J. FAC. SCI., SHINSHU UNIVERSITY, Vol. 21, No. 2, 1986

*The Earth, Living Beings and Entropy**

By ATSUSHI KATSUKI

Department of Physics, Faculty of Science,
Shinshu University
(Received Dec. 22, 1986)

Abstract

A unificative entropical view of Nature is proposed. The situation of the Earth is analyzed from the viewpoint of entropy, and it is pointed out that water circulation is very important for the Earth to be a "living" celestial body. The idea that living beings have two kinds of low-entropy materials, clean liquid water and carbohydrate, is proposed. Photosynthesis is analyzed as a process to regenerate carbohydrate. The conditions necessary for a celestial body to be a "living" one are discussed and it is concluded that the conditions are generally too severe to be realized; it is suggested that the Earth is a rare (perhaps unique) celestial body on which the conditions are satisfied. Soil for plants and the digestive organs of animals are analyzed and compared. Mention is made of the hierarchical multiple structure of entropy elimination. A critical discussion is made of a certain aspect of the present ideological situation, and the possibilities of producing crops fruitful even in the desert and of the realization of space colonies existing independently of the Earth are called in question. A schematic diagram of the global circulation of materials and entropy elimination attendant on processes of living is given in conclusion.

1. Introduction

There are many questions to be answered concerning life and living.

To live we breathe air. It is usually said that we inhale fresh air (oxygen) and exhale dirty air (carbon dioxide). As seen by using chemical formulae, in breathing we put out more materials than we take in, that is, we take in O_2 and give out $\underline{C}O_2$. A similar situation occurs with drinking and urination, that is, taking in H_2O and putting out $H_2O+\underline{CO(NH_2)_2}$ (urea).

These situations seem to be somewhat "uneconomical". Is living bad economy? Why does a person drink water, eat food and breathe air? Why does life exist only on the Earth and not on Mars, Venus and the Moon? What is it that distinguishes the Earth from the others?

To answer these questions, it is necessary to examine the situations from the viewpoint of entropy.[1]

From the viewpoint of entropy, the phenomena presented by living beings, for example maintenance and growth of the individual, propagation and so on, seem to be unaccountable, because they seem to be contrary to the law of increasing entropy. A living being, though it is very special, is one of the general modes of existence of materials, and must be subject to the laws governing these general modes; a living being, then, must not be an exception to the general law of increasing entropy.

If this is the case, why does a living being appear to be an exception to this law ?

SCHRÖDINGER characterized a living being by saying of it that "it feeds upon negative entropy".[2] This statement is not in fact an answer to the above question, but is a question much the same as the one above, while suggesting that the key concept to understanding life is entropy.

Again, why does a livig being seem to be an exception to the law of increasing entropy ? It is because of the fact that a living being is an open system, which takes low-entropy materials from the environment and puts out high-entropy ones into the environment; this is the real process of SCHRÖDINGER's idea of feeding upon negative entropy.

For living beings to be able to maintain their lives, the environment has to be kept in a low-entropy state; if not, they could not take low-entropy materials from the environment. For the environment to remain in a low-entropy state, the environment itself has to have a mechanism to eliminate entropy.

For living beings existing on a celestial body, the environment is the celestial body itself. Let us call a celestial body on which living beings exist a "living" celestial body.

In order for a star or a planet to be a "living" celestial body, it must have a mechanism to dissipate entropy. Generally, radiation from another celestial body as a heat source with a high temperature and space as a heat absorber with a low temperature offer the possibility to eliminate entropy from the concerned celestial body. In the case of the Earth, these are the Sun's radiation and the space surrounding Earth. But this is only a possibility, and a special mechanism is needed to realize it. Indeed, as far as the Sun's radiation is concerned, the situation is essentially the same among the Earth, Mars, Venus and the Moon. What is the special mechanism which distinguishes the Earth from the others and makes possible to eliminate entropy from the Earth ?

It is the circulation of water.

The situation of the Earth, which is just right for water circulation, is discussed in § 2. In § 3, it is pointed out that, for the delicate process of life to proceed, living beings use two kinds of low-entropy materials antithetical to each other in thermal properties, clean liquid water and carbohydrate. Photosynthesis as a process to regenerate carbohydrate is viewed from the standpoint of entropy, and the importance of water, which does not appear in the chemical equation of photosynthesis but vapourizes and escapes through stomata, is pointed out in § 4. In § 5, the conditions necessary for a celestial body to be a "living" celestial body are summarized, and it is pointed out that these conditions are generally too severe to be realized and that the Earth is a rare (perhaps unique) body on which the conditions are actually satisfied. In § 6, roots and soil for plants and the digestive organs of animals as places of intake are compared with each other from the viewpoint of entropy. It is argued that an ecosystem is a symbiosis-system cyclically connected by a chain of utilization of low-entropy materials, and that pollution is an accumulation of entropy that can not be dispelled into space through water circulation. In § 7, the hierarchical multiple structure of entropy elimination is mentioned. In § 8, the central ideas of this article are applied in critical discussions of the possibilities of producing crops fruitful even in the desert and of the realization of space colonies existing independently of the Earth. A conclusion is given in § 9 with a schematic diagram of the global circulation of materials and elimination of entropy attendant on processes of living.

2. Situation of the Earth

The mechanism of entropy elimination of the Earth due to water circulation is as follows: Absorbing heat Q at the ground (about 300K) water becomes vapour, then goes up to the upper atmosphere, emitting the heat there (250K) as infrared radiation to space, becomes again liquid (or solid) water, then returns as rain (or snow) to the ground. By this process, a net amount of entropy $Q/250-Q/300$ is eliminated from the Earth.[3]

The Earth satisfies miraculously the very severe conditions necessary for entropy elimination through water circulation to be realized.

