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P. Spillantini: ENERGY, ENTROPY, EVOLUTION AND
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On a physical system, statistical thermodynamics allows us to define the contained energy, E , and the entropy, S , as function of observable information alone.

The energies of the microscopic components of the physical system can be considered as "purely mechanical", so that, owing to the additivity of the forces, they can be added. Statistical thermodynamics allows us to extend this additive property to the energies of a physical system of any kind, regardless of its macroscopic form.

Entropy is related to the missing information of the physical system. In fact it is computed, after registration of all observable information, from the number of the possible alternatives for the system, Ω , as follows¹:

$$S = k \ln \Omega ,$$

where k = Boltzmann's constant = $1,38 \times 10^{-23}$ J/°K. For a system completely specified by its macroscopic observables, $S = 0$.

A system with only one digit of information (1 bit) which is not observable (for ex. one particle carrying an unobserved spin) has an entropy $S = 0,96 \times 10^{-23}$ J/°K, and gives us a basis for the measurement of the energy in "bits"².

Any system indeed can be characterized by its energy E and its missing information S , or equivalently and more effectively by its energy E and its remaining information content $I = S - S_0$, where S_0 = entropy of the system in an equilibrium state.

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For an isolated physical system its energy and entropy (or remaining information) contents stay constant in time :

$$\frac{dE}{dt} = 0 , \quad \frac{dS}{dt} = 0 \quad (\text{or} \quad \frac{dI}{dt} = 0) .$$

When the entropy is maximum ($S = S_0$, and the information content is indeed $I = 0$) its ratio to the energy S_0/E depend only on the equilibrium temperature of the system.

When equilibrium is not attained, the entropy S of the isolated system tends to increase toward S_0 , while the energy goes on to be constant in time

$$\frac{dE}{dt} = 0 , \quad \frac{dS}{dt} > 0 \quad (\text{or} \quad \frac{dI}{dt} < 0) .$$

Energy conservation is related to the uniformity of the measurement scale in time³. This scale is such to increase with increasing entropy.

The value of the entropy-energy ratio S/E tells us how far the system is from the equilibrium, while its derivative can be considered as a measure of the velocity of evolution towards equilibrium.

This velocity is very important in many (also practical) problems, worthy of a special symbol

$$R = \frac{1}{E} \frac{dS}{dt} = \text{evolution velocity} ,$$

$$(\text{or } R = - \frac{1}{E} \frac{dI}{dt} = \text{loss of information content}) .$$

R can be measured in units of $^{\circ}\text{K}/\text{sec}$ or $\text{bit}/\text{sec}/\text{J}$. It summarizes very well the above concepts and is also used in the theory of communication⁴ to indicate the rate of "actual transmission"; indeed it suggests an informatic meaning of the entropy.

Experience suggests that the value of R is related to the actual "complexity" of the physical system, and decreases with it (see Fig. 1).

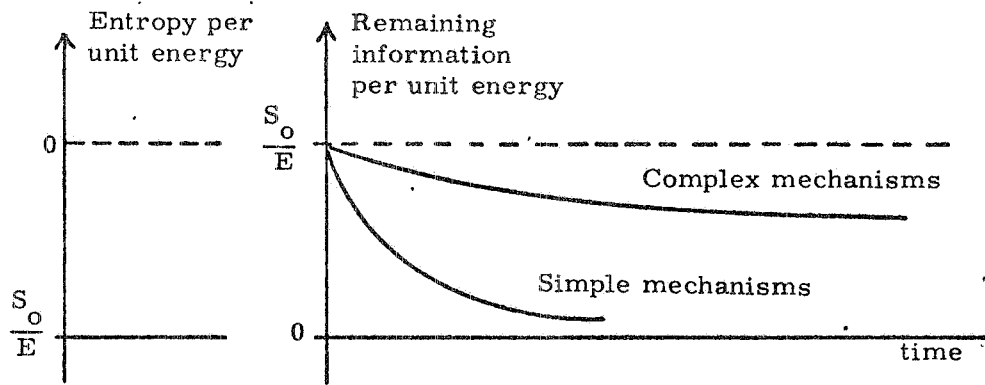


FIG. 1

I wish now to discuss two simple examples on this subject; the first one is an illustrative model of what daily experience suggests to us, and the second allows a generalization rich in speculative interest. The systems considered in the examples are not closed nor isolated, but the inputs and outputs (in matter, energy and entropy) can be computed and taken into account, so that the above description remain valid.

