in a society is represented as a question of reproducing socially available natural resources. Under economic crisis, a society can fail to reproduce one or more of its "production factors", fixed capital, the work force, and available natural resources. It is shown that the exergy flow concept can be useful in the analysis of world trade.

2. Energy, negentropy, and exergy

Energy and entropy

Energy is a universally conserved quantity. Thus there are no sources or sinks of energy. When energy is used in a system, often very little energy is stored in the system. However, the quality of the energy is decreasing during this use. Energy is being dissipated from a small number of degrees of freedom into a large number. Quantitatively this is described in statistical mechanics as an increase in entropy S for the system.

$$S = -k \sum_{i \in \Omega} P_i \ln P_i \; ; \; \sum_{i \in \Omega} P_i = 1, \qquad k = \text{Boltzmann's constant} \qquad (1)$$

where Ω is the set of states, over which the probabilities P_i describing the knowledge about the system, are distributed.

Statistically, concentration of energy into a smaller number of degrees of freedom is an unlikely process which takes place only in very limited fluctuations. Instead energy tends to get shared among a steadily increasing number of degrees of freedom.

Any conversion of energy which takes place at a finite (non-zero) rate leads inevitably to an entropy production which has to exceed some minimum value depending on this rate.

Energy is not used for its own sake but as a carrier of a quality that is being consumed during its use. Entropy S describes the lack of this quality; negentropy = - S can be used as a measure of the quality of the energy [12]

Available work and the concept of exergy

The necessity to determine the useful part of the energy or - which is the same - the amount of mechanical work that could be extracted from it, has long been felt in technical contexts [13 - 16] .

In 1953 Z. Rant suggested that the term exergy (Exergie) be used [7] to denote "technische Arbeitsfähigkeit". A clear definition was given by H.D. Baehr:

"Die Exergie ist der unbeschränkt, d.h. in jede andere Energieform umwandelbare Teil der Energie" [8] . (Exergy is the totally convertible part of the energy, i.e. that part which may be converted into any other energy form.)

Baehr's definition is obviously completely general. However, in its applications - mainly in German engineering literature - it has not been exploited in its fullest thermodynamical generalization.

R.B. Evans [9] has shown that exergy (although he prefers to call it "essergy") in itself incorporates previous concepts of free energy used by Helmholtz and by Gibbs and "availability" introduced by Keenan [16,17] Another - quite adequate - name for the same thing "available work" was used by a working group within the American Physical Society (APS) recently [11].

We suggest that the term "exergy" be used for the general concept as suggested by Rant and we emphasize that the quoted definition by Baehr is completely general.

Exergy is a measure of how far a certain system deviates from equilibrium with its environment. In the Appendix we express the exergy E for a system in a large environment accordingly,

$$E = T_o(S^{tot}_{eq} - S^{tot}) \tag{2}$$

where T_0 is the temperature of the environment and $S^{tot}_{eq} - S^{tot}$ is the deviation from equilibrium of the negentropy of the system and its environment. In the Appendix we also show how this follows from the expression of E as the maximal amount of work that can be taken out from the system in its interaction with the environment. Thus (2) is equivalent to Baehr's definition

Another expression for the exergy given in the Appendix is [9]

$$E = U + p_oV - T_oS - \sum \mu_{io}N_i \tag{3}$$

where U, V, S, and N_i denote extensive parameters of the system (energy, volume, entropy, and the number of molecules of different chemical components and p_o, T_o, and μ_{io} are intensive parameters of the environment.

A very useful formula for determining the exergy was given by the APS group [11

$$E = U - U_{eq} + p_o(V - V_{eq}) - T_o(S - S_{eq}) - \sum \mu_{io}(N_i - N_{i\ eq}) \tag{4}$$

where on the right side easily determined quantities appear. ("eq" denotes equilibrium with the environment.) A derivation is given in the Appendix. It is thus an easy task to determine the exergy content of a given system in a given environment.

Some examples of exergy contents

One way to express the quality of a particular form of energy is through the amount of entropy (per unit of energy) which is connected to that form. The purest forms of energy are mechanical energy and electrical energy, which are connected to zero entropy. Heat is a less valuable form of energy with a value that decreases with decreasing temperature. Baehr's definition makes it clear that the concept of exergy incorporates both the quantitative and qualitative properties of energy.

In Table 1 different forms of energy are listed according to their quality, given as relative exergy contents. The quality index ranges from 100 for potential energy, kinetic energy and electricity (which is pure exergy and thus can be totally transformed into all other forms of energy) to 0 for the exergy-lacking heat radiation from the earth.

However, not only energy-containing systems carry exergy. If a system is deprived of energy (and thus deviates in this way from the environment) it carries exergy. An ice-block in an environment at room temperature is an example of such a system. When the ice melts it takes energy from the surrounding air, but one can use the difference in temperature between the ice and the air to drive a heat engine and extract useful work. The ice is thus a source of exergy. In an analogous manner an empty container, i.e. a vacuum, is exergy-containing. A thermodynamical discussion of a very simple example, an ideal gas, can be found in Box I.

Other examples of exergy-rich systems are concentrated materials. In practice this form of exergy can be used in electrical batteries of the concentration type. At a river mouth the fresh river water carries exergy which in principle can be extracted, if the fresh water is made to mix with the salt water in a controlled process. This could become an important source of exergy in the future. The exergy content of concentrated minerals will be further dealt with in our discussion of resource accounting.

Global and local standards

Since the exergy of a system is defined relative to its environment it is important to make agreements on suitable reference environments to be used. We suggest that a global standard environment be defined in terms of a standard atmosphere and standard sea water in equilibrium at sea level [x)] where the standards are related to average geophysical conditions. For exergy analyses (se below) of traded goods and for the use of exergy in the earth sciences such a standard is necessary.

Temperature conditions differ widely between different places of the earth as does the air pressure. Similarly the chemical potentials of the water in lakes and rivers differ substantially from those of the sea. Thus it is necessary to introduce also local standards of exergy. The most obvious advantage of such local standards is in describing the energy use (the exergy consumption) in space heating.

We therefore also suggest that local standards be adopted after a penetrating discussion of the appropriate principles to be applied in this context. The relation between globally and locally defined exergy of a system is given in the Appendix.

To what extent local standards should be averaged in time or vary with seasonal or daily variations is a question that needs to be studied. Clearly for the description of space heating seasonal variations are essential.

When local standards are used one consequence is that the local exergy content of a system varies with location. This variation may be related to the economic value of the system. An ice-block is worthless on Greenland, but could be valuable in tropical Africa.

[x)] Clearly for describing gravitational exergy (ordinary potential and tidal energy) the average sea level is a suitable altitude standard.

3. Exergy and information

Exergy is a measure of how far a system deviates from its equilibrium state. The more the system has departed from the equilibrium state the more information is needed to describe it and the larger is its capacity to carry information. Exergy and information (or information capacity) are thus intimately connected and this connection is of a fundamental nature. This is discussed in Box II. The relation between exergy E in joules and information I in binary units (bits) is

$$E = k' T_o I \tag{5}$$

where T_o is the temperature of the environment and where

$$k' = k \ln 2 \approx 1.0 \cdot 10^{-23} \text{ J/K} \qquad \text{(k=Boltzmann's constant)} \tag{6}$$

plays the role of a fundamental constant [10].

As an example the net inflow of information capacity to the earth from the sun per second is roughly (see Box III, eq. (III.6) [10])

$$1.8 \cdot 10^{17} \text{ J} \cdot \left(\frac{1}{290} - \frac{1}{5\ 800}\right) \text{K}^{-1} \approx 5.9 \cdot 10^{37} \text{ bits} \tag{7}$$

Information must be stored and transferred in a way which is as safe as possible. To achieve this, one uses redundant codes and in copying one allows dissipation of some extra energy to make the process more strongly irreversible, thus increasing fidelity at the expense of some information capacity.

In everyday communication of information the powers used are quite high. Thus the exergy per bit ratio is high which means that only a small fraction of the available information capacity is used. Therefore in practice the tremendously large number in (7) is greatly reduced and one may be tempted to think of it as only a matter of curiosity. Considering, however, the conversion of the exergy in solar radiation by the plants into ordered structures, one realizes that even if the amount of information capacity being used is only a fraction of the primary information capacity, it is still tremendous.

It is interesting to compare the efficiency in transfer of information between different systems. One measure of efficiency is the amount of exergy spent per bit information. This has the dimension of temperature. The lower this temperature is, the more efficient is the transfer of information. If this temperature gets too low, however, thermal fluctuations can destroy the information. (See Table 2)

The sensitivity of the retina is such that the human eye functions close to the quantum mechanical limit. Actually we may see just a few quanta. The storage of information in a computer memory has a characteristic temperature about 10^5 times the temperature of sight. On the other hand its time resolution and consequently its speed is better than that of the eye by roughly 10^5. The conclusion is that living beings and computers are efficient in using exergy to receive or transfer information. The biosynthesis of the cell, however, is still several orders of magnitude more efficient.

Electronic circuits, the human ear and eye and biosynthesis of protein are mapped in a logarithmic frequency-power diagram where room temperature is marked by a straight line (Fig. 1). Ordinarily a process should be well above this line to remain undisturbed by thermal fluctuations. The biosynthesis of protein, however, falls very close to this critical line. Actually the steps from messenger-RNA to protein which take half of the power required would fall below that line. This is possible because as much as 4.3 bits are transferred in each step. The ear and the eye occupy strikingly large areas in the diagram, covering many orders of magnitude. Electronics is probably the best technology we have from an exergy-economic point of view. Still, as Fig. 1 shows, life itself is much more efficient in its use of exergy in constructing biological material.