One of the necessary conditions concerns the temperatures of the upper atmosphere and the ground.

STEFAN-BOLTZMANN's law $U=\sigma T^4$, where U is the energy of radiation emitted through the surface of a black body of temperature T per unit area and per unit time, with $\sigma=2\pi^5k^4/15c^2h^3=5.77\times10^{-8}$ watt/m^{2}K^4, and the following data,

$T_\odot$, the temperature of the surface of the Sun, about 5,770 K,

R, the radius of the Sun, about 6.96×10^8m and

D, the distance from the Sun to the Earth, 1 a.u. $=1.5\times10^{11}$m, enable us to estimate the overall energy density of the Sun's radiation on the Earth as it corresponds to that of a black body of temperature $T_D=393\ K$, obtained from the relation $(T_D/T_{\odot})^4=(R/D)^2$.

The Earth absorbs the heat by its cross section $\pi\rho^2$ (ρ is the radius of the Earth) and emits it through the whole surface $4\pi\rho^2$; the balance of absorbed and emitted heat,

$$\pi\rho^2(1-r)T_D{}^4=4\pi\rho^2 T_U{}^4,$$

where T_U is the temperature of the surface (=upper atmosphere) of the Earth and $r\sim 0.3$, the reflectivity of the Earth, enables us to estimate T_U as $T_U=254$ K.

Because the Earth is covered by an atmosphere, which is essentially transparent to the Sun's radiation but opaque to infrared radiation, the temperature T_G of the ground, i.e., at the bottom of the atmosphere, is higher than that of the upper atmosphere, T_U. this is the "greenhouse effect": $T_G>T_U$. In fact the roughly averaged value $T_G\sim 15°C=288K$ is higher than $T_U=254K$. (For simplicity, we assume $T_G=300K$ or $298K=25°C$ and $T_U=250K$ in this article.)

The astronomical situation (the Sun's size, the temperature of the surafce of the Sun, and the distance from the Sun to the Earth) and the physical properties of the Earth (form [sphere] and reflectivity) have determined the temperature T_U to be 254K. The existence of atmosphere has made T_G sufficiently higher than T_U that water can exist as liquid on the ground.

It is very important for entropy elimination due to water circulation that T_G should be sufficiently higher than T_U and should be such a temperature that water exists as liquid and easily vapourizes.

The other necessary condition concerns keeping water on the Earth in a liquid state.

The mean square root of the velocity of H_2O molecules of vapour at 300K, 645m/s, is much lower than the first astronautical velocity, 7.9km/s. This means that Earth is sufficiently heavy for water to be kept on it. On the other hand, molecules with this velocity are able to go up to a height of 21km; this is enough to reach the upper surface of the atmosphere. This means that Earth is sufficiently light to permit the rising of vapour to a height where the temperature T_U is sufficiently lower than T_G.

The fact that ice is lighter than water has great importance for the circulation of water to proceed. When water has been solidified due to lowering of temperature, ice is easily able to return to a liquid state by receiving heat from the Sun, as it floats on the surface of water. If ice were heavier than water, then when it froze, it would sink to the bottom and would not be melted by the Sun's radiation, so early in the history of the Earth all the water would have frozen as cold rock and only a thin layer of the surface would have melted when warmed by the Sun. There would not be abundant liquid water on the Earth and there would be no water circulation.

The high latent heat of vapourization of water makes the elimination of entropy by water circulation effective.

The situation of the Earth and the unique physical properties of water are, miraculously, just right for water circulation.

3. Living Beings and the Two Kinds of Low-Entropy Materials

To live, a living being must keep itself in a low-entropy state or construct its own organs of various materials. For example, living beings synthesize proteins from amino acids. In this process, roughly, the assemblage of concerned nitrogen atoms decreases in entropy because of reduction in range of distribution —— initially they are distributed over a wider range, as in amino acids, and finally they are concentrated in a narrower region, as in proteins. On the other hand, any process must involve an increase of entropy in general, so there should be an associated process to compensate for the decrease in entropy of the assemblage of nitrogen atoms. This process should be one in which certain low-entropy materials become high entropy and leave the system. What are the low-entropy materials that compensate for the entropy reduction of the living system in bio-chemical reactions and enable living beings to live ?

Living beings take in two kinds of *low-entropy* materials: clean liquid water with low energy and carbohydrates with high energy; to maintain themselves in a low-entropy state, living beings take in water and carbohydrates with low entropy and discharge waste matter with high entropy (vapour, "soiled" water, CO_2, etc.) and heat.

Clean liquid water is able to function as low-entropy material because it enters a high-entropy state by dissolving waste products or by absorbing heat (for the system concerned this means releasing heat and reducing its entropy) and *goes out* of the living body into the environment as soiled water or as vapour.

Carbohydrates are able to function as low-entropy material because they enter a high-entropy state by oxidation and by generating heat and *go out* of the living body into the environment as CO_2 and as heat carried off by vapour. Oxygen is needed for this process, i.e., to make carbohydrates function as low-entropy material. —— This is the reason we breathe air.

The thermal properties of liquid water and carbohydrates contrast with each other. When liquid water functions as low-entropy material, it *absorbs heat* and becomes vapour, so it may be called "low-energy and low-entropy" material, while when carbohydrates function as low-entropy material, they *generate heat* by oxidation, so they may be called "high-energy and low-entropy" material. The heat generated by the oxidation of carbohydrates is essentially absorbed by water in organs.

