THERMODYNAMICS OF THE HUMAN BRAIN

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ABSTRACT The human brain may be regarded as an irreversible system which is constrained by a fixed inflow of free energy in the form of chemical nourishment from within the body and information from the environment. The evolution of the internal spontaneous process may be described as a path on the saddle surface of entropy production rate in the configuration space of the process variables. From any initial state of high entropy production the system evolves towards the saddle point by a series of regessions to temporary minima alternating with fluctuations which introduce new internal constraints and open new channels for regression. The spontaneous regression steps of the process are to be associated with the learning process and the deductive processes of thought since information is necessarily being stored, whereas the fluctuation or nucleation steps are to be associated with the inductive or creative part of the thought process. The state of consciousness is to be associated with the system undergoing regression. If, under certain boundary conditions, the system attains the stable saddle point, a state of unconsciousness is attained in which no change of state variables occurs in time. The stability of this state is indicated by its resistance to perturbation.

INTRODUCTION

In a series of previous papers we have tried to rationalize the behavior of a number of kinetic systems on the basis of the variational principles of irreversible thermodynamics. In the accompanying paper, in particular, (Kirkaldy, 1965) we have noted that the progressive tendencies of terrestrial evolution can be understood in terms of the search of the system for the stable saddle point in the surface of entropy production (rate). We noted further that many biological subsystems are sufficiently circumscribed by their local boundary conditions that their course of development can be understood as a stability-seeking path in a subsurface of the master potential for the earth.

The human brain appears to be an ideal subject for such a thermodynamic analysis. It is a substantially isothermal, isobaric system which for experimentally significant times is supplied with a constant source of free energy. The source is provided by the chemical nourishment of the blood and by the information-gathering channels of the body.

The idea that information and Gibbs' free energy (or negentropy) are equivalent physical quantities seems to have originated with Boltzmann. The idea was further developed by Szilard (1929) and has become a firm part of the thermodynamic literature in the postwar era through the contributions of Shannon and Weaver (1949), Brillouin (1962), and Jaynes (1957*a* and *b*), to name a few. Although the inflow of free energy to the brain may appear as electromagnetic signals or as chemical free energy, the thermodynamic model need not, in view of their physical equivalence, distinguish between them.

THERMODYNAMIC MODEL OF THE BRAIN

The kinetic free energy balance for an isothermal, isobaric kinetic system takes the form

$$\frac{dF}{dt} = -\int_V \operatorname{div} j_F \, dV - T\frac{d_iS}{dt} \quad (1)$$

where dF/dt is the rate of increase of free energy. The second term containing the free energy flux, j_F, represents the excess of free energy inflow over outflow. The last term represents the rate of dissipation of free energy within the system and is numerically equal to $-Td_iS/dt$ where d_iS/dt is the rate of entropy production. It is particularly to be noted that the Gibbs' free energy is not a conservative quantity.

We write equation 1 alternatively in the form

$$\frac{dF}{dt} = (J_{I1} + J_{C1} - J_{I2} - J_{C2}) - T\frac{d_iS}{dt}, \quad (2)$$

where J_I represents a total free energy flow as information (or radiation signals) while J_C represents chemical forms of free energy flow through the surface. *1* and *2* represent inflow and outflow, respectively. The balance is indicated schematically in Fig. 1. The idealized thermodynamic model assumes the free energy inflow to

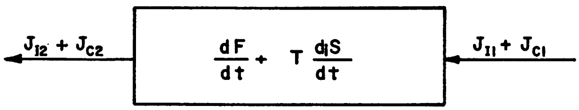

FIGURE 1 Thermodynamic model of the brain.

be a fixed boundary condition and within this constraint the system migrates from any prescribed initial kinetic condition along a quasi-steady path ($dF/dt \sim 0$) in the search for the stability point in the surface of entropy production in the configuration space of kinetic variables (fluxes or forces). This search may follow regressive paths by diffusion or chemical reaction, in which the tendency is to minimize the entropy production, or the system may open new channels for the search by random nucleation of internal constraints which institute intermediate states of higher entropy production. The situation is indicated schematically in Fig. 2.