Biological structures maintain and reproduce themselves by transforming energy from one form to another. Thus the exergy of the radiation from the sun is used to build the highly ordered organic materials. The information laid down in the genetic material is developed and transferred from one generation to another. When biological materials, e.g. wood as such or cellulose, are used as construction materials it is in fact these structures and this information that are taken advantage of.

Essential for the connection between exergy and information is the fact that both concepts measure the amount of deviation from a reference background. As we stated earlier the exergy of such a deviation can be used to perform work. Conversely work is often done in order to construct or maintain ordered structures deviating from their environment, and the amount of order is most conveniently described in information theory. Thus the connection between exergy and information is of a deep nature, and as we shall discuss below, it makes exergy a suitable physical concept to be used as a tool also in economic analysis.

4. Efficiency concepts

Corresponding to the two concepts energy and exergy one can define two efficiency concepts in an energy (and exergy) conversion process,

i) the fraction of the input energy which goes into the desired outputs. This was called by APS [1] "first law efficiency". We shall call it energy efficiency and denote it by η_{en}.

ii) the fraction of the input exergy which goes into the desired outputs. This was called by the APS [1] "second law efficiency". We shall call it exergy efficiency and denote it by η_{ex}.

Clearly the "exergy efficiency" concept is the one directly related to the practical use of energy. However the second law of thermodynamics allows 100% exergy efficiency only in the case of reversible processes which in principle take place at an infinitely slow rate. A conversion process taking place at a non-zero rate v (exergy per unit time) must be driven by a non-zero gradient.

The entropy production and the accompanied exergy loss connected to a conversion process is discussed in Box IV. A maximum exergy efficiency $\eta_{max}(v)$ is introduced. It depends on the rate of conversion v. The nature of this dependence under simplifying assumptions is shown in Box IV.

It may be convenient to introduce also a relative exergy efficiency η_{rel} connecting η_{ex} and $\eta_{max}(v)$ as in (IV.7),

$$\eta_{ex} = \eta_{rel}\eta_{max}(v) \qquad (8)$$

5. Exergy in the earth sciences and the life sciences

On the earth's surface, at many different levels of size and time scale, systems are operating which process matter of many kinds in a complex pattern. The atmosphere, the sea, the earth's crust, the soil, and living organisms are all operating and interacting within this pattern. In those processes energy is be dissipated; solar energy, gravitational (tidal) energy and geothermal energy, of which the solar energy is of dominating importance.

In the geophysical dissipative processes crude structures are being formed, like weather systems or patterns of ocean currents. Much more complex structures, rich in information and capable of self-reproduction are formed in biologcal systems.

The idealized systems which are discussed in Box III are too simple to account for this richness. The statistical mechanics for energy dissipating systems far from equilibrium has been developed by Glansdorff and Prigogine and applie to systems in which structures emerge [24]. The storage, reproduction, and enrichment of information have been thoroughly studied by Eigen [25] and his group. Some basic principles of life and of biological evolution are thus becoming understood.

For the steering of a certain process, e.g. a metabolic process in a living organism along a unique direction thermodynamical irreversibility is used. An increased certainty can be obtained through an increase in irreversibility. This is bought at the price of increased energy dissipation, which means increased exergy consumption. The steering of any process in the direction of a certain aim is thus fuelled by exergy. As we have seen already, life has achieved this without wasteful spending of exergy.

In the scientific descriptions of dissipation processes at various levels it is therefore useful to account for the remaining exergy as the dissipation proceeds.

In H.T. Odum's diagrammatic description of ecological systems [6] energy plays a fundamental role which could probably be better played by exergy.

6. Exergy applied to the social field

Metabolic processes taking place in living organisms and eco-systems have analogous counterparts in human societies. Experience in the description of natural systems is helpful in the formation of a description of human societies [26], Also any society, in order to be sustainable, must have sound relations to the natural system on which it basically depends.

The learned society itself can be viewed as an ecological system processing information. This perspective is taken by Blackburn in an amusing article [27] , in which among other things the trophic levels of different sciences are discussed.

Exergy analysis

The physical exergy content in a certain goods item does not represent the total amount of exergy going into the process of its production. To make up an exergy budget it is necessary to account for the exergy going "into" a product from many different sources [28]. At recent conferences [29] organized by the International Federation of Institutes for Advanced Study this kind of accounting was named energy analysis, and free energy (Gibbs) was used as the basic concept. We suggest however, that one switch to exergy, as soon as generally acceptable standards have been introduced, and that this accounting be named exergy analysis.

In applying exergy analysis to production processes or services, one should try not to stop at the level of a particular process but also look at the roles of the process and the product or the service in a larger context. One should also apply exergy analysis at the systems level for different functions in a society, e.g. transportation. We think that exergy analysis would be useful also at an aggregated level in analyzing the metabolism of the society itself, as we have indicated in Fig. 2.

The exergy of natural resources

Using the exergy concept, one can describe various types of resources used in a society in terms of a common physical unit.

The so-called energy resources have exergy contents that are very close to the energy values often given. Either they are of a mechanical form (hydropower, windpower) which by definition is 100 percent useful work or they are of a high-grade chemical form (fuels), for which the commonly accounted heat of combustion (enthalpy) is rather close to the exergy value [30]. In conversion via heat one loses a large fraction of the exergy. The way to overcome this difficulty is to technically develop fuel cells that can convert chemical exergy directly into electricity.

In ascribing a definite exergy value to nuclear fuels several difficulties arise such as radiation losses and the lack of a well-defined final state.

But also other resources than the "energy resources" have exergy. A concentrated metal ore contrasts against the normal chemical composition of the background. The exergy due to this contrast is retained when the ore is mined. When the ore is enriched and reduced to metal, the exergy of the mineral is increased, the added exergy coming from fuels and reducing agents used in the process. The exergy is not destroyed until the metal products made from the metal piece in question are rusting or being dispersed [28].

Minerals that are very common in the earth's crust or in seawater - like sand salt or water - have little exergy, and also they are generally less of a resource problem. In an arid zone, water can be a precious resource but in that local reference environment it also carries exergy.

Biological materials have exergy in two forms - chemical and structural of which quantitatively the chemical exergy dominates. When a fuel is burnt the chemical energy is transformed into heat whereby - depending upon the flame temperature - more or less of the exergy is destroyed.

The structural exergy lies in the low-entropic ("improbable") shapes that living matter takes. We utilize these when using wood as a construction material or wool as a fibre. When using biological matter as food, we use both the chemical exergy (for powering the metabolism) and the exergy of the microstructure of amino acis and vitamins (for building the body and substituting worn-out cells). After a biological material has been used as a structural material almost all of the exergy is left, and can be exploited as a chemical exergy source, e.g. in combustion.

When organic matter is used as a soil conditioner what is important is both the mineral content and the organic structure which improves the mechanical properties of the soil. To some extent, chemical exergy for feeding the soil bacteria is also important, but for many plant systems some chemical exergy can, without harm, be taken out in e.g. an anaerobic digestion process as long as the mineral-rich and soil-conditioning sludge is brought onto the fields.

The interesting point of the above discussion is that all kinds of natural resources evidently can be accounted in the common entity, "exergy", which is an expression for both the ability to perform work and the structure or information of the system. What it measures is the <u>alternative physical work</u> that would be required if all inputs to the process instead - with optimal processes - were taken from the standard reference environment.

There are strong physical limitations to the transformation of resources into each other and to the possibilities to substitute one kind of resource for another. There are inevitable losses of exergy in all energy conversions at finite rates (see Box IV). Each chemical element has its own unique set of physical properties. For a use with very narrow restrictions it may be impossible to substitute. Similarly many organic compounds have important specific properties that make them difficult or impossible to substitute.

<u>Sweden as an example</u>

The exergy conversions in the Swedish society in 1971 are shown in the diagram of Fig. 2. This diagram is based partly on the energy conversion diagram of Fig. 3 [31]. There is a striking loss of exergy for such energy flows that go via heat or end up as heat. For them the exergy content is much lower, and some of the small exergy flows like electrical heating or district heating systems are not shown at all in Fig. 2.

By including all exergy-rich inputs the diagram of Fig. 2 clearly shows the high extent to which Sweden is dependent upon continuously flowing inputs, contrary to the widespread talk of 80 per cent dependence on imported fossil fuels. The natural exergy flows also support the society in another important respect. They clean to a very large extent water, air, and soil [32] and deposit for instance heavy metals as sulphides. A crude estimate of what this might mean in terms of exergy per year gave as result one-half terawatt-hc which is too small to be included in Fig. 2. However, if the same processes had to be done wholly by technical means, they would probably be extremely costly.

7. Natural resources in social and economic analysis

The fundamentally common nature of all natural resources provides an improved way of representing the resource utilization in a society, as shown in the previous paragraphs. It does not, however, solve the problem of how to value and how to use resources within a society. The theoretical interchangeability of resources is never fully attainable and only seldom technically feasible with an efficiency approaching 100 percent. And what is technically feasible, is socially possible only with investments which require exergy and labour themselves. Such a use of fixed capital and labour has to be weighted against other possible uses of the same resources.

Obviously, exergy accounting and analysis cannot replace ordinary economics as a science of allocation of resources in a society. What it can do is to provide a back-bone of concepts, which are valid in all societies, irrespective of technical knowledge and social structure. These concepts could be used for comparisons of the physical resource endowments of different areas. They provide a skeleton for the flesh and blood of economic and social analysis.