Some living beings do not need oxygen to live. In such cases, the "high-energy and low-entropy" materials are carbon compounds which function as low-entropy materials, for example, by fermentation needing no oxygen (not by respiration needing oxygen). For all living beings, the "low-energy and low-entropy" material is liquid water.

Also, in regard to the progress of the reaction from a low-entropy to a high-entropy state, water and carbohydrates contrast with each other. The vapourization of water actually acts against the vapourization (by a fall in the temperature of the water due to loss of latent heat and by increasing vapour pressure due to vapourization), i.e., the vapourization of water has a negative feedback mechanism.

Oxidation of carbohydrates generates heat, and the elevation in temperature accelerates the oxidation, i.e., the oxidation of carbohydrates has a positive feedback mechanism. Rapid growth or rapid propagation of living beings is possible because the oxidation of carbohydrates has a positive feedback mechanism. What prevents an excessive progression of oxidation is the vapourization of water.

The delicate process of life has been made possible by the fact that living beings use two kinds of thermally antithetical low-entropy materials.

Water circulation regenerates clean liquid water and photosynthesis regenerates carbohydrate. In photosynthesis sunlight makes carbohydrate of high energy, and water, which does not appear in the chemical equation of photosynthesis, makes it of low entropy. The role of water is very important for carbohydrate to be low entropy.

4. Photosynthesis

Usually, photosynthesis is expressed by the following chemical equation: $6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$, and this reaction is usually considered to be a process to fix light energy (from the Sun) into glucose. With regard to water, it seems that only the water appearing in the above chemical equation ($6H_2O$) plays a role; the most important point of the reaction is usually considered to be the fixing of light energy. But such a view is one-sided; a view of energy only, but not of entropy.

The amount of change in entropy by photosynthesis is to be estimated from the data on thermodynamic properties[4] as follows: ΔS(chemical) in the standard state is $-31.2R$[5]; ΔS(gas), associated with the change from CO_2 (regarded as an ideal gas) with pressure 0.0003 atm in atmosphere to O_2 (regarded as an ideal gas) with 0.21 atm in atmosphere, is $-39.3R$[6]; the total change in entropy is $-70.5R$ per the molar chemical equation above.

As shown above, the entropy of the chemical system is reduced by photosynthesis. So, there should be something whose entropy is increased by the process of photosynthesis.

What is it?

It is water, which has been vapourized by the process and does not appear in the chemical equation above.

Because $\Delta S(\text{water}\rightarrow\text{vapour})=17.7R$ (298K),[7] the amount of water needed to compensate for the reduction in entropy $-70.5R$ is at least about 4 moles (70.5/17.7=4).[8]

In addition, more water is needed to dispose of the thermalized energy of light which took part in the photosynthesis and was ultimately thermalized. The amount of water needed is estimated to be about 200 moles per the molar chemical equation above, from data of quantum yield[9] (to fix a molecule of CO_2, the number of photons needed is 8～12; to produce a molecule of $C_6H_{12}O_6$, 48～72 photons are needed) and those of free energy (or enthalpy) of formation.[4]

Free energy ΔG and enthalpy ΔH of formation of one mole of $C_6H_{12}O_6$ from H_2O and CO_2 are estimated as $\Delta G=6.88\times10^5$cal/mole and $\Delta H=6.70\times10^5$cal/mole in the standard state (25°C=298K and 1 atm),[10] corresponding to $\Delta g\equiv\Delta G/N=4.78\times10^{-11}$erg/molecule and $\Delta h=4.65\times10^{-11}$erg/molecule, where N is AVOGADRO's number; because the energy of photons with a wave length of 680nm is 2.9×10^{-12}erg, Δg and Δh correspond to the energy of about 16 of these photons; this means that the energy of 48−16=32 or 72−16=56 photons per one molecule of $C_6H_{12}O_6$ is thermalized by the process of photosynthesis; the thermalized energy is $1.4\sim2.4\times10^6$cal[11] per the molar chemical equation above. Because the vapourization heat of water at 25°C is 1.05×10^4cal/mole,[7] 130～230 moles of water are needed to dispose of the heat of thermalized photons.

It might be argued that the thermalized light has compensated for the reduction in entropy of the chemical system. But we must remember that when we talk about an increase in entropy Q/T accompanied by generation of heat Q due to liberation of energy from the system concerned, it is implied that the increase in entropy is embodied by a change of state of the environment. With regard to the thermalized light in photosynthesis, the environment is essentially liquid water, because the reaction takes place in the cells of leaves.

Therefore, we have to say that what compensates for the reduction in entropy of the chemical system is water, which does not appear in the chemical equation and has evaporated and escaped through stomata.