THE LEARNING PROCESS

Consider for the sake of argument a brain which has suffered complete amnesia, but which is otherwise functional. At time, $t = 0$, we switch on the external source of free energy (J_{I1}) which takes the system to an initial state, A, (Fig. 2) and the

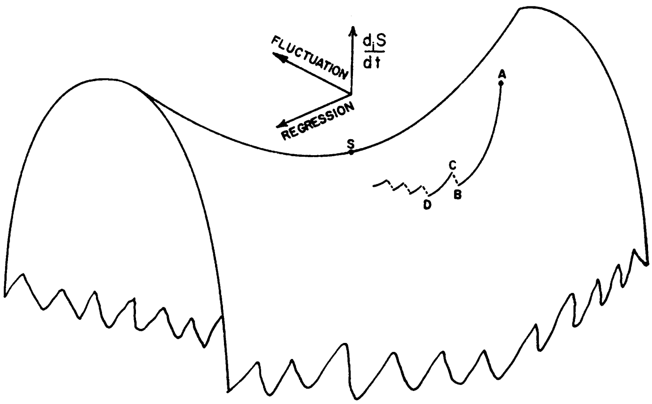

FIGURE 2 Schematic saddle surface of entropy production rate showing a spontaneous path corresponding to the thought process.

system thereafter proceeds by regression and fluctuation towards the saddle point, S. Let us assume that the first step is a regression towards a temporary minima at B and refer to equation 2 for a description of this regression. It is to be generally expected that there will be a lag in the adjustment of surface fluxes to spontaneous changes in the potential, d_iS/dt. Thus, dF/dt will be positive during this regression resulting in a gradual accumulation of free energy within the system (Prigogine, 1955). It is this storing of free energy (or information) which constitutes the learning process and its persistence which constitutes memory. In the chemical sense, the system must be tending towards an increasingly supersaturated state and therefore towards instability against nucleation fluctuations.

As the system approaches a temporary minimum at point, B, dF/dt must take its zero steady state value. With $J_{I1} + J_{C1}$ fixed, the outgoing free energy flux, $J_{I2} + J_{C2}$, must increase to a steady value which matches the prior adjustment of d_iS/dt. The system must therefore return more free energy to the chemical sources in the body or increase the information flow (J_{I2}) out of the brain. Thus, the process of learning, which is a spontaneous process, necessarily leads to a change in behavior.

Since point B, is shown as lying off the saddle curve it is macroscopically unstable. The system is therefore likely to show broad fluctuation excursions in a search for a channel which carries it closer to the saddle point. It can achieve this by nucleating a new metastable internal constraint (probably a macromolecular complex) which causes a spontaneous increase in the entropy production to point, *C*. If this is a successful fluctuation new channels of regression will be opened and the learning (or storage) process will continue on the path to point, *D*. This fluctuation step represents the act of concept formation, and is the key to understanding of the creative process.

THE CREATIVE PROCESS

There is general agreement (Ghiselin, 1952) that the mental state which precedes a creative act is best described as one of uncertainty and confusion. This picture is quite consistent with our view of this state as an unstable minimum of the kinetic potential function which is undergoing rather broad fluctuations.

For simplicity, let us consider a situation in which the external source of free energy is cut off and the system lies in an unstable state like *B* which is close to a local minimum. In this state the system will undergo fluctuation excursions as the continuous source of chemical free energy and stored information interact and interchange. If the system succeeds in a further slow regression at this stage we recognize this as the process of analysis which precedes the synthetic step, for the system increases its stored free energy by increasing the organization of the current stores of information with the help of the incoming chemical flow. The synthetic, inductive, or creative step involves the nucleation by fluctuation of a metastable internal state or constraint which instantaneously increases the entropy production. If this is a successful fluctuation, the system will begin to regress towards a new minimum which is closer to the stability point. If not, the system may evolve by further fluctuations and regressions back to the original unstable state.