The physical resource endowment is immense, for example the exergy flow from the sun to our planet is $1.8 \cdot 10^{17}$ J/s. In that sense no resource supply problem exists. But constrained by its technical knowledge and social structure, a society can run short of usable resources. It can also destroy some resources in the use of others.

Resources produced by the biosphere

Of special importance are the resources produced by the biosphere. If all products of biological origin that are now used in society were instead produced from mineral resources by fully synthetic means, enormous amounts of exergy would be needed because technical methods are generally less efficient than the living processes. Also, totally unreasonable amounts of labour and fixed capital would have to be utilized to replace "production systems" autonomously built by organisms of all sorts. Especially this is true for food.

The biosphere also converts solar radiation into other exergy forms, more easily acessible for processing with available technologies like wood, leather, cotton and linseedoil. Among the resources that the biosphere creates, are also the basic conditions for life as we know it on earth. Together with geophysical processes it cleans the air and controls its composition and cleans the fresh water bodies.

Now the function of the biosphere is threatened by various forms of pollution and environmental disturbances. All these effects upset the biosphere and decrease its ability to produce easily accessbile resources. This degradation could be measured in terms of a lowered exergy flow through the biosphere.

Pollution has at least two more aspects. One is that it often implies dispersion of concentrated substances like heavy metals and sulphur or phosphorous compounds, which are important resources. The dispersion of these can be measured as an exergy loss.

The third aspect of pollution are the deleterious effects on health and beauty. These effects, which cannot easily be accounted for in terms of exergy, will be touched upon below.

Stock and flow resources

In ecology "stock" and "flow" are important concepts, stock being the amount of biological material (or biomass) within the area considered and flow being the rate with which energy or a certain element is running through the area. Of course, stocks can be measured by their exergy contents and flows as exergy passing per unit time. An ecosystem of a given kind needs a biomass of a certain size and quality to produce a given flow. A society, which is living from the ecosystem can use only a part of that flow, if it is not to devastate the system.

It is possible to extend these exergy stock and flow concepts into the social field. We can talk of a "sociomass", made up by all technically transformed materials and the social organization of these. They are all possible to describe in exergy terms. The flow of goods and services from this sociomass can be counted as an exergy flow. Both types of stock*) thus yield flows which are important for the human society. Beside these "living stocks" there are also "dead stocks" or deposits, like fossil fuels and other minerals which do not drive any exergy flows of social importance. When they are extracted, they are either turned into a flow of limited duration or into a living stock as part of the sociomass.

Schrödinger noted in his remarkable little book What is life? [12] that we feed on a flow of negentropy. In this paper we suggest that the interest now be focused on the closely related concepts exergy and exergy flow. Exergy flows that are available for use in a society are yielded by living stocks and funds of the natural and the social kinds.

Man doth not live by natural resources alone [34]

Not all aspects of the relation between a human society and its natural habitat can be expressed in resource or exergy terms. On the contrary many of the finest features of this relationship are impossible to capture in hard data. In the discussion of these features we are all amateurs. One amateur who has given a lot of thought to this matter is E.F. Schumacher [35]. He suggests that man's relation to his natural environment should be directed towards attaining Health, Beauty, and Permanence. The resource concept only covers the permanence aspect. The two first aspects are tied to the fact that man is basically a part of the biosphere with deep-rooted psychological dependences on the "natural world" [36].

In Norway a new philosophical tradition is evolving through the thinking over basic questions of human ecology. This thinking has a strong ethical component and is allowed to have a practical influence over one's daily life and on one's way of acting in society [37].

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*) Georgescu-Roegen [33] makes a distinction between funds, which have capacity only for a limited flow of utilities, like a piece of land or a building, and stocks, which may be exploited directly and turned into utilities without any severe limitation on flow (but for which a high flow may mean short durability), like an oil reserve.

Production and resource reproduction

The use of natural resources in a society cannot be described only in exergy terms. Different kinds of resources have differing degrees of social availability. This has to be taken into account for the allocation of natural as well as human and social resources. Here we can only give a rough outline of some ways in which the natural resources could enter social and economic analysis.

The production of utilities in a society requires a set of so-called production factors: human labour, fixed capital, and natural resources. Fixed capital stands for machines, tools, and buildings (factories and offices). Natural resources are the contributions of the physical environment to the production process, i.e. raw materials, power (from natural flows or "dead stocks"), and the environment's ability to receive and neutralize various rest products from the process.

This production is used for reproducing the production "factors". The humans working in the production process get food, housing and other utilities needed for continuing to work, for reproducing, getting educated and so on. Worn-out machines and buildings are replaced, and to replace used resources new ones are made socially available. Beside what is used for reproducing the various production "factors", there is usually a social surplus production capacity. This can be used for "luxury consumption" among certain sectors of the population, investment in a changed or increased production capacity or in one that has deviated into obvious irrationalities like the arms race, the space race, or today's private motorism.

It is thus possible to see the total production as a sum of four terms: reproduction of each production "factor" ("term" would be a more appropriate term) and a social surplus. A society in crisis may have difficulties to maintain all four of these, and can then survive for some time with incomplete reproduction of one or more of the terms or a diminished surplus. The latter solution appears most "natural", but is in practice difficult to bring about, as the surplus generally is controlled by an upper class with good opportunities to defend its interests. Therefore, the crisis is often thrown upon the lower classes within the nations or of the world as unemployment and mass poverty. For a large part of the world population today this means inadequate food supply and housing and also disruption of social relations, all resulting in deep human misery of previously unknown extensions.

The crisis can also hit resource reproduction, a possibility which has not been thoroughly analyzed by economists and social scientists so far.

Today, at least in the "western world", natural resources are used (i.e. their exergy is used) in a way which threatens the possibilities to make new resources of a similar kind and quantity socially available. This may turn into an unsustainable situation (a real resource crisis). The crisis may be overcome by thrifty use of resources - more recycling, better purification of effluents, lighter and/or more durable constructions, a shift in consumption from material to immaterial things, more effective use of existing production capacity instead of new investments, reductions of the irrational use of the social surplus. Or the crisis may be postponed or exported to other parts of the world in various efforts to make new resources socially available to a heavily resource-consumung production system.

Obviously it is the latter approach that has been favoured in recent decades. The developing of oil and gas technology and the nuclear program are some examples. Intensified geological surveys, also by satellite, and the increasing interest for the deep sea resources are others. However, these attempts have run into problems. By utilizing the new resources, deleterious effects on others - especially biological flows - have resulted. Another major problem is that the new sources for both power and materials generally are increasingly costly to develop and, thus, give serious doubts as to the possibility to exploit them for more than a small wealthy sector of the world community.

The alternative way of meeting the resource crisis is the thrifty way. [38] It can, in the short run, alleviate the pressure on available resources and in the long run facilitate a "good society" that works on continuous exergy flows that are then socially available. To achieve this, the bulk of the presently available dead stocks will have to be invested in long-lasting patterns of socio-mass, especially in the third world, and not be wasted in luxury consumtion or irrational uses.

To make use of the continuous exergy flows it is also important to develop technology (both technical equipment and organisational means) for utilizing local, small-scale or dispersed resources [35]. Older societies often took care of small-scale resources close to the place of production. With the presently prevailing large-scale methods for production and mining, such resources now attract a much smaller interest. The modern society thus perceives what may be called aggregated or "coarse-grained" information about natural resourses. Using statistical mechanics one can compute the entropy increase and thus the loss of information or of exergy in the neglect described by coarse-graining:

If the total number of states N, is divided into K classes $C_1,\ldots,C_K$ with $N_1,\ldots,N_K$ indices respectively,

$$N = \sum_{J=1}^{K} N_J \tag{9}$$

and the aggregated probabilities $\pi_1,\ldots,\pi_k$,

$$\pi_J = \sum_{i \in C_J} P_i \qquad \left(\sum_{J=1}^{K} \pi_J = 1\right) \tag{10}$$

the information loss is

$$-\left(I^{aggr.} - I \right) = \frac{1}{\ln 2} \left\{ \sum_{k=1}^{N} P_k \ln P_k - \sum_{J=1}^{K} \pi_J \ln \pi_J + \ln \frac{N}{K} \right\} \geq 0 \tag{11}$$

In a society which combines large-scale operations with a substantial part of small-scale locally dispersed operations, and makes physical planning not only with the help of maps but also by on-the-site inspections, it will be possible to utilize also the exergy contents of local small-scale resources.

World trade and exergy flows

International trade can be seen as a resource flow, measurable in terms of exergy. Exergy analysis might throw some new light on international trade by providing information which is complementary to the monetary data mostly used.

An interesting point is that the exergy requirement for production of a given product differs from place to place, depending on the differing reference environments. This is one of the reasons for trade. An analysis of this would help in finding to what extent trade is caused by differencies in the resourse endowments, in the local reference environments, or in the structure of production systems.

World trade can be used by powerful nations and corporations as an instrument for resource exploitation and surplus allocation at the global level. The previously mentioned irrationalities of the industrial world are clearly very important on this level.

8. Concluding remarks

Any dissipating system stays in a flow of energy (and/or matter). It receives energy (and/or matter) at low entropy and gives it away at high entropy (Fig. III.3) thus making a net gain of negentropy or exergy, which keeps the system running. In the case of living organisms this means that exergy is used to fuel the metabolic processes and to help the system evolve and build structures at the molecular level or higher levels. It is thus important to keep account of how this fuel is used in the process of dissipation. Therefore we believe that the exergy concept with an origin in the technical science has an important role to play also in the geophysical and biological sciences.

