

An interpretation of intelligence based on mathematical integration of elementary mechanisms in biology.

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Abstract - Although it is more and more well accepted that modeling is a help for experimental biology, little is known about how to integrate physiological processes in general. The fact that no general theory exist in biology has big consequences, the most important being the difficulty to integrate biological phenomena. I will present a solution for the three dependent following issues: i) in an appropriate theoretical framework, integration consists in coupling models that each describe physiological mechanisms (formalization is a necessary condition to integration); ii) a biological theory with its own concepts leads to unifying principles in biology that are different from and complementary to physical principles; iii) such a formalized theory consists in a *representation* in terms of functional interactions and a specific *formalism* (S-Propagator).

Hence a biological theory is of a topological and geometrical nature, in contrast to physical theories that are of a geometrical nature. An application to the interpretation of intelligence is proposed, based on the "intelligence" of movement.

I. HIERARCHICAL REPRESENTATION FOR A BIOLOGICAL THEORY OF FUNCTIONAL ORGANIZATION

A. The conceptual framework: functional interactions, 3D representation

In the course of our work on physiological models, ranging from the molecular to the organismal levels [1], some novel ideas specific to the study of biology have been introduced, in particular the concepts of *non-symmetric* and *non-local functional interactions* in hierarchical space [2]. These basic concepts emerged from a 'bottom-up' approach to living systems, i.e. from a systematic study of *isolated* physiological functions, followed by the *integration* of these functions at the level of the organism. A significant consequence of this theory is that living organisms can be given not only a double organizational representation, simultaneously structural and functional, but also a double mathematical representation, simultaneously geometrical and topological.

The usual definition of a physiological function such as vision, digestion, memorization and so on, is unfortunately not operational. I have defined a physiological function as a set of functional interactions between structures. Such functional interactions describe the action between two structural units. The *source*, for example u_i , acts upon a *sink*, u_j , after the action has undergone a transformation in the source. This interaction, called an *elementary function*, is represented by ψ_{ij} and constitutes an element of the mathematical *graph* representing the organization of the formal biological system (O-FBS). The dynamics of the functional interactions are then described by a system of equations of the type:

$$\dot{\psi}_{ij} = f_{ij}(\psi_{12}, \psi_{13}, \dots; \rho_1, \rho_2, \dots), \quad i, j = 1, \dots, p \quad (1)$$

where the ρ 's are specific physical or geometrical parameters for the *structural units* defined as the sets of anatomical or physical elements intervening in the physiological function.

This action clearly possesses the property of *non-symmetry*, but also that of *non-locality*, a notion somewhat more difficult to appreciate since it stems from the structural hierarchy of the system [3], i.e. certain structures are included in others. It may be explained as follows. (i) From a mathematical point of view, in a continuous representation, the action of one structure on another is necessarily the action of one point on another. This does not correspond to the action of one cell on another in physical space since a cell contains regions with specialized functions and therefore cannot be reduced to a point. (ii) The interaction between one structure and another has to operate across other structures, which we have called *structural discontinuities*, within which the processes follow a *different* course. Thus, other levels of organization in the hierarchical system contribute to the working of a given structure at a given level in the hierarchy.

The same reasoning applies to the dynamic processes of functional interactions operating in the whole organism, e.g. between neural groups or between endocrine glands. We have formulated the hierarchical theory of functional organization as follows [2]: *in a multiple-level hierarchical system, each functional interaction is described by the transport of an activating and/or inhibiting signal (in the form of an action potential, a hormone or some other type of interaction)*

between a source and a sink, and each physiological function results from a combination of such interactions. This idea can be conveniently expressed in terms of a field theory according to which an operator transmits an interaction at a certain rate from a source to a sink situated in the space of units, with the source and the sink each being reduced to a point (see below).

In this framework, a physiological function is represented by a mathematical graph in which the nodes correspond to the structural units and the edges correspond to the oriented, non-symmetric interactions. They are linked relatively to space, which is evident, but also to time, which represents the decoupling of physiological functions with respect to time. Each level of the functional organization will correspond to a particular physiological function, i.e. a process that occurs on a certain time scale (as the intricate time loops of the algorithm that represents the working of the function). We therefore consider the structural hierarchy and the functional hierarchy of the system.

