BIOLOGICAL INTELLIGENCE AND COMPUTATIONAL INTELLIGENCE

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Contents

Summary

Historically, the concept of intelligence has often been presented in philosophical and psychological terms. Today, biological intelligence may be defined in physiological terms on the basis of the anatomical structures involved, taking into account the

mechanisms of learning and memory. This method leads to a very general, algorithmic definition of intelligence (the advanced mathematics required are succinctly presented and may be skipped at first reading). Research on the cerebellum and the coordination of movement demonstrates the validity of this approach. Thus the "intelligence" of movement may be considered as a particular case of the general phenomenon of intelligence. Further, the neurophysiological investigation of biological intelligence allows a comparison to be made with computational intelligence. Intelligent activity may be implemented on a computer in two ways: (i) by means of a program derived from a mathematical model of intelligent activity (e.g. pattern recognition); and (ii) by means of processors with an architecture designed for an analogical representation of the physiological function. Such neuromimetic circuits may eventually be used for the replacement of deficient organs in medicine or even for the execution of human functions by machines. The brain and the computer could then be profitably compared from the standpoint of the cognitive sciences.

1. Introduction

What is intelligence? Although the term has long been commonly used, the notion behind it is peculiarly difficult to define. Intelligence, once believed to be a defining characteristic of the human condition, was supposed to distinguish mankind from other forms of life. Today we know this to be untrue since current research on various animals, particularly primates, has demonstrated that these too are gifted with intelligence, albeit to a lesser degree than humans.

A sound definition of intelligence would surely help to avoid metaphysical problems and open up a scientific approach to the field of psychology, and possibly to that of neurobiology as well. However, this calls for a general theory encompassing not only the mechanisms of memory and learning but also the working of the mind and the state of awareness. This gigantic task would need a conceptual framework within which all these different aspects could be formalized. Although the intuitive notions of memory, learning, consciousness, and intelligence are obviously linked, the main difficulty lies in determining the precise nature of the interrelationships involved. If we consider the psychological aspect alone, taking into account merely the activity observed, the consequences deduced from such operations as "producing A under the conditions B and C, without considering D" might suffice to produce a reasonable definition of these notions. But if we wish to elucidate mind-body relationships we must investigate the neurobiological aspects of intelligence.

We shall therefore use a systemic or cybernetic approach to define intelligence, based on the actual support of the cognitive functions, i.e. the anatomic properties of the brain (see *Psychological and Cultural Dynamics of Sustainable Human Systems*). Thus, from the wider standpoint of living processes, the main question is whether intelligence is in fact a physiological function. If so, can it be coupled to other cerebral functions to produce an operational definition that could eventually be used to qualify the "intelligence" of a machine? This paper will explore the central role of biological intelligence and extend the results first to the field of computational intelligence, and then to the larger domain of artificial intelligence.

The importance of these studies is evident. The definition, or better still, the representation of cerebral intelligence in the form of an algorithm would enable the construction of neuromimetic circuits capable of implementing the processes underlying intelligent activity. These circuits could then be implanted in the brain so as to compensate for certain human handicaps by the programmed execution of appropriate adaptive processes. Clearly, the social and philosophical issues raised by such innovative techniques would be formidable.

A good understanding of intelligence requires knowledge of the historical background and the ideas that have contributed to the notion of intelligence. The early philosophical approach to human intelligence dates back at least to the Middle Ages. From the late nineteenth century onwards, scientific investigation led to the development of psychological intelligence tests that were often used—or rather misused—without any clear-cut definition of intelligence, throughout the twentieth century. Indeed even Alfred Binet, the French physiologist who invented psychometric testing, could offer no more than a circular definition stating that intelligence was precisely what his tests measured.

Today, the three main approaches to intelligence are based on psychometry, Piaget's structural theory and information processing. We shall present these in the following sections before discussing a novel physiological theory of intelligence. To simplify the presentation for non-mathematical readers, the essential mathematical tools used are described in section 4.1.4 and the corresponding equations have been grouped together in Tables 1 and 3. Finally, we shall compare biological intelligence with artificial intelligence. (See *Structure and Function of the Brain* and *Complexity in Biological Evolution*.)

2. Historical Concepts of Intelligence

In contrast with the stereotyped nature of instinctive behavior, intelligent activity is based on the property of plasticity, involving the operation of modifiable neural circuits (see *Adaptive Systems*). Intelligence allows the construction of abstract objects leading to the elaboration of systems of thought distinct from real systems, in other words the creation of *models* obeying operational rules. From this point of view, mathematics and logic are perfect examples of intelligent activity. In fact, all abstract constructions are governed by operational rules, whether we consider creative work in literature or art, or science.

Abstract construction is reinforced by *intuition*, a nobler aspect of intelligence. The act of intuition may be thought of as an idea that emanates at a given instant from a set of mental representations. Mental creation and intuition are activities that certainly characterize human intelligence, but which nevertheless elude analysis. Abstract construction, intuition, and creation are the three expressions of intelligence that raise questions concerning divinity, living organisms, and machines. For instance, are animals capable of intuition and creative intelligence? Perhaps not, in general, although some higher mammals, such as chimpanzees, are known to be capable of responding to environmental changes through simple but apparently intelligent actions. Then again, a machine equipped with an adaptive neural network might similarly be credited with making “decisions“. But could it actually be considered intelligent? Obviously, intelligent activity may be expressed in various ways and may be of different degrees. We therefore need a theoretical framework within which intelligence can not only be defined but also quantified.

The definition of intelligence raises