The metabolic processes of societies are studied mainly in the economic but also in the social and political sciences. Also these processes are fuelled with exergy. It would therefore be appropriate to base social and economic analysis of a society on an account of the exergy flows through this society and an account of the living stocks and funds (of the natural and social kinds) that keep these flows running as well as of the dead stocks that could be brought into use by the society. At a global level similar considerations would give a description of the globally available resources, their distribution and use. World trade would be analyzed in terms of exergy flows and in terms of its effects on available stocks and funds.

In democratic decisions on a nation's resource use, the available knowledge should be presented as correctly and clearly as possible. This may not be necessary for the experts who know how to correct for different biases. But correctness and clarity are essential in the presentation of knowledge to laymen - and in the democratic process all of us are laymen. As an example for the description of the Swedish energy system we think that our exergy diagram (Fig. 2) is a step towards a more correct picture of reality as compared to the conventional rather misleading "energy" diagram (Fig. 3).

By including some properties of the environment, the exergy of a system already takes into account possible interaction with its environment. This leads - as discussed above in Section 2 - to the necessity of defining a workable global standard and a convention on the principles to be applied in adopting local standards for exergy. We suggest that this work be done within or in close contact with the international unions of pure and applied physics and chemistry (IUPAP and IUPAC).

We believe that the conceptual outlines sketched in this paper could be worked out to form a firm conceptual basis for a broad interdisciplinary collaboration in the field of human ecology. The problems of overwhelming importance in this field are i) how to satisfy basic human needs for the poor majority of the world population and ii) how to develop permanent sound relations between human societies and their natural habitat. In developing such relations one must also not neglect Schumacher's aspects of health and beauty which may be impossible to catch in physical terms.

9. Acknowledgements

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At various stages of the work on this paper we have received help and constructive criticism from colleagues active in many different sciences: G. Adler-Karlsson, M. Almgren, C.G. Aurell, J. Christensen, I. Dahl, T. Eriksson, T. Fernholm, G. Grimvall, S. Lindeberg, B. Malmström, M. Månsson, G. Rosenblad, N. Svartholm and T. Wallmark. We thank them all for their support. We also thank Margareta Bourdin for typing the manuscript.

Appendix

Work available from a system in a reference environment

Consider a system A in a large homogeneous reference environment (heat bath) A_o which is characterized by the intensive parameters T_o, p_o, μ_{io} (for temperature, pressure and chemical potentials). Let the intensive parameters of A be T, p and μ_i. For the extensive parameters describing A and A_o we use U, V, S and N_i (for energy, volume, entropy and the number of molecules of different chemical components) and U_o, V_o, S_o, and N_{io} respectively (Fig. A.1). We assume that all extensive variables of A are small compared to the corresponding quantities of A_o and further that the combined system of A and A_o is isolated, apart from work W taken out from the system in a controlled way,

$$\begin{cases} U \ll U_o \\ V \ll V_o \\ N_i \ll N_{io} \end{cases} \tag{A.1}$$

$$\begin{cases} U + U_o + W = \text{const.} \\ V + V_o = \text{const.} \\ N_i + N_{io} = \text{const.} \end{cases} \tag{A.2}$$

We assume each of A and A_o to be in internal equilibirium. Interaction between A and A_o can take place in a controlled way across the boundary. Because of the relative smallness of A (eq. (A.1)), changes in A do not influence the intensive parameters of A_o appreciably.

$$dT_o = dp_o = d\mu_{io} = 0 \tag{A.3}$$

The differential form of (A.2) is

$$\begin{cases} dU_o + dU + dW = 0 \\ dV_o + dV = 0 \\ dN_{io} + dN_i = 0 \end{cases} \tag{A.4}$$

where dW is the energy taken out from the system as external work.

The entropy differential of the environment is from thermodynamics

$$dS_o = \frac{1}{T_o}(dU_o + p_o\, dV_o - \sum \mu_{io} dN_{io}) \qquad (A.5$$

which according to (A.4) may be transformed into

$$dS_o = -\frac{1}{T_o}(dU + p_o dV - \sum \mu_{io} dN_i) - \frac{dW}{T_o} \qquad (A.6$$

The total entropy differential of system and environment is

$$dS^{tot} = dS + dS_o = -\frac{1}{T_o}(dU + p_o dV - T_o dS - \sum \mu_{io} dN_i) - \frac{dW}{T_o} \qquad (A.7)$$

This may be written (cf [40])

$$dS^{tot} = -\frac{1}{T_o}(dE + dW) \qquad (A.8)$$

where we have introduced

$$\boxed{E = U + p_o V - T_o S - \sum \mu_{io} N_i} \qquad (A.9)$$

If we insert the Gibbs relation

$$U = TS - pV + \sum \mu_i N_i \qquad (A.10)$$

into (A.9) we get

$$\boxed{E = S(T - T_o) - V(p-p_o) + \sum N_i(\mu_i - \mu_{io})} \qquad (A.11)$$

which means that E vanishes at equilibrium,

$$\begin{cases} T = T_o \\ p = p_o \\ \mu_i = \mu_{io} \end{cases} \qquad (A.12)$$

The quantity E defined in (A.9) will be named exergy. To understand the meaning of this quantity let us assume that the system A is brought to equilibrium with its environment A_o and that in the process it performs an amount of work ΔW. Assume further that during this process the total entropy S^{tot} changes by ΔS^{tot}. The exergy changes from E by an amount -E to 0 . Then (A.8) gives us

$$\Delta S^{tot} = -\frac{1}{T_o}(-E + \Delta W) \qquad \text{(A.13}$$

or

$$\Delta W = E - T_o \Delta S^{tot} \qquad \text{(A.14}$$

Since

$$\Delta S^{tot} \geq 0 \qquad \text{(A.15}$$

according to the second law of thermodynamics we have that

$$\boxed{\Delta W \leq E} \qquad \text{(A.16}$$

with equality only for $\Delta S_{tot} = 0$, i.e. for a reversible process.

Thus the exergy E is an upper limit for the amount of work available from the system A through its interaction with the (reference) environment A_o.

The relation between exergy and entropy

Let us now assume that the system A goes to equilibrium with A_o without doing any work. Then the exergy changes from E to 0 and the total entropy changes from S^{tot} to S^{tot}_{eq}. Then (A.8) gives

$$S^{tot}_{eq} - S^{tot} = -\frac{1}{T_o}(-E)$$

or

$$E = T_o(S^{tot}_{eq} - S^{tot}) \qquad \text{(A.17}$$

Negentropy is defined as minus entropy. The total excess negentropy of A and A_o (as compared to equilibrium) is $S^{tot}_{eq} - S^{tot}$. Thus (A.17) gives a relation between exergy, environment temperature, and negentropy. Since $S^{tot}_{eq} - S^{tot} \geqslant 0$, <u>the exergy is a positive semidefinite quantity</u> x).

Although the exergy E is related through (A.17) to the total entropy of system <u>and</u> environment (A and A_o) the exergy itself can be ascribed to the system A only. The properties of the environment A_o enter only through the constant parameters T_o, p_o, μ_{io} in (A.9) or (A.11) as long as the environment is large, eq. (A.1).

For several systems in a common large environment the exergy is clearly additive, since the work that may be extracted is additive.

<u>Exergy expressed as a systems deviation from equilibrium</u>

Let U_{eq}, V_{eq}, S_{eq} and $N_{i\,eq}$ be extensive parameters of A after final equilibrium has been attained. Then $E_{eq} = 0$ and we get from (A.9) applied at equilibrium

$$0 = U_{eq} + p_o V_{eq} - T_o S_{eq} - \sum \mu_{io} N_{i\,eq} \qquad (A.18)$$

which after subtraction from (A.9) gives

$$\boxed{E = U - U_{eq} + p_o(V - V_{eq}) - T_o(S - S_{eq}) - \sum \mu_{io}(N_i - N_{i\,eq})} \qquad (A.19)$$

This is the expression used for the exergy by the APS group. (See Chapter 2 of ref. [11])

The extension of this description to more general cases including for instance gravitational energy and electromagnetic field energy is straight forward.

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x) In engineering literature sometimes conventions are used that may lead to negative exergy [41] . We think that such conventions should be abandone and that exergy should mean the work that may be taken out from a systen in its interaction with the environment.

"Local" and "global" exergy

Exergy is a physical measure of the deviation of a system from its environment. It is then interesting to see what a local environment, differing from the global one, implies for the exergy content of a system. We introduce a local environment system A_L surrounding the system A and surrounded by the global environment system A_o (Fig. A.2). Then we have a "local" exergy

$$E_L = U + p_L V - T_L S - \sum_i \mu_{iL} N_i \qquad (A.20)$$

and a "global" exergy (A.9)

$$E = U + p_o V - T_o S - \sum_i \mu_{io} N_i \qquad (A.9)$$

The two are related through

$$E = E_{Lo} + E_L \qquad (A.21)$$

where E_{Lo} gives the contribution due to the deviation of the local environment from the global one,

$$E_{Lo} = (T_L - T_o)S - (p_L - p_o)V + \sum (\mu_{iL} - \mu_{io}) N_i \qquad (A.22)$$

which according to (A.11) is the exergy of A with the intensive parameters of A_L replacing those of A. Clearly E_{Lo} is not an exergy function and thus not positive definite.

Boxes

I. The exergy of an ideal monatomic gas

Let the system A of the Appendix be N molecules of a certain monatomic ga in a container in an environment A_o made up by the same gas. (Fig. I.1). Let T_o and p_o be the temperature and the pressure of A_o and let T and p be the temperature and pressure of A. If T or p deviate from T_o or p_o, work may be extracted from A.