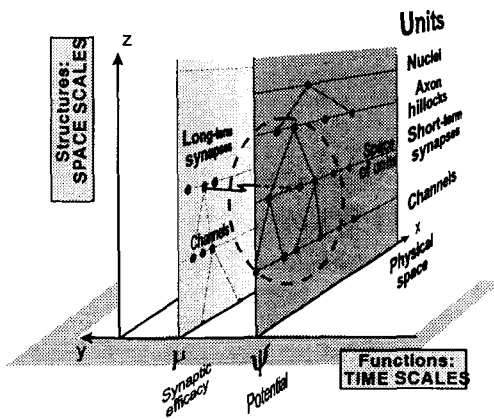


Figure 1

This "separation" may be viewed as follows. Using axes for the space scales, the time scales and the space of structural units (Fig.1), we have a three-dimensional representation of a physiological function, showing:

(i) The structural units in space for a given function; and the hierarchical organization of physiological functions for a given space scale.

(ii) The integration of physiological functions, i.e. the identification of the couplings between the functions, requires determination of the functional interactions at the different hierarchical levels involved.

For example, the interactions at the molecular level between angiotensin and renin will be situated at the lowest level of the hierarchical organization representing blood circulation, and will themselves be coupled with the neural network. This complex task can only be undertaken using the highly abstract and technically advanced mathematical methods presented below.

B. The S-Propagator formalism describes the dynamics in the structural organization (D-FBS)

Within the theoretical hierarchical framework described above, a physiological process, is expressed as the transport of a field variable submitted to the action of a field operator. Let $\psi(r,t)$ be the field variable defined in the r -space, e. g. membrane potential, and let \mathcal{H} be the field operator which depends on ψ and on successive derivatives $\psi^{(n)}$ with respect to time and space coordinates. The general form of the field equation is given by:

$$(\mathcal{H}(\psi^r, \psi^{r,(n)}, n=1, 2, \dots)\psi^r)(r,t) = \Gamma(r,t) \quad (2)$$

where superscript r denotes the level and Γ is the source term [2]. In this equation, \mathcal{H} describes the propagation of the field variable ψ from r' to r , and the local transformation in r is represented by $\Gamma(r,t)$. Since the operator acts from one point in space onto another, it must take into account the distance between these two points, and thus include an interaction operator.

The units u_i and u are assumed to be at level r in the structural organization (space scale κ), and at level T in the functional organization (time scale T). The couple (κ, T) in the 3-D representation defines the organization of the physiological function ψ . There is a structural discontinuity between the two units u_i and u . As shown in Figure 2, in going from u_i at r' to u at r , the non-local functional interaction represented by the field $\psi(r,t)$ [where $r(x,y,z)$ is the coordinate in the space of units referred to coordinates (x,y,z) in the physical space] must cross the structural discontinuity at the lower level, i.e. it must use processes "outside" the level. Using operators, the local time-variation may be expressed as:

$$\mathcal{H} \psi^r = \Gamma \quad \text{with} \quad \mathcal{H} = \frac{\partial}{\partial t} - D\nabla^2 - \mathcal{H}_l \quad (3)$$

where \mathcal{H}_l is the non-local operator. This equation governing the transport of the interaction constitutes the basis of a new formalism [4] involving what we have called structural propagators (S-propagators). It leads from Eq.3 to the local time and non-local space equation for the dynamics of the field variable ψ :

$$\frac{\partial \psi^r}{\partial t}(r,t) = \nabla_r (D^r \nabla_r \psi^r(r,t)) + \int_{D_r(r)} \rho^r(r') P\Psi(r) P(r') \psi^r(r', t - \frac{d(r',r)}{v_r}) dr' + \Gamma_r(r,t) \quad (4)$$

where the summation is on the domain $D_r(r)$ of the u -units connected with the units at r . Here, D^r need not be constant, as the medium may not be homogeneous, in which case the term may be space-dependent; the time scale is T , and $d(r',r)$ is the distance between r' and r in the space of units u . The S-propagator describes the functional action of u' at r' onto u at r per unit time,