Let us assume that sunlight energy reaches a sandy surface and there is a dynamical equilibrium with the environment. After a short time Δt_1 the energy is returned entirely to the sky, but a portion of it, ε , loses about $\sim 95\%$ of its information content, for it is returned as long wave radiation; its R value is indeed

$$R_1 = \frac{1}{\varepsilon} \frac{\Delta S_1}{\Delta t_1}$$

(ΔS_1 = increase of the entropy or equivalently the loss of information content).

If the same energy ε were degraded by the same ratio $\Delta S_1/\varepsilon$ on the surface of a lake, it would have been used to evaporate water, in which case we would wait a long time Δt_2 for the rain to dissipate this energy, with a sharp fall of the evolutionary velocity of the system

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$$R_1 = \frac{1}{\varepsilon} \frac{\Delta S_1}{\Delta t_1} \gg R_2 = \frac{1}{\varepsilon} \frac{\Delta S_1}{\Delta t_2} ,$$

and the evaporation-condensation mechanism should have been able indeed to store the energy ε for some time (some days) in the system.

In the second example we discuss a system consisting of a plant planted on a plot of ground. Let us consider the following three states of our system (see Fig. 2):

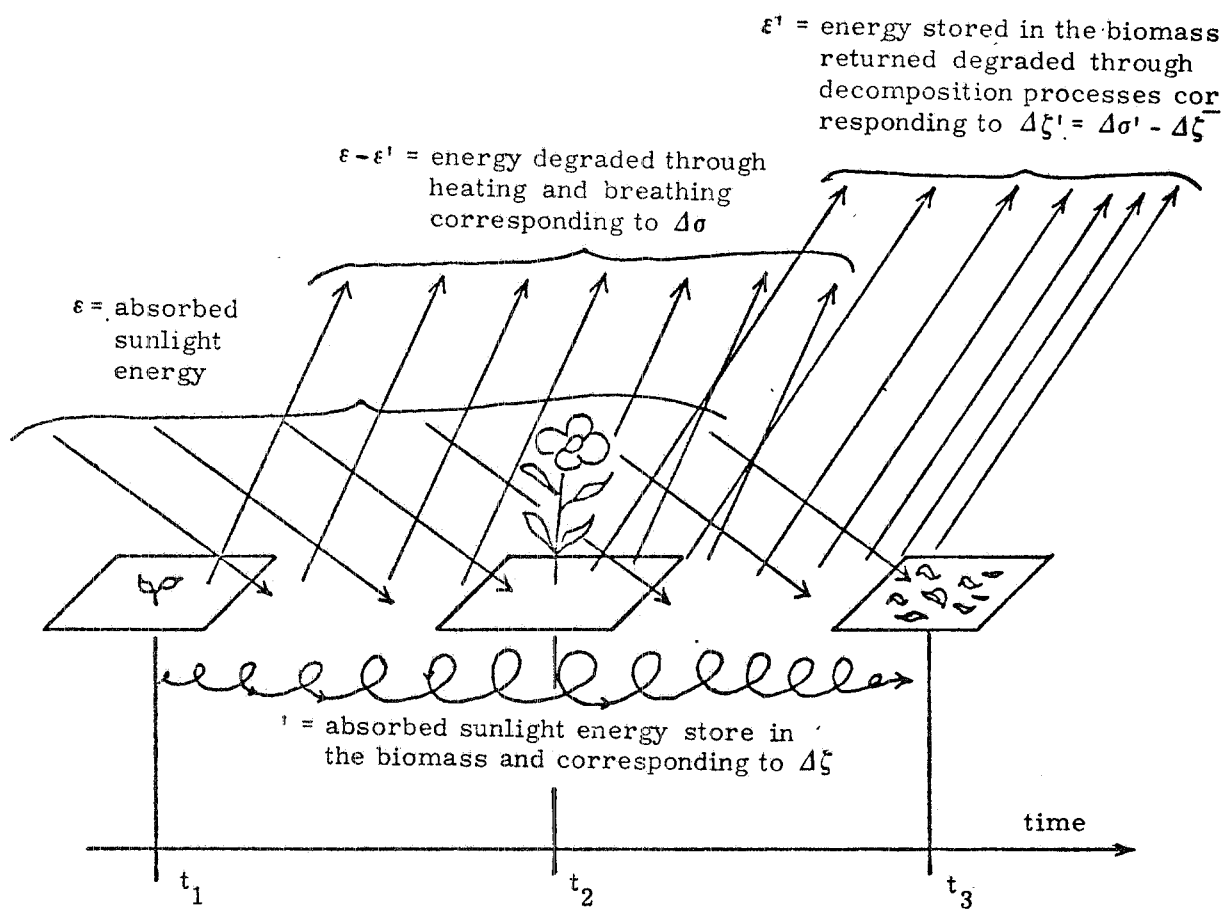
at time t_1 : the plant is starting to grow ;

at time t_2 : the plant is maximally developed (which is difficult to define but we assume it to be when it blooms) ;

at time t_3 : the plant is dead, and the decomposition process of its organic material is already in an advanced stage. To simplify the calculation we can fix the time t_3 such a way that the energy stored in the not yet decomposed materials should be equal to the energy stored in the plant at time t_1 .

Now suppose we can compute correctly all the inputs and outputs of energy, entropy and material, and thus take into account only the evolution of the system through the energy ε absorbed by the plant during its growth, senescence, death and decomposition extended from t_1 to t_3 . During this time interval the plant fixes in its own biomass an energy ε' , with an increase $\Delta\zeta$ in its associated entropy. The entropy associated with the remaining energy $\varepsilon - \varepsilon'$ increases by $\Delta\sigma$ (with $\frac{\Delta\sigma}{\varepsilon - \varepsilon'} \gg \frac{\Delta\zeta}{\varepsilon'}$), since it is returned as long wave radiation by the heating and breathing phenomena. The entropy associated with ε' undergoes an additional increase $\Delta\sigma' - \Delta\zeta$ only when the organic materials of the dead plant are decomposed in the soil. Indeed after the time t_3 the total increase of the entropy per unit energy associated with ε' is equal to that associated with $\varepsilon - \varepsilon'$, i. e.

$$\frac{\Delta\sigma'}{\varepsilon'} = \frac{\Delta\sigma}{\varepsilon - \varepsilon'} .$$



thermodynamical balance (from t_1 to t_3)

$$\left\{ \begin{array}{l} \Delta E = 0 \\ \Delta S = \Delta\sigma + \Delta\zeta + \Delta\sigma' - \Delta\zeta = \Delta\sigma + \Delta\sigma' \end{array} \right.$$

(with $\frac{\Delta\sigma}{\varepsilon - \varepsilon'} \approx \frac{\Delta\sigma'}{\varepsilon'}$)

evolution velocities :

for $\varepsilon - \varepsilon'$ $R = \frac{1}{\varepsilon - \varepsilon'} \frac{\Delta\sigma}{t_2 - t_1}$

for ε' $R' = \frac{1}{\varepsilon'} \frac{\Delta\sigma'}{t_3 - t_1} \ll R$

FIG. 2

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However the rates of increase of the entropy with respect to time are very different:

$$R = \frac{1}{\varepsilon - \varepsilon'} \frac{\Delta\sigma}{t_2 - t_1} \quad \text{relative to the energy } \varepsilon - \varepsilon',$$

$$R' = \frac{1}{\varepsilon'} \frac{\Delta\sigma'}{t_3 - t_1} \ll R \quad \text{relative to the energy } \varepsilon'.$$

If the plant were to live for an infinite time, we could write:

$$R' = \lim_{t_3 \rightarrow \infty} \frac{1}{\varepsilon'} \frac{\Delta\sigma'}{t_3 - t_1} = 0$$

i. e. the energy ε' ceases to degrade since it is fixed in the plant, with its associated entropy.

This limit cannot be applied to any living organism on the earth, but surely can be applied to life as a whole on earth, at least on a "trans-historical" time scale of some millions or tens millions of years. In effect life as a whole is the only living organism which can be treated in a same way as the single plant in the above system, but a somewhat more complex treatment is required.

First we fix our attention on the cellular structure of the plant. The ratio of the number of new cells to the number of cells which die exceeds one during the growth of the plant, but inverts during its senescence and falls to zero at its death. The energy ε' stored in the biomass of the plant can be considered to consist of two parts: ε'_1 stored by the biomass in all the cells, and ε'_2 due to the organization of the cells in the plant structure⁵ (we know from biology that $\varepsilon'_2 \ll \varepsilon'_1$). Hence the thermodynamical problem concerning the plant can be re-garded as the problem of a population of cells whose number and orga-nization vary in time, increasing first from time t_1 to t_2 , and after-wards decreasing from t_2 to t_3 . Therefore the substitution of the word "cell" for "living" and the word "plant structure" with "eco-system structure" is straightforward, and leaves the thermodynami-

cal considerations above effectively unaltered. Finally, the operations of addition and time-averaging make these thermodynamical considerations effective for the whole biosphere.