We shall calculate the exergy E of A under the assumption that the gas is thin enough to be considered as an ideal gas. Then we have for the volume V, energy U and entropy S of A

$$\begin{cases} V = \frac{NkT}{p} \\ U = \frac{3}{2} NkT \\ S = S_{eq} + Nk(\frac{3}{2} \ln \frac{T}{T_o} + \ln \frac{V}{V_{eq}}) \end{cases} \tag{I.1}$$

where k is Boltzmann's constant and where V_{eq} is the equilibrium volume

$$V_{eq} = \frac{NkT_o}{p_o} \tag{I.2}$$

The equilibrium energy is

$$U_{eq} = \frac{3}{2} NkT_o \tag{I.3}$$

For the exergy we have in this case ((A.19) with $N = N_{eq}$; there is only one component in the mixture and no index i is needed.)

$$E = U - U_{eq} + p_o(V - V_{eq}) - T_o(S - S_{eq}) \tag{I.4}$$

Inserting now (I.1) and (I.2) and (I.3) into (I.4) we get E as a function of T and V

$$E = NkT_o\left[\frac{3}{2} (\frac{T}{T_o} - 1 - \ln \frac{T}{T_o}) + \frac{V}{V_{eq}} - 1 - \ln \frac{V}{V_{eq}}\right] \tag{I.5}$$

In terms of the relative deviations (from equilibrium) in temperature and volume

$$\begin{cases} t = \dfrac{T-T_o}{T_o} & \text{(I.6)} \\ v = \dfrac{V-V_{eq}}{V_{eq}} & \text{(I.7)} \end{cases}$$

we have

$$E = NkT_o\left[\frac{3}{2}\,g(t) + g(v)\right] \tag{I.8}$$

where the function g(x) is defined as follows

$$g(x) = x - \ln(1+x) \tag{I.9}$$

This function is plotted in Fig. I.2. One sees that T increases rather rapidly with increasingly negative argument. For the temperature term in (I.8) this means that if the gas is significantly colder than its environment it can carry a large amount of exergy.

The logarithmic divergence in the g(x) at x = - 1 is artifical however. It arises out of the use of Stirling's formula in the derivation of (I.1) for large n

$$\ln n! \approx n(\ln n - 1) \tag{I.10}$$

down to small n where it is no longer valid. (Cf. comments on this in Ch. 2 of ref. [11])

II. Exergy and information

Thermodynamics deals with the physical laws of systems containing many particles. To have a detailed knowledge of the motion of individual particles is impossible. In statistical mechanics which provides the theoretical basis for the understanding of thermodynamics one takes advantage of the large particle number and uses statistical methods to describe macroscopic properties as average properties resulting from the motion and interaction of many particles.

The handling of incomplete information is dealt with in information theory [42]. The general problem of how to take into account, in an unambiguous way, the available (incomplete) information was successfully tackled by Jaynes [43]. As Jaynes showed statistical mechanics is a special instance of information theory. Conversely, powerful concepts and methods developed in statistical mechanics may through information theory be extended to other fields.

Let the system under description consist of N particles. The number of possible states Ω depends exponentially on N. Let the probability for the jth state to be realized be P_j,

$$\sum_{j=1}^{\Omega} P_j = 1 \qquad \text{(II.1)}$$

The entropy then is defined in statistical mechanics as

$$S = -k\sum_{j=1}^{\Omega} P_j \ln P_j \qquad (k = \text{Boltzmann's constant}) \qquad \text{(II.2)}$$

The probabilities at equilibrium $P_j^{(o)}$ are those that maximize S under whatever constraints that may be given on the system

$$S_{eq} = S_{max} = -k\sum_{j=1}^{\Omega} P_j^{(o)} \ln P_j^{(o)} \qquad \text{(II.3)}$$

The (excess) negentropy of the system described by the probabilities P_j then is

$$S_{eq} - S = k\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^{(o)} \ln P_j^{(o)}\right) \qquad \text{(II.4)}$$

The information content I is, according to information theory [43], in binary units (bits)

$$I = \frac{1}{\ln 2}\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^{(o)} \ln P_j^{(o)}\right) \qquad \text{(II.5}$$

As an example, if the system contains N different particles with 2 possible states each, then $\Omega = 2^N$. If there are no constraints, all $P_j^{(o)}$ are equal to 2^{-N}. Complete information about the system (one P_j equal to unity, the others vanishing) then gives I = N. For each particle there is then information equivalent to one yes or no answer to a specific question. Each such answer amounts to one binary unit (bit) of information.

From (II.4) and (II.5) we see that negentropy and information are very simply related

$$S_{eq}^{tot} - S^{tot} = k'I \qquad \text{(II.6}$$

where

$$k' = k \ln 2 \approx 1.0 \cdot 10^{-23} \text{ J/K} \qquad \text{(II.7}$$

plays the role of a fundamental constant. Thus one bit is equivalent to $1.0 \cdot 10^{-23}$ J/K of negentropy.

The relation (A.17) between exergy and negentropy

$$E = T_o(S_{eq}^{tot} - S^{tot}) \qquad \text{(II.8}$$

combined with (II.6) gives us the following relation between exergy and information

$$E = k'T_oI \qquad \text{(II.9}$$

Thus $k'T_o \approx 2.9 \cdot 10^{-21}$ J is the amount of exergy connected to one bit of information at room temperature.

It should be noted that "information" is a measure not necessarily of actual meaningful information but rather of information capacity. It can also be thought of as a measure of order or structure.

III. Some idealized thermodynamical systems

A. Equilibrium

An isolated system A at equilibrium has maximum entropy, $S = S_{eq}$.
Let the system be described by the intensive variables $X_i(\underline{x},t)$ depending on position $\underline{x}$ within A and time t. The values of the variables X_i are determined through the condition of maximum S,

$$\frac{\delta S}{\delta X_i} = 0 \qquad \text{(III.}$$

The entropy may decrease only temporarily through fluctuations, as indicated in Fig. III.1

At equilibrium, parameters like temperature and entropy are well-defined.

B. A system not deviating too far from equilibrium

Consider a small volume ΔV around the point $\underline{x}$ of the system A (Fig. III.2
If ΔV is macroscopically small but still large enough to contain a large number of particles it may be considered at a certain time to constitute a system which has reached equilibrium. (The relaxation time for reaching internal equilibrium in ΔV is assumed to be small compared to a typical time describing interaction with the surroundings.) Thus temperature, pressure, entropy density and so on may be defined as functions of $\underline{x}$ and t.

Flows $J_i(\underline{x},t)$ are driven by gradients of the intensive variables X_i. A linear relationship can be assumed

$$\underline{J}_i(\underline{x},t) = \sum_j L_{ij} \underline{\nabla} X_j(\underline{x},t) \qquad \text{(III.2}$$

where the coefficients L_{ij} satisfy the Onsager relations

$$L_{ij} = L_{ji} \qquad \text{(III.3}$$

When the system evolves the entropy increases. Let the entropy production per unit volume and time be $\sigma(\underline{x},t)$. Then [44]

$$\frac{dS}{dt} = \int_A d^3x \; \sigma(\underline{x},t)$$

$$\sigma(\underline{x},t) = \sum_{i,j} L_{ij} (\underline{\nabla} X_i) \cdot (\underline{\nabla} X_j) \geqslant 0 \qquad \text{(III.4)}$$

We see from (III.4) that for systems which are not isolated, $L_{ij} \neq 0$, whenever there is a gradient, there is entropy production. The entropy production has its minimal value for a source-free gradient,

$$\underline{\nabla} \cdot (\underline{\nabla} X_i) = 0 \qquad \text{(III.5)}$$

C. Non-equilibrium systems. The stationary case

A system may be maintained away from equilibrium if it lies in an energy flow and receives energy from one system and gives it away to another. For such a system A (Fig. III.3) the inflow of energy (temperature T_1) carries low entropy and the outflow (temperature $T_2 < T_1$) carries high entropy. If the power is W and the average temperature of A is T_o, then the net exergy gain per unit time is

$$T_o W \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \qquad \text{(III.6)}$$

This exergy flow can be used to construct and maintain structures far away from equilibrium.

For organisms equilibrium means death. Human beings as animals in general are staying away from equilibrium (i.e. staying alive) by extracting chemical energy in the processing of food to waste. This energy is then given away to the environment as heat. The whole biosphere lives by converting high frequency (heat) radiation given away into space (Fig. III.4). The fundamental process here is the photosynthesis in the plants.

Physically, of course, living systems are extremely complicated. A much simpler phycical example of Fig. III.3 is a metal rod conducting heat from a reservoir to a cold reservoir.

If the deviation from equilibrium is not too large a system in a position between a steady energy giver and a steady energy receiver evolves into a stationary state. This is for instance true of the metal rod in the example just mentioned.

A stationary state not to far from equilibrium is characterized by minimal entropy production,

$$\frac{\delta}{\delta X_i}\left(\frac{dS}{dt}\right) = 0 \qquad \text{(III.7)}$$

and the boundary conditions imposed by the energy giver and the energy receiver.

Thus in the evolution towards a stationary state, the entropy production decreases steadily until it reaches the minimum value determined by (III.7).

IV. Maximum efficiency in finite rate exergy conversion

A conversion process taking place at a non-zero rate v (exergy per unit time) must be driven by a non-zero gradient g. For many applications it is probably sufficient to assume linearity, as in (III.2),

$$v = \varepsilon g \qquad \text{(IV.1}$$

where ε is a constant independent of g.