B. The cerebellum and the 'intelligence of movement

The knowledge we have of our body's movements in space is a cognitive function. A typical manifestation of this function is the coordination of movements during locomotor activity. Clinical and experimental studies have established that this coordination is due to cerebellar activity. But can the anatomical structure of the cerebellum and local physiological mechanisms, such as nervous transmission and synaptic plasticity, account for the learning and the memorization as well as the coordination of movements? Does this correspond to intelligent activity as defined above? The coordination of a given movement M with a set of movements M_i requires the following operations (expressed mathematically below):

1. Memorization of movements M_i on the basis of experience, as for example in the case of a child learning to walk;
2. Stimulation by a given movement M , a movement made necessary when confronted by an unexpected situation, such as an obstacle;
3. Situation of the movement M within the *context* of the learned movements M_i ; and
4. Making a decision, i.e. choosing the correct context M_{io} with the environmental constraint imposed by M .

C. Extension to a definition of intelligence

We may extend the previous derivation of the intelligence of movement to any process of understanding an event E . Intelligence thus requires the following steps:

1. Memorization of the experimentally acquired elements (learning) of E ;
2. Cognitive stimulation corresponding to E ;
3. Situation of E in its appropriate *context* in the memory; and
4. Establishing relationships (explication) between E and other memorized contexts.

The last step may lead to satisfaction (or dissatisfaction) according to the adequacy (or inadequacy) of the explication. We thus have the notion of intelligence as a set of operations that allows learning through the comparison of present and past experience. Such an interpretation has also been given by R.C. Schank [9] on qualitative bases.

Therefore, intelligence, even under the computer-style algorithm above, is based on a set of neuro-physiological mechanisms. We may then affirm that intelligence can be considered as a physiological function. In this case, there would be no difference between intelligence viewed as a function producing reflection (or rather a cycle of reflections), and, for instance, respiration as a function producing energy to maintain the organism.

The definition of intelligence as a physiological function has the advantage of bringing intelligence

within the scope of a physiological theory that allows rigorous experimentation and measurement. Moreover, intelligence can then be readily related to the functions of memorization and learning on a neurobiological basis.

III. CONCLUSION

In a systemic approach, the anatomical distribution of neurons and the associated neurophysiological mechanisms generate the mental activity that leads to abstract decision (e.g. the formulation of a problem) or to locomotor action (e.g. a movement of the hand). The generalization of the 'intelligence' of movement to an intelligent activity constitutes the basis of our definition of intelligence as a physiological function in a rigorous theoretical framework. In other words, locomotor activity and abstract activity may be considered identical from the neurobiological point of view, and may be treated using the same theory [10].

References

- [1] Chauvet G. A., *Theoretical Systems in Biology: Hierarchical and functional integration*, Pergamon Press, 1996.
- [2] Chauvet G.A., Hierarchical functional organization of a formal biological system. I-III. *Phil. Trans. R. Soc. Lond. B.*, **339**, 425-481 (1993).
- [3] Chauvet G.A., Non-locality in biological systems results from hierarchy. Application to nervous system, *J. Math. Biol.*, **31** (5), 475-486 (1993).
- [4] Chauvet G.A., S-propagators: a formalism for the hierarchical organization of physiological systems. Application to the nervous and the respiratory systems. *Int. J. General Systems*, **28**(1), pp. 53-96 (1999).
- [5] Chauvet G.A., Biological intelligence and computational intelligence, *Encyclopedia of Life Support Systems (EOLSS)*, UNESCO (2001).
- [6] Chauvet P., Chauvet G.A., Purkinje local circuits with delays: Mathematical conditions of stability for learning and retrieval, *Neural Networks*, **12**, pp. 59-77 (1999).
- [7] Daya B., Chauvet G.A., On the role of anatomy in learning by the cerebellar cortex. *Mathematical Biosciences*, **155**, pp.111-138 (1999).
- [8] Chauvet G.A., On associative motor learning by the cerebellar cortex: From Purkinje unit to network with variational learning rules, *Math. Biosciences*, **126** (1), 41-79 (1995).
- [9] Schank R.C., *Dynamic memory: A theory of learning in computers and people*, Cambridge University Press, Cambridge, 1982.
- [10] Chauvet GA (2002) On The Mathematical Integration Of The Nervous Tissue Based On The S-Propagator Formalism. I. Theory. *J. Integ. Neurosci.* 1:31-68.