For the thermodynamical problem so extended the total "biotic" energy E' (and its associated entropy S') can be thought of as divided into two parts: the energy E'_1 stored on the biomass of the living organisms, and the energy E'_2 necessary for the living organisms to maintain their mutual interactions and their interactions with their environment.

Since the interactions tend to protect and give stability to life, they work to prolong the storage of the energy E' in the biomass, giving it an evolution velocity R'_E which approaches zero with increasing time:

$$\lim_{t_3 \rightarrow \infty} R'_E = \lim_{t_3 \rightarrow \infty} \frac{1}{E'} \frac{\Delta S'}{t_3 - t_1} = 0.$$

Thus the energy E' is permanently stored (in the "trans-historical" time scale mentioned above) in the biosphere, with its information content used to organize matter into living organisms, and to organize living organisms into ecosystems.

The important fact that this simple model suggests to us is that the energy responsible for the persistence of the biomass is not the entire energy E' stored in it nor is it the main fraction, E'_1 , but only the smaller fraction E'_2 which needs to be spent to give protection and stability to life. Concerning the actual value of E'_2 we cannot say nothing at present, but only that in any ecosystem it is certainly very much smaller than E'_1 .

This observation is very important because it makes the value of "natural energy", when compared with the energy E_u released to the environment by present human activity, comparable to E_u but probably also smaller. The current energy crisis when viewed as a crisis chiefly of the natural environment disturbed by the use of the

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energy E_u seems justified also from a "purely" energetic point of view.

Naturally not all of the energy inputs to the environment, even if massive, should affect the amount of the total biotic energy E' stored in the living system in a negative way. But two main observations must be made.

The first observation is that the rate of release of E_u is usually much higher than the rates of time variation of any other variable fundamental to the ecosystems.

The second observation sounds like an obvious one. Since we know nothing about E'_2 , but only that $E'_2 \ll E'$ and at present time probably also $E'_2 \ll E_u$, a positive⁶ effect of the massive introduction of energy, E_u , into the environment is improbable. In effect the reason for this is a little less obvious. It is related to the fact that the human use of energy is very inefficient from the point of view of "information coupling" per unit energy. In fact man is not able to handle information using less than $\sim 10^{-5}$ J/bit. Considering the value of $\sim 3 \times 10^{-21}$ J/bit required by thermodynamics at room temperature, the relative efficiency is less than 10^{-15} . Surely nature is much cleverer than man in this respect. Hence all the energy E_u is quickly dispersed in the environment, stripped of its information content, and only an insignificant fraction of it can be possibly stored in "information-full" systems, as ecosystems are.

From these observations two operative conclusions can be derived:

- a) - an attempt must be made to identify and evaluate E'_2 (perhaps in the sphere of a special branch of physical science, to which the name "ecophysics" could be associated);
- b) - since a very natural parameter for measuring the quality of natural life is the evolution velocity in time of the information content coupled to the used energy, the values of the associated "Ruffle"

$$R_u = \frac{1}{E_u} \frac{dS_u}{dt}$$

must be obtained for dominant human activities, and used as an important parameter for any operative choice concerning them.

REFERENCES AND FOOTNOTES.

- 1 - Information in Physics was discussed by L. Szilard, Z. Physik 53 58-62 (1925), and by J. von Neumann, Mathemat. Foundations of Quantum Mechanics (Berlin, 1932), Chap. V.
- 2 - C. E. Shannon and W. Weaver, The Mathematical Theory of Communication (Univ. of Illinois Press, 1949), pp. 48-53 and Appendix 2.
- 3 - See for example: L. Landau and E. Lifchitz, Mécanique (Editions MIR, Moscow, 1969), pp. 22-24.
- 4 - C. E. Shannon and W. Weaver, see ref. 2, pp. 67-69.
- 5 - The use of a plant and not of an animal in this example simplifies the discussion as the plant does not change its position and an estimate of material, energy and entropy inputs and outputs can be conceived. However the new cells of the plant differentiate during their growth, so that the separation between ϵ'_1 and ϵ'_2 could pose some problems. To overcome them it is sufficient to add the simplifying hypothesis that at time when the plant blooms (t_2 in the example) the number of not yet differentiated cells is negligible in comparison with the total number of cells in the plant.
- 6 - In order to define "positivity" in an objective way it is enough to consider the effect that would increase the ratio ϵ'_2/ϵ' without decreasing ϵ' , as positive.