The entropy production per unit time connected with such a conversion is quadratic in v (compare (III.4))

$$\frac{dS}{dt} = \chi v^2 \qquad \text{(IV.2}$$

where χ does not depend on v. If several ways are possible for the conversion from the initial to the final form of energy then let χ_o be the lowest possible value for the conversion process under study. Then we have a minimum entropy production per unit time

$$\left(\frac{dS}{dt}\right)_{min} (v) = \chi_o v^2 \qquad \text{(IV.3}$$

and hence a minimum exergy destruction per unit time $T_o \left(\frac{dS}{dt}\right)_{min} (v)$ where T_o is the environment temperature. Thus the maximum power that can go into desired outputs (exergy per unit time) is

$$v - T_o \chi_o v^2 \qquad \text{(IV.4}$$

we are thus led to define

iii) the maximal exergy efficiency connected to the conversion rate v as

$$\eta_{max}(v) = 1 - \frac{v}{v_o} \qquad \text{(IV.5)}$$

where

$$v_o = \frac{1}{T_o \mathcal{X}_o} \qquad (IV.6)$$

is a characteristic power related to the conversion process.

iv) We can also connect (ii) and (iii) and define a relative exergy efficiency η_{rel} for a non-zero rate conversion process

$$\eta_{ex} = \eta_{rel} \, \eta_{max}(v) \qquad (IV.7)$$

Table 1. Energy forms according to their relative exergy contents.

Form of energy	Quality index (% exergy)
Potential energy	100
Energy of motion	100
Electrical energy	100
Nuclear energy	nearly 100
Sun radiation	95
Chemical energy	varying, 90 to 100
Hot high-pressure steam	60
Steam in distant-heating systems	30
Heat in cooling-water	5
Heat radiation from the earth	0

Table 2. Efficiency in information transfer

	J/bit	Temp (K)
Electric typewriter x)	1	10^{23}
Radio (receiver) x)	$5\cdot10^{-4}$	$5\cdot10^{19}$
Television x)	$2\cdot10^{-5}$	$2\cdot10^{18}$
Computer memory	10^{-12}	10^{11}
Human speech	10^{-16}	10^{7}
Human ear	10^{-17}	10^{6}
Human eye	$5\cdot10^{-18}$	$5\cdot10^{5}$
Protein synthesis in a cell xx) (overall process)	$4.6\cdot10^{-21}$	460

x) The data were obtained from [10] .

xx) The data were obtained from Lehninger [39] .

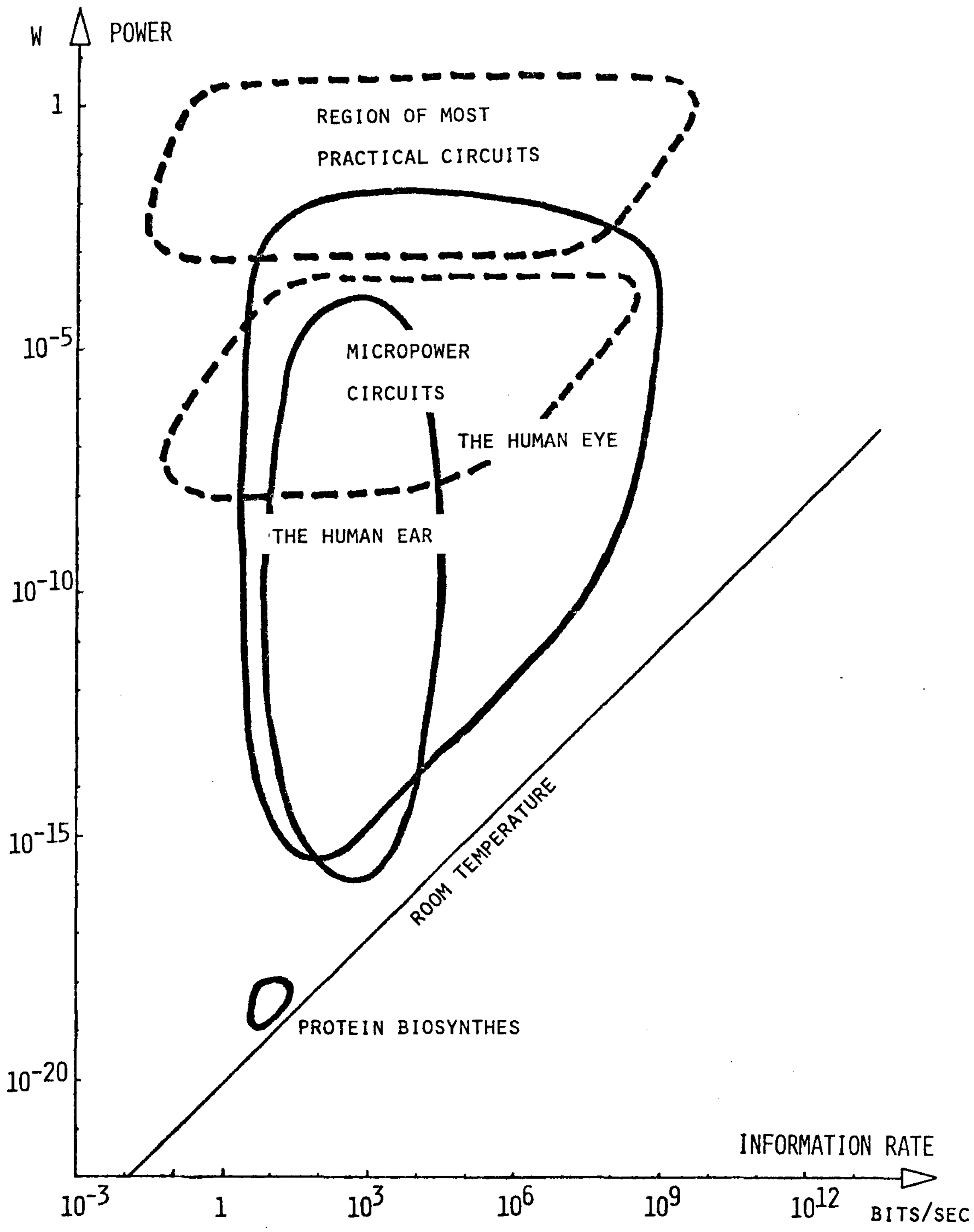

FIG.1 FREQUENCY-POWER DIAGRAM OF INFORMATION TRANSFER

The minimum power in integrated circuits has been treated by several authors [18-21]. It has been shown by Brillouin [22] that an elementary process in a circuit, such as a measurement, a storage of one bit, or a logical operation, requires an energy dissipation which is large in comparison with $kT \approx 4 \cdot 10^{-21}$ J (at room temperature). This is necessary to avoid thermal agitation which is the origin of noise in electric circuits, Brownian motion, etc. The energy value $4 \cdot 10^{-23}$ J is indicated by the straight line in the diagram. Information transfer must take place above this line. The protein biosynthes [23] can stay very close to this line because of the fact that in every elementary transfer 4.3 bits of information are exchanged.

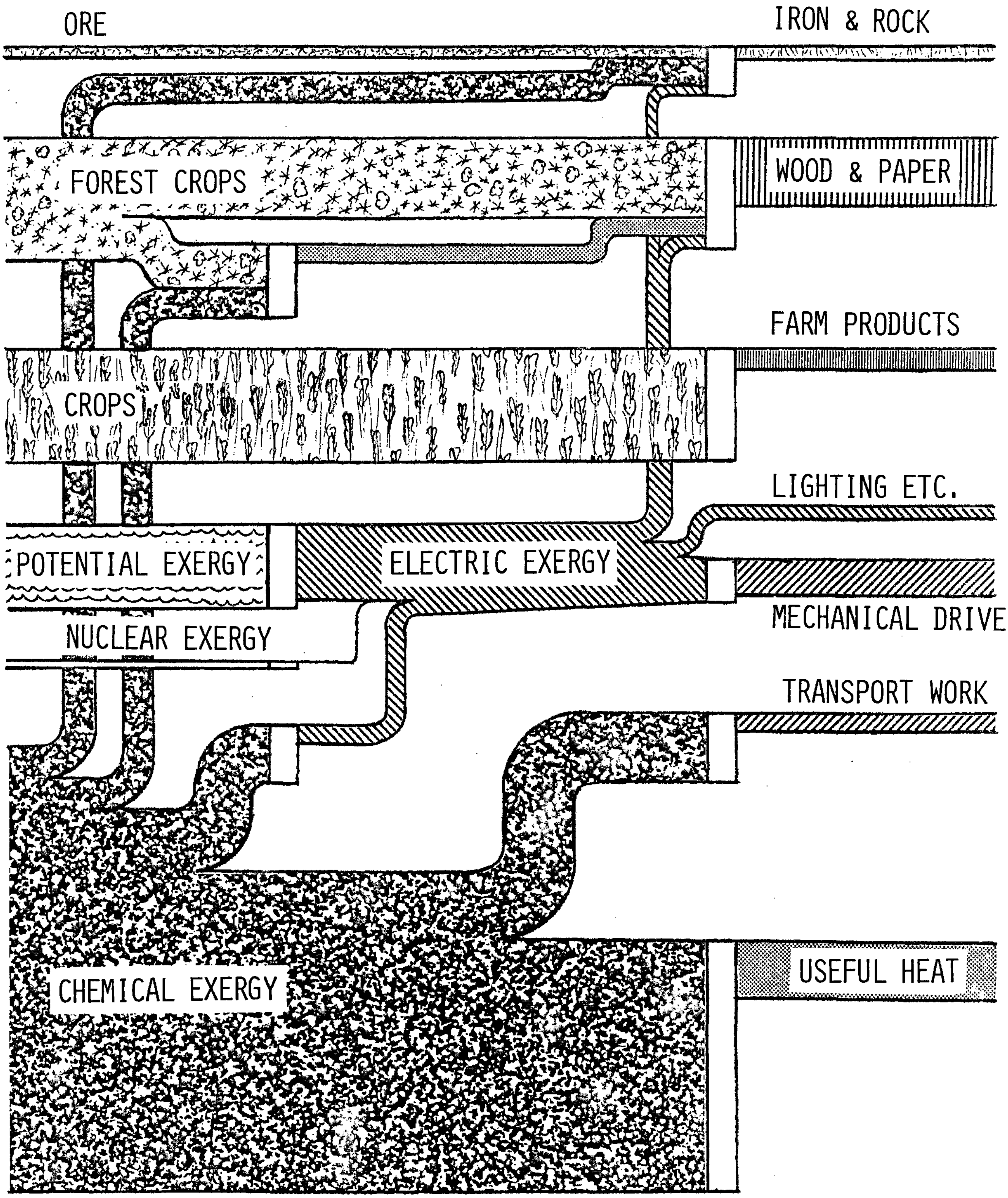

FIG.2 THE EXERGY CONVERSION SYSTEM IN THE SWEDISH SOCIETY 1971

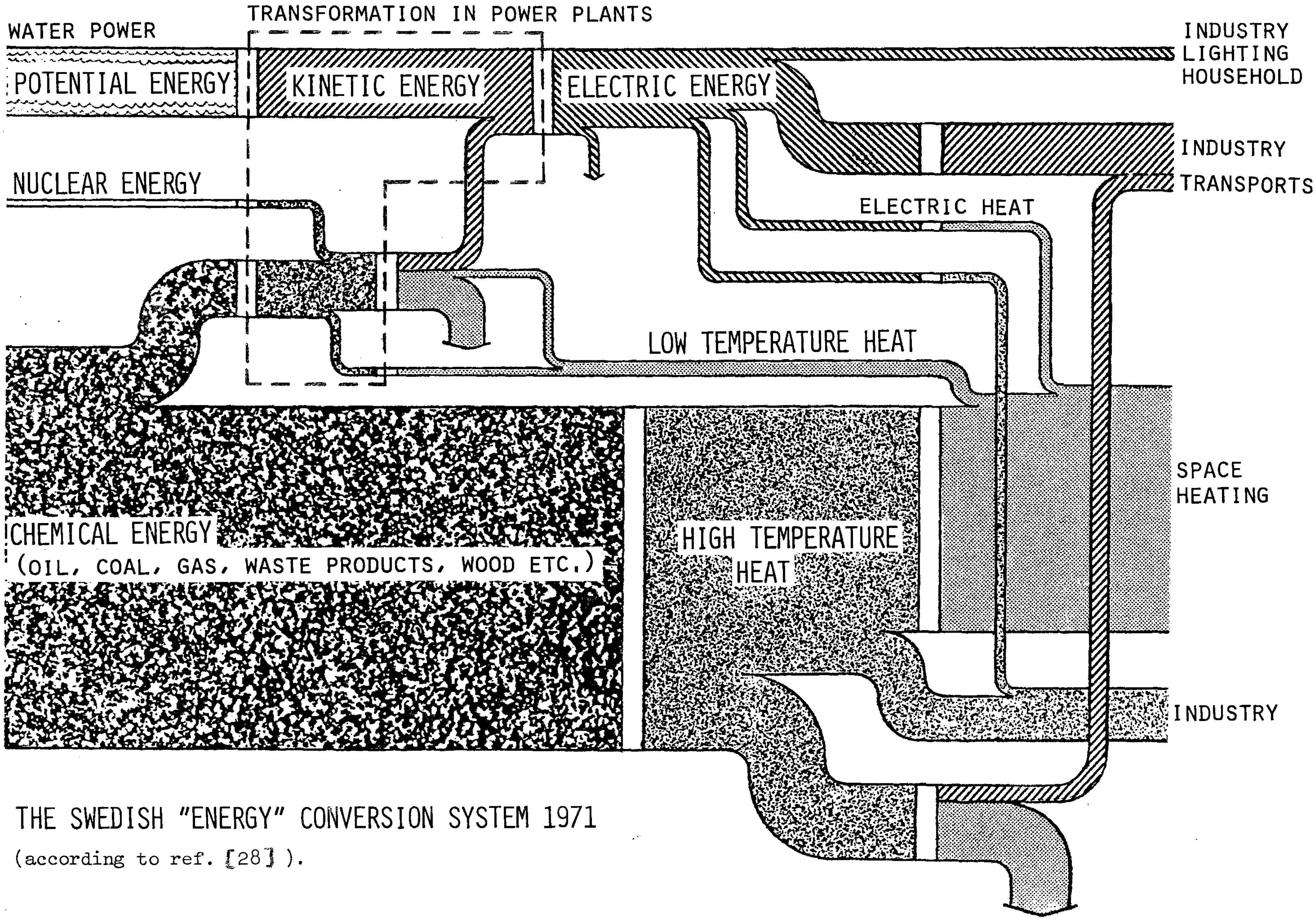

FIG.3 THE SWEDISH "ENERGY" CONVERSION SYSTEM 1971

(according to ref. [28]).

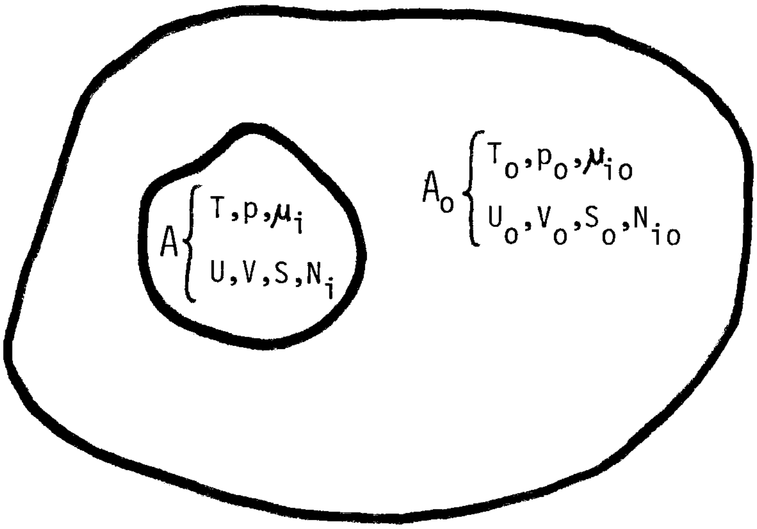

Fig. A.1 A system A in an environment A_o.

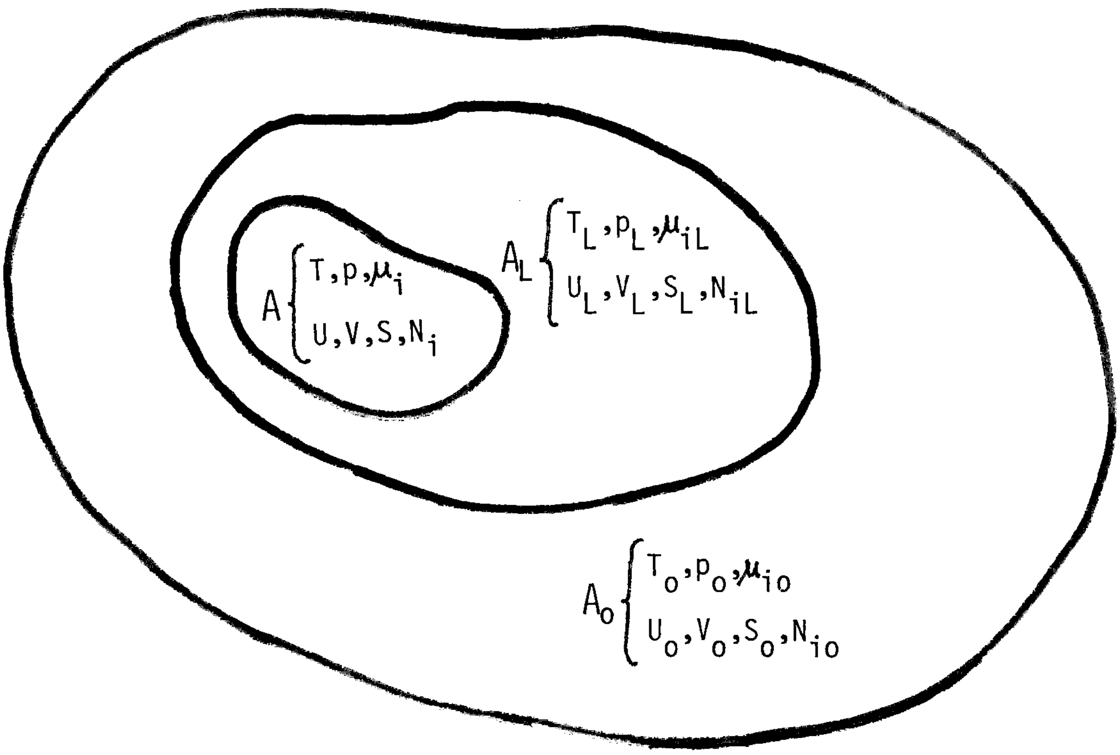

Fig. A.2 A system A in an local environment A_L in an environment A_o.

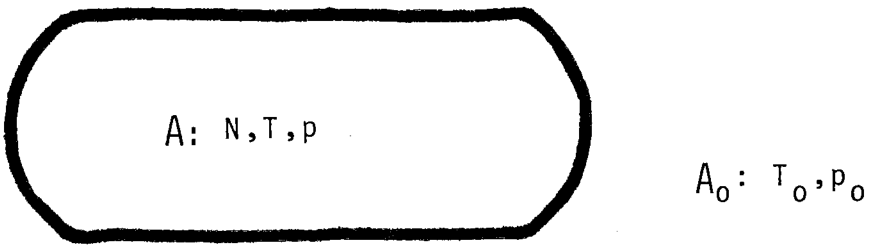

Fig. I.1 A gas in a container in an environment of the same gas.

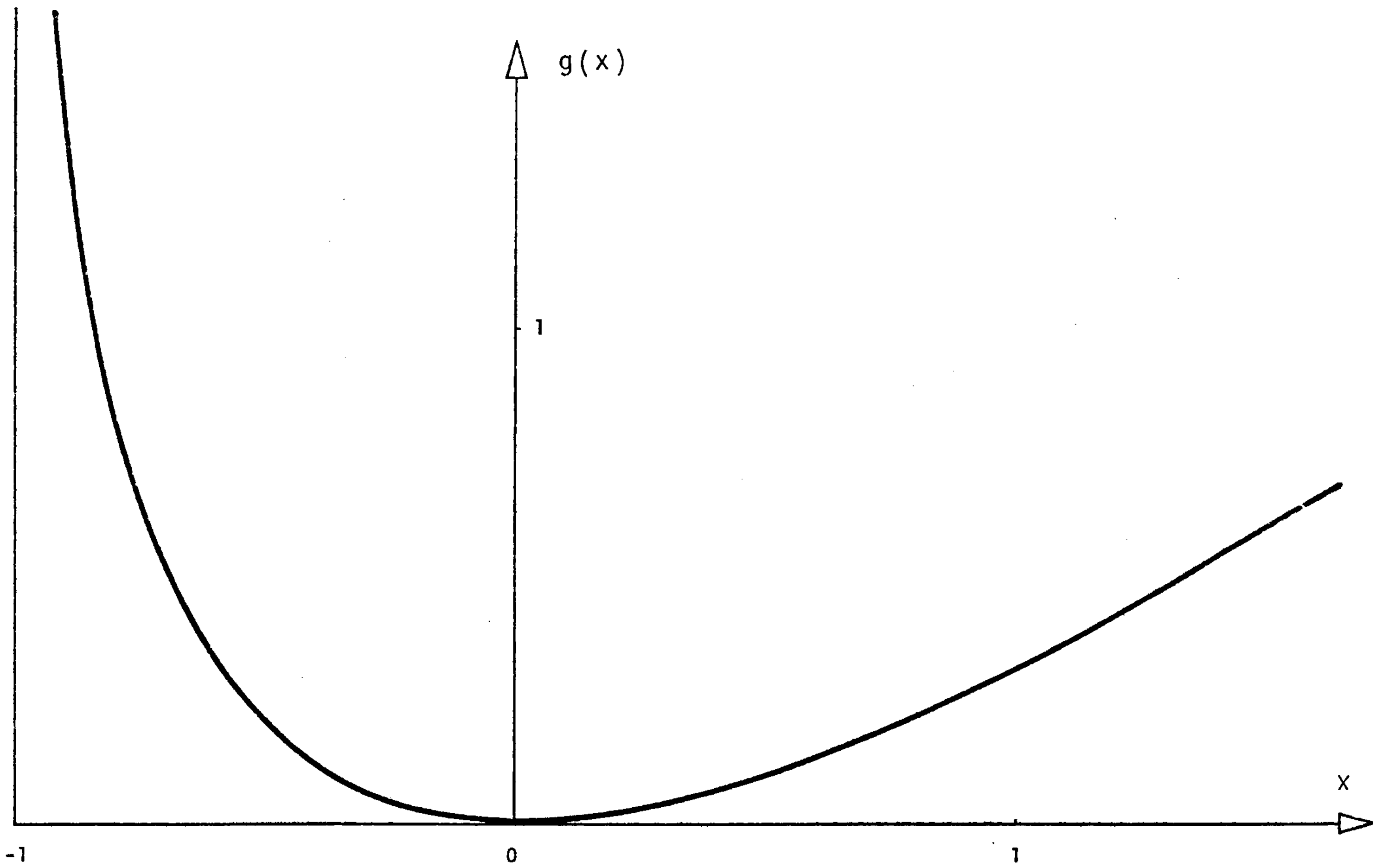

Fig. I.2 The function $g(x) = x - \ln(1+x)$

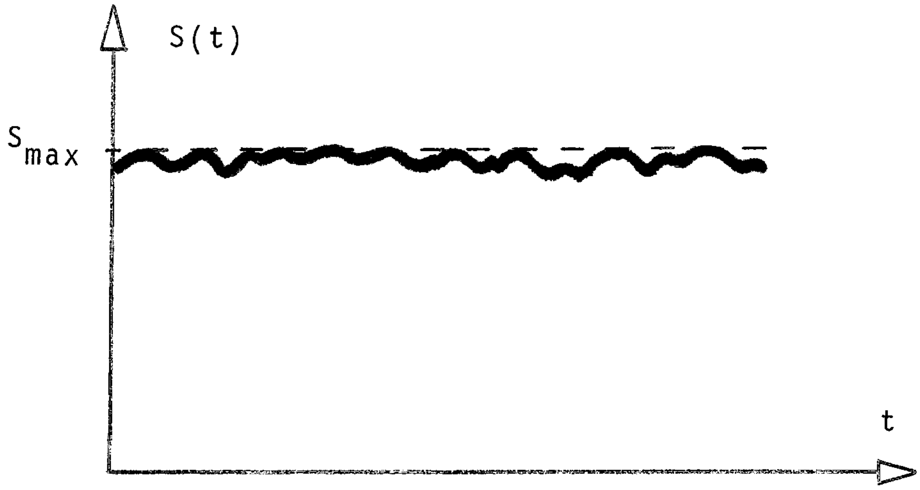

Fig. III.1 Entropy as a function of time for a system in equilibrium.

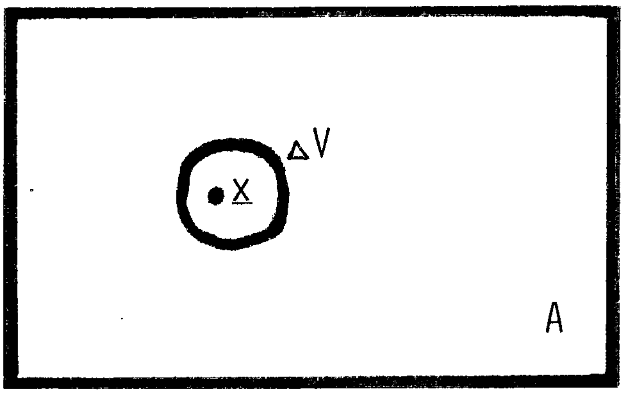

Fig. III.2 A small volume ΔV around the point X of the system A.

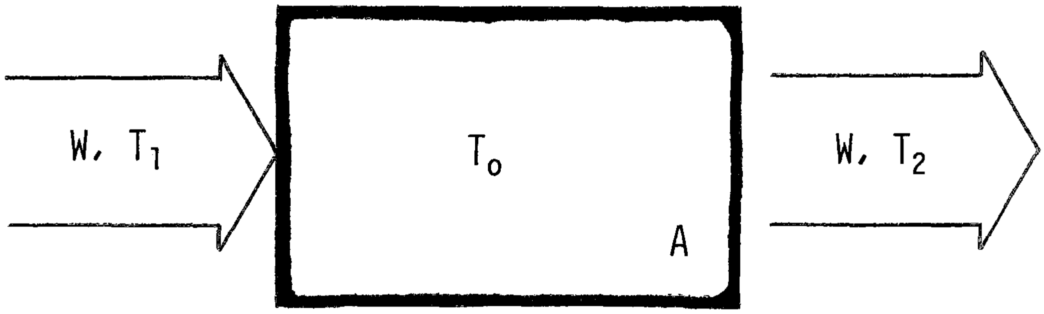

Fig. III.3 A system A of average temperature T_o in an energy flow W .

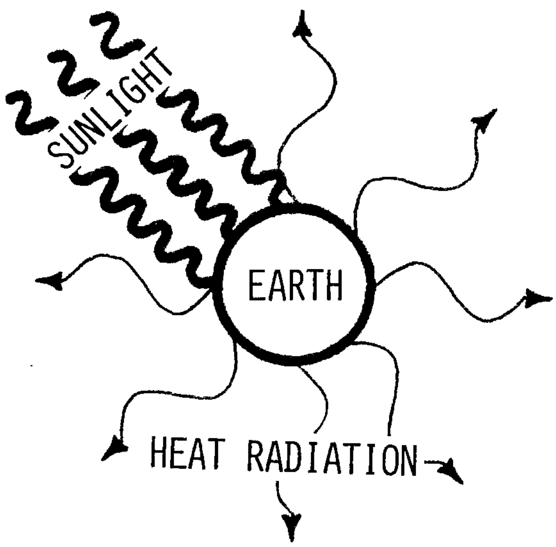

Fig. III.4 The SUN-EARTH-SPACE system.

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