Moreover, much water is needed to dispose of the thermalized energy of the Sun's radiation which took no part in photosynthesis. According to the absorption spectra of chlorophyll and chlorophyll-protein complex,[12] it might be concluded

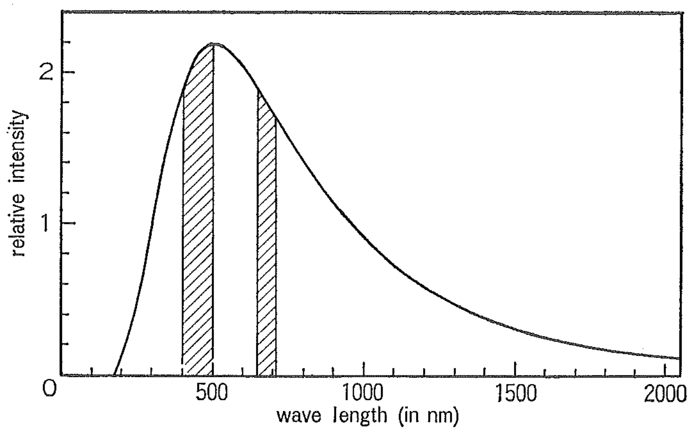

Fig. 1 Spectrum of radiation of the Sun regarded as a black body of 5,770K and its effective region for photosynthesis. The effective region shown by hatching occupies about 19% of the whole region in energy.

that the region of radiation effective for photosynthesis is of the wave length 450± 50nm and 680±30nm. In the spectrum of the Sun's radiation, this region occupies about 19% of energy[13] (Fig. 1). Therefore, the region ineffective for photosynthesis occupies about 81%, about 4 times 19%. If all the radiation of the ineffective region is absorbed by the concerned plant and then eliminated, the amount of water needed is about 1000 moles. If about a half of the radiation is assumed to be reflected at the surface of the plant and the other half absorbed, the amount of water needed to dispose of the absorbed heat is about 500 moles per the molar chemical equation above.

Disposal of heat through vapourization of water has an advantage over that through radiation. The former is able to eliminate much heat with no change in the temperature of the system. On the other hand, in the latter, because the temperature of the system has to be higher to eliminate more heat, it is impossible to eliminate much heat without destroying the system.

For photosynthesis to proceed, several hundred moles of water are needed per the molar chemical equation above. The glucose produced is a material with high energy and low entropy. The light fixed as chemical energy has made it high energy, while the water, vapourized and escaping through stomata, has made it low entropy.

5. Conditions for a "Living" Celestial Body

For a celestial body to be a "living" one, it has to have a mechanism to eliminate entropy from it; there must be:

1) Another appropriate celestial body as a heat source with an appropriate

temperature and appropriate size at an appropriate distance, to make the "living" celestial body able to take in heat at a higher temperature and disperse it at a lower temperature into space.

2) An appropriate "fundamental substance" to embody the mechanism above.

3) A circulation system with the "fundamental substance" as working substance.

For the Earth, (1), (2) and (3) are the Sun, water and water circulation.

If it is most effective for the elimination of entropy from the celestial body to use the difference in entropy between gaseous and liquid states of the "fundamental substance", then it has to have a high vapourization heat, to be liquid under the temperature and pressure at the ground level of the celestial body and to be easily vapourizable under the prevailing conditions.

In order for the vapourized "fundamental substance" to be able to reach the upper atmosphere, an atmosphere heavier than the vapourized "fundamental substance" should exist on the surface of the celestial body; and the atmosphere should be essentially transparent for the radiation from the heat-source body in order to make the temperature at the ground of the celestial body sufficiently higher than that in the upper atmosphere where emission of heat (=elimination of entropy) takes place.

The celestial body has to be sufficiently heavy in order to keep the vapourized "fundamental substance" on it; it has to be sufficiently light in order for the vapourized "fundamental substance" to be able to reach the upper atmosphere, where the temperature is suitably lower than that at the ground.

When the "fundamental substance" is solidified due to lowering of temperature, in order for it to return easily to a liquid state by receiving heat from the heat-source body, the solid "fundamental substance" should float on the liquid "fundamental substance", i.e., the density of the solid "fundamental substance" should be lower than that of the liquid one.

For most celestial bodies, the conditions:

Existence of an appropriate celestial body as heat source with an appropriate size and temperature at an appropriate distance.

Existence of an atmosphere and a "fundamental substance" with appropriate physical properties.

Appropriate mass of the celestial body.

are generally too severe to be realized.

The Earth is a rare (perhaps unique) celestial body on which the conditions are satisfied.

6. Soil and Digestive Organs

A living being is an open system which exchanges materials and heat with the environment. Here, a few comments are made on roots and soil for plants and digestive organs of animals as a place of intake.

When a plant absorbs nutrients through its roots from soil or an animal by villi in its bowels, the nutrients are absorbed as small molecules which have been decomposed or digested from high polymers. Because high polymer molecules are too large to pass through boundaries and generally have specificity different from the high polymers making up the organisms, a plant or animal is not able to take in high polymers as they are, and absorbs decomposed molecules, although the entropy of decomposed molecules is higher than that of the original high polymers.

After absorbing decomposed molecules, a plant or animal builds its own organs with low entropy from the decomposed molecules by consuming low-entropy materials, i.e., stored carbohydrates and ingested clean liquid water.

It might be thought that what produces the non-increase in entropy of an animal is the entropy difference between food and excrement, but this is a misunderstanding. The main components of excrement are unabsorbed remains of digested food after nutrients have been absorbed, and they have no essential connection with maintenance of the life of the animal.

Fallen leaves, excrement, dead plants and carcasses, the entropy of which is lower than that of the nutrients decomposed, are not absorbed by plants as they are. Microbes in soil use them as low-entropy (and high-energy) materials for the microbes themselves to live, and decompose them into molecules of nutrients of higher entropy absorbable by plants.

An ecosystem is an extensive symbiosis-system of organisms cyclically connected with each other by the chain of utilization of low-entropy materials.

Pollution is an accumulation of entropy which can not be put out into space through water circulation.

Plants absorb water and nutrients from soil through their roots, so plants are not able to move about. Why is an animal able to move about freely? It is because an animal has organs correspondnig to soil for plants, i.e., its own digestive organs inside itself. Digestive enzymes, corresponding to microbes in soil, work well in the digestive organs; villi correspond to the roots of plants.

7. Hierarchy of Multiple Structure of Entropy Elimination

To understand the hierarchy of multiple structure of entropy elimination, let us consider a living human body as an example. Living cells take in the nutrients and oxygen needed to live from arterial blood in capillaries and eject an aqueous solution of CO_2 and waste matter into blood, changing arterial blood in to venous blood. This is entropy elimination of cells. The blood containing CO_2 and waste matter is filtrated in the lungs, kidneys and sweat glands, to remove CO_2 and waste matter; the removed CO_2 is exhaled as breath and the removed waste matter dissolved in water is excreted as urine and sweat. Urination, perspiration, expiration and heat emission by perspiration and by expiration are the main processes of removing entropy from the body and putting it into the environment at the ground level. The entropy of the environment on the ground is dispelled into space through water circulation.

The process of removing entropy from living organisms is a very delicate one; for the process to proceed normally, suitable conditions of body temperature, pressure, components and concentration of body fluid, and so on, must be maintained throughout. Illness is a deterioration of the conditions and prevention of the process of entropy removal.

It should be noticed that there is the following relation among temperatures:

T(interior of the living body)$>T$(surface of the living body)$>T$(environment on the ground)$>T$(upper atmosphere)$>T$(space).

This ranking is a natural consequence of the following fact: in each stage of entropy elimination, the emission of heat from the systm into its enviroment is necessary for the system to live; for the emission of heat to be possible, the temperature of the system has to be higher than that of its environment. It is because the temperature of the Earth is higher than that of space that Earth is able to eliminate entropy through water circulation. It is because the temperature of the human body is higher than that of the environment that the human body is able to dispel entropy into the environment. It is because the temperature of the interior of the body is higher than that of the surface of the body that cells of living organs are able to eliminate entropy. If space had a temperature comfortable for human beings to live in, it would be too hot for the Earth as a "living" planet. If the environment on the ground had a temperature comfortable to the cells of organs inside the body, it would be too hot for human beings to live.

Concerning the conditions of existence of living beings, we must not view the conditions (temperature, pressure, humidity, chemical components and so on) of the immediate environment alone, but in the global framework of the hierarchical multiple structure of entropy elimination through which water circulation runs.

8. Application

One might criticize the above discussions as speculation in natural philosophy having no relation with the real world and inadequate for solving actual problems. This, however, is not the case.

Today we are frequently confronted with deceptive arguments put forward by pseud-scientists to the effect that advancement in science should be directed toward fulfilling any and every desire of the human race. An important function of science, however, is to declare what is impossible of fulfillment. In thermodynamics, for example, the establishment of the first and second laws destroyed any illusions about the possibility of perpetual motion, and so enabled genuine scientists to avoid wasting their time and put swindlers out of business.

Nowadays, something corresponding to the two laws of thermodynamics is needed, and this may well be the unificative view of Nature based on the entropical viewpoint.

In the following, I would like to show that the thinking developed in the present paper is not irrelevant to, and not powerless in solving actual problems by showing that, from the viewpoint of entropy (or the importance of water circulation in entropy elimination), clear judgments can be made about certain arguments whose deceptiveness is not always easy to recognize.

1) *Is it possible to make crops fruitful even in the desert by bio-technology?*

There are regions which, in consequence of long-standing exploitation as colonies by imperialistic powers, have not yet succeed in creating conditions of economic independence and are suffering from a bad economic situation——the Third World.

To justify experiments with recombinant DNA in genetic engineering, the bad food situations of some countries in those regions are sometimes mentioned; it is said that if we created crops that will grow even in the desert, it would be a great contribution toward solving the food problem in the regions. But such arguments are not valid. As shown in the section on photosynthesis (§4), for the reaction of photosynthesis to proceed, not only sunlight but also a lot of water carrying away entropy is needed. Where water is lacking, however hot the sunlight that may beat down upon the ground, no vigorous photosynthesis can proceed and crops can not be fruitful. One might create crops fruitful in fertile land, but these crops would be fruitless in the desert. There may be plants that will grow even on land poor in water, but they will be of slow growth. A lot of water is necessary for plants to grow rapidly and to be fruitful.

In order to solve the food problem, what science and technology have to do is not to try to create new crops fruitful even in the desert (the very effort would be in vain), but to protect fertile land from devastation and to reclaim desert and turn it into fertile land.

2) *Is it possible to construct a space colony existing independently of the Earth?*

When the Space Shuttle Program was proceeding succesfully, people declared that the successes would open up a new age, "the era of space colony". They made a plan to set up a space colony——where the colony would be constructed, from where the construction materials would come, how they would be transported, what scale and what form the colony would have, how many people would live there, what the interior of the colony would be like, and so on.

But these "space colonialists" did not recognize the importance of entropy elimination or the important role of water circulation. For them, water is a familiar material, which merely enlivens a rural landscape as a stream running through fields and is needed only for paddyfields and breeding ponds in a space farm attached to the colony. Because of their biased view of almighty energy, they are interested in obtaining energy alone, and are unconcerned with the elimination of entropy; they are under the illusion that if only we succeed in harnessing the Sun's light sufficiently for the colony to continue to live by solar cells, all will go well in the colony.

But this is not the case. No space colony can satisfy the conditions necessary for a celestial body to be a "living" one. Water will not circulate in a space colony because the colony will be too light to keep in water without walls and ceilings; therefore, water can not function as a "fundamental substance" for entropy elimination.

A space colony can not be self-sustaining and self-sufficient; it could only work as a "parasite" on the Earth, i.e., with a good supply of low-entropy materials (water, food and so on) from the Earth; it would not be a colony, but no more than a space station.

9. Conclusion——Global Circulation of Materials and Elimination of Entropy Attendant on Processes of Living

Global circulation of materials and elimination of entropy attendant on processes of living are summarized in a schematic diagram (Fig. 2).

At the top of the figure, is shown vapour returning to liquid (or solid) water by heat radiaton in the upper atmosphere; the radiation of heat is nothing other than elimination of entropy from the Earth. White arrows and grey arrows are assigned to low- and high-entropy materials, respectively.

In the middle region, photosynthesis is shown; by introducing and consuming water (low entropy), CO_2 (high entropy) and the Sun's light (energy), carbohydrate (low entropy and high energy) is produced and stored and vapour (high entropy) and O_2 are produced and exhaled. The notation CH_2O in the figure means a 1/6 molecule of $C_6H_{12}O_6$.

In the lower region is shown synthesis of protein (nitrogen compound of low entropy) from amino acids (nitrogen compound of high entropy), as an example of vital processes, with extreme simplification. In the process shown, carbohydrate

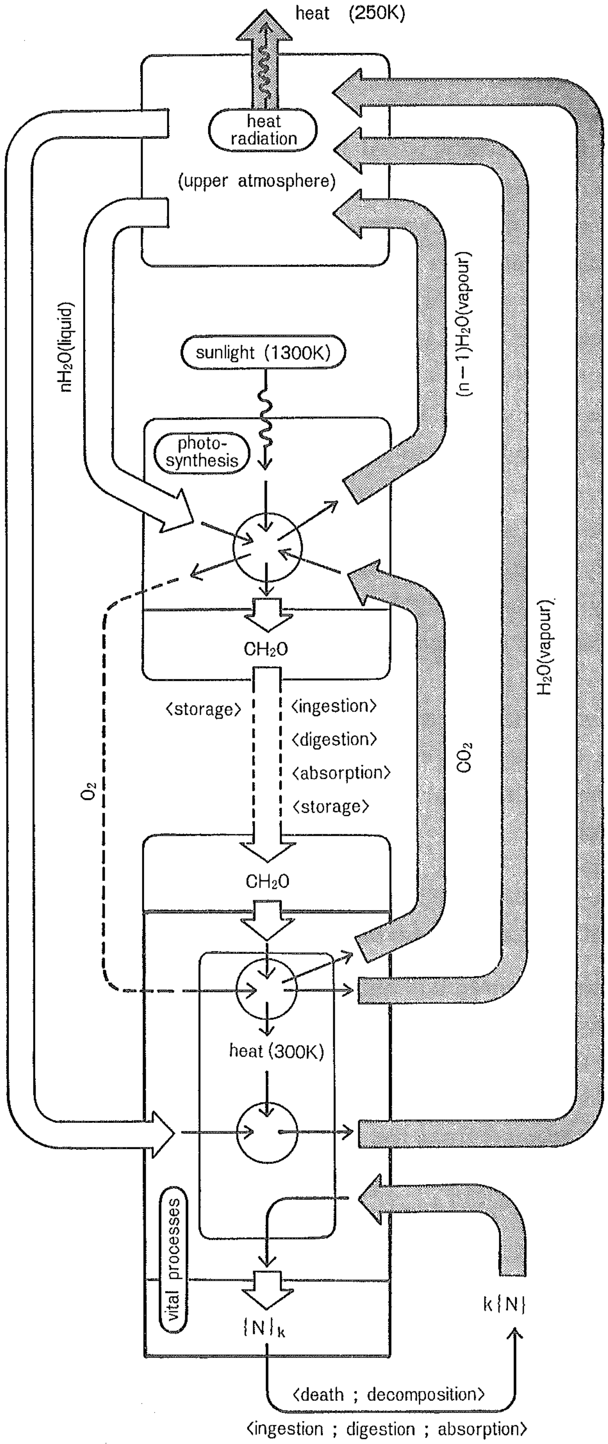

Fig. 2 Global circulation of materials and elimination of entropy attendant on processes of living.

(low entropy) stored in plants or eaten, digested, absorbed and stored in the body of animals, oxygen as oxidizer of carbohydrate, water (low entropy) and amino acids (high entropy) which plants have absorbed by roots or animals have eaten, digested and absorbed, are introduced and consumed, and then protein (low entropy) is produced and at the same time CO_2 (high entropy) and water in a high entropy state (vapour or aqueous solution of waste matter) are produced and excreted. Heat generated by oxidation of carbohydrate is exhaled ultimately from the surface of the body by vapourization of water. The symbol $k\{N\}$ in the figure means amino acids and $\{N\}_k$ means protein. In the global circulation of nitrogen, the atmosphere plays the role of nitrogen reservoir.

In the case of plants, although the process $\{N\}_k \rightarrow k\{N\}$ is annotated simply as death and decomposition, if we consider the activity of microbes in the soil, there should be inserted there a diagram comparable with the whole of Fig. 2 modified by substituting the photosynthesis section by other appropriate processes.

Notes and References

*) I have a lecture on General Physics for 2nd-year students of the Physics, Chemistry, Geology and Biology Departments, together. Students who intend to obtain a qualification as a teacher of science in high schools must attend the lecture. Some students like more mathematical explanations and others like explanations with images and analogies. Their interests are diverse according to their speciality. Therefore, I try to give them a unificative view of the Earth and living beings based on the concept of entropy, a physical viewpoint. It is expected that all students are interested in the subject. This article is an outline of the semiannual lecture above. Parts of this article were published in Japanese in 1985 and presented at the International Conference on Trends in Physics Education, 1986, Tokyo.

A. KATSUKI : "A Tentative Consideration of Living Beings and the Earth from the Viewpoint of Entropy" (in Japanese ; 「エントロピー的な視点からみた生物と地球（試論)」) *Entropy* (in Japanese ; 『エントロピー』) ed. by S. ONO and others, Asakura Shoten, Tokyo, 1985, pp. 77—102.

A. KATSUKI : "On the Role of Carbohydrates as Low-Entropy Material" (in Japanese ; 「炭水化物を考える——低エントロピー源としての役割」) Kagaku (『科学』——Science) 55 215 (1985).

A. KATSUKI : "The Earth, Living Beings, and Entropy" Proc. International Conference on Trends in Physics Education, Aug. 24—29, 1986, Tokyo, 350 (1986).

1) Nowadays, a "unificative" view of Nature based on the law of conservation of energy is well established. But such a view is imperfect and one-sided. To understand the intrinsic nature of Nature, we have to consider it not only from the viewpoint of energy but also from the viewpoint of entropy, which means considering it on the basis of the second law of thermodynamics, or the law of increasing entropy in irreversible

processes. Irreversible processes can be reduced to two fundamental ones : 1. transmission of heat or diffusion of energy from a region or system of higher temperature to one of lower temperature, and 2. diffusion of matter from a region or system of higher concentration or pressure to one of lower concentration or pressure; more precisely we may say, by introducing the concept of entropy, that these two phenomena, quite different from each other as phenomena in themselves, are two aspects of an identical phenomenon, the phenomenon of increasing entropy. Indeed, in the simplest case of transmission of heat Q from a system of temperature T_1 to that of T_2 ($T_2 < T_1$), change in entropy ΔS is $\Delta S = -Q/T_1 + Q/T_2 > 0$; in the simplest case of adiabatic expansion of an ideal gas to vacuum, change in entropy ΔS is $\Delta S = R\ln(V/v) > 0$ or $\Delta S = R\ln(p/P) > 0$, where R is the gas constant, and v and p are volume and pressure of the gas before and V and P those after the expansion; these two different phenomena are two aspects of a general phenomenon, increase in entropy.

For any phenomenon, the law of conservation of energy shows what relation must hold between states of the system before and after the change, and the law of increasing entropy indicates the direction of change in the phenomenon concerned; based on these two fundamental concepts, energy and entropy, a truely unificative view of Nature can be established. Someone might take the concept of free energy or exergy as a key concept to understand natural phenomena ; but these concepts are to be derived from energy and entropy and can not be a fundamental concept to establish a unificative view of Nature, although they might be useful and convenient concepts to understand individual special phenomena; by also connecting thermodynamics with statistical mechanics by the relation $S = k\log W$, entropy has the qualification to be one of the fundamental concepts to establish a unificative view of Nature.

2) E. SCHRÖDINGER: *What is Life ?——The Physical Aspect of the Living Cell*, Cambridge Univ. Press, 1944; Japanese Translation: S. OKA and Y. SHIZUME『生命とは何か』, Iwanami Shoten, Tokyo, 1975.

The late Professor EGAMI, a prominent biochemist, has stated in his excellent book *Searching for Life*, [2a] that there is nothing which by itself characterizes life and distinguishes the existence of life from its absence, because any biochemical reaction proceeding in a living system is able to proceed in the absence of life. Therefore, he stated, we have to try to understand the intrinsic nature of life by chemical and physical investigations of bio-phenomena, but not to ask for an ideological definition of life. His opinion suggests that, even looking for the inherent essence of life in any physical or chemical elementary process of vital phenomena expected to be unable to proceed without the existence of life, there is no doubt that further advancement in experimental method and in experimental technique will show that any elementary process should be able to proceed without any ad hoc existence of life. In one view, his opinion might be a clear-sightedness not to open the way to mysticism. But viewed from a different angle, his opinion seems to derive from his failure to grasp the key concept for understanding the essence of life; the key concept is entropy.

2a) FUJIO EGAMI: *Searching for Life* (in Japanese;『生命を探る』) 2nd ed., Iwanami Shoten,

Tokyo, 1980.

3) The essential idea of entropy elimination from the Earth through water circulation was first put forward by TSUCHIDA, in embryonic form in 1976 and in more extended form in 1978.

A. TSUCHIDA: "Limitation of Nuclear Fusion and Physics of Resources" (in Japanese; 「核融合の限界と資源物理学」) Proc. Phys. Soc. Japan (『日本物理学会誌』) 31 938 (1976).

A. TSUCHIDA: "An Attempt at a Physics of Resources" (in Japanese; 「資源物理学の試み」) Kagaku (『科学』——Science) 48 76, 176, 303 (1978).

A. TSUCHIDA: *Introduction to Physics of Resources* (in Japanese; 『資源物理学入門』) Nippon Hoso Shuppan Kyokai, Tokyo 1982.

4) The data used are as follows:

ΔH, enthalpy of formation, in kcal/mole,

ΔG, GIBBS' free energy of formation, in kcal/mole,

S, entropy, in cal/mole K,

all these quantities are in the standard state (25°C, 1 atm).

	ΔH	ΔG	S
CO_2 (gas)	− 94.015	− 94.25	51.06 (=25.70 R)
$C_6H_{12}O_6$ α-D-Glucose (solid)	−304.6	−217.6	50.7 (=25.5 R)
H_2O (liquid)	− 68.315	− 56.687	16.71 (= 8.410R)
H_2O (gas)	− 57.796	− 54.634	45.10 (=22.70 R)
O_2 (gas)	0	0	49.003 (=24.66 R)

The data are quoted from the Table given in the Appendix (p. 816) of the book *Physical Chemistry* by IRA N. LEVINE (McGraw-Hill, 1978).

5) $$\begin{aligned}\Delta S(\text{chemical}) &= S(C_6H_{12}O_6)+6S(O_2)-6S(CO_2)-6S(H_2O)\\ &=(25.5+6\times24.66-6\times25.70-6\times8.410)R\\ &=-31.2R\end{aligned}$$

6) $$\Delta S(\text{gas}) = -6R\cdot\ln\frac{p(O_2)}{p(CO_2)} = -6R\cdot\ln\frac{0.21}{0.0003} = -39.3R$$

7) $$\begin{aligned}\Delta S(\text{water}\rightarrow\text{vapour}) &= S(H_2O\ \text{gas})-S(H_2O\ \text{liq.})\\ &\quad -R\ln p(\text{saturated vapour pressure in atm})\\ &=22.70R-8.410R+3.46R=17.7R\end{aligned}$$

Here, the value of saturated vapour pressure at 25°C, 0.0313 atm has been used. From this value of ΔS, the latent heat of vapourization of water at 25°C is estimated as $17.7 R\times298\text{K}=1.05\times10^4$ cal/mole.

8) By taking into consideration the fact that in the first stage of photosynthesis H_2O is decomposed into H and O and in the second stage $C_6H_{12}O_6$ is composed from CO_2 and other H_2O, the following more appropriate expression for photosynthesis is sometimes used

$$6CO_2+12H_2O=C_6H_{12}O_6+6O_2+6H_2O,$$

in which is included the vapourization of $6H_2O$, more than $4H_2O$, enough to compensate for the redution in entropy of the chemical system, $-70.5R$.

9) For example, R. EMERSON and C. M. LEWIS: Am. J. Botany 28 789 (1941). Or see any standard textbook on photosynthesis.

10) $\Delta H = \Delta H(C_6H_{12}O_6) + 6\Delta H(O_2) - 6\Delta H(CO_2) - 6\Delta H(\text{liq. } H_2O)$
$= -304.6 + 0 - 6\times(-94.051) - 6\times(-68.315)$ kcal/mole K
$= 670$ kcal/mole K $= 6.70\times10^5$cal/mole
$\Delta G = \Delta G(_6H_{12}O_6) + 6\Delta G(O_2) - 6\Delta G(CO_2) - 6\Delta G(\text{liq. } H_2O)$
$= -217.6 + 0 - 6\times(-94.25) - 6\times(-56.687)$ kcal/mole K
$= 688$ kcal/mole K $= 6.88\times10^5$cal/mole

11) $(6.88 \text{ or } 6.70)\times10^5$cal/mole $\times(32\sim56)/16$
$= (1.4\sim2.4)\times10^6$cal/mole

12) For example, A. S. HOLT and E. E. JACOBS: "Spectroscopy of Plant Pigments. I. Ethyl Chlorophyllides A and B and their Pheophorbides; II. Methyl Bacteriochlorophyllide and Bacteriochlorophyll" Am. J. Botany 41 710; 718 (1954); I. IKEGAMI and S. KATOH: "Enrichment of Photosystem I Reaction Center Chlorophyll from Spinach Chloroplasts" Biochem. Biophys. Acta 376 588 (1975). Or see any standard textbook on photosynthesis.

13) According to PLANCK's law of radiation, the energy density of radiation between frequency ν and $\nu+d\nu$ is given by

$$u(\nu,\ T)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3}{\exp(h\nu/kT)-1}d\nu,$$

where T is the temperature of the black body from which the radiation radiates, h PLANCK's constant, k BOLTZMANN's constant and c the velocity of light. The effective region bears the following ratio, η, to the whole region:

$$\eta = \frac{\sum_{(i=1,2)}\int_{\nu_i-\Delta\nu_i}^{\nu_i+\Delta\nu_i}\nu^3 d\nu/\{(\exp\frac{h\nu}{kT})-1\}}{\int_0^\infty \nu^3 d\nu/\{(\exp\frac{h\nu}{kT})-1\}},$$

where $\nu_1=6.67\times10^{14}$Hz, $\Delta\nu_1=1.5\times10^{14}$Hz, $\nu_2=4.4\times10^{14}$ Hz and $\Delta\nu_2=0.4\times10^{14}$Hz corresponding to, respectively, $\lambda_1\pm\Delta\lambda_1=450\pm50$nm and $\lambda_2\pm\Delta\lambda_2=680\pm30$nm. Integrating the denominator and replacing the integrand of the numerator by the values at ν_i, we have

$$\eta = \frac{\sum_{(i=1,2)}\delta_i x_i^3/(\exp x_i - 1)}{\pi^4/15},$$

with $x_i \equiv h\nu_i/kT$ and $\delta_i \equiv h\Delta\nu_i/kT$; for the Sun's radiation ($T=T_\odot=5,770$K), $x_1=5.55$, $\delta_1=1.25$, $x_2=3.66$ and $\delta_2=0.33$ from which we have $\eta=0.19$. The effective region for photosynthesis is shown by the hatched areas in Fig. 1.