The consequences of a successful fluctuation, which corresponds to the inductive formation of a useful concept or synthesis, can be investigated with the help of equation 2. Assuming, as before, that the external fluxes respond slowly to the internal fluctuation, dF/dt will suddenly become negative. That is, the system is instantaneously forced to draw on its internal sources of free energy to sustain the increased dissipation. This may come from the chemical stores in the blood of the brain, but it can also come from the information stored in the memory. This latter result corresponds to the rejection of prior information which is inconsistent with the new synthesis or concept formed.

As regression proceeds towards a new minimum of d_iS/dt, dF/dt will ultimately change sign and information storage or learning begins again. This regressive stage of the intellectual process is to be associated with the process of deduction following an inductive step. When the new unstable minimum is reached, dF/dt becomes zero and $J_{Is} + J_{Cs}$ must attain an increased value. To the extent that the increase involves the term J_{Is}, the behavior of the organism will be altered. The increase in the value of this term might, for example, lead to the commitment to paper or verbal presentation of the excess free energy.

CONSCIOUSNESS

In the thermodynamic model, consciousness is to be equated with states of instability. Awareness of the passage of time stems directly from regressive changes in the rate of entropy production which are taking place continuously within the brain. Since the regressions are unidirectional in time, so is our subjective sense of time unidirectional. Thus, the universal spontaneous decrease in the rate of entropy production is "time's arrow."[1] Our subjective sense of rate of time passage is associated with the rate of regression of the system. If the rate is high as when a new source of information is imposed on the system, time appears to pass quickly. On the other hand, as the system slowly approaches an intermediate minima which is relatively stable a state of boredom occurs in which time passes slowly (see also Denbigh, 1953).

If the sources of external and internal free energy are cut off or substantially reduced as in the approach to sleep it becomes possible for the system to regress right to the saddle point in its new configuration space. It is this stable steady state which signifies the mental state of complete unconsciousness. Since no change in the state variables takes place in this state our index for the passage of time vanishes. The resistance of this mental state to external perturbations supports the view that it represents an exceptionally stable steady state.

RESPONSE TO FAMILIAR STIMULI

A brain with a deep pool of stored information is continually encountering incoming information which duplicates that already stored. The system is therefore *"a priori"* stable with respect to this source and will try to maintain $dF/dt = 0$, and d_iS/dt at a constant value. Since $J_{I1} + J_{C1}$ has necessarily increased, the system can only accommodate by a corresponding increase in $J_{I2} + J_{C2}$. There will therefore be an immediate increase of the flow of free energy to other parts of the body. Our alarm and pleasurable responses fall into this class of phenomena.

SOME COMMENTS ON MECHANISM

The current advances of the microbiologists in elucidating the biological mechanism provide an encouraging complement to the present thermodynamic considerations. The contributions to date have been primarily structural in nature, the mechanisms of regulation and development thus far eluding comprehension (Bonner, 1960). It is our view that this gap in the mechanical description will only be filled by an increased understanding of cooperative molecular processes and chemical stability

[1] For an extensive bibliography on time and entropy, refer to Grünbaum (1955).

in organic systems. There is a store of knowledge in the inorganic field referring to phase transitions, order-disorder phenomena, nucleation and growth, and to the stability of hydrodynamic and chemical systems which must be the starting point for advance in the kinetics of complex biological systems. Until such time as these cooperative mechanisms become elucidated we must be satisfied with the thermodynamic method of description of regulation and development, in the present or some more advanced and inclusive form. Just as the free energy minimum principal is used, in the absence of detailed kinetic knowledge, to relate and correlate equilibrium states in time, the principles of irreversible thermodynamics can serve this function for steady states.

The rapidly developing view that the molecular elements of the genetic mechanism are also involved in the memory process (Hyden and Egyhazi, 1962) suggests the exciting possibility of a physical synthesis of the processes of general evolution and the evolution of knowledge, in complete vindication of Huxley's (1957) philosophic views in the matter. The existence of inherited behaviorism is a long standing sign in this direction. Such a synthesis is strongly suggested by the close analogy between the thermodynamic description of terrestrial evolution and the processes of the brain presented in this and the accompanying paper.

The research program on irreversible processes is supported by a grant from the National Research Council of Canada.

Received for publication, March 1, 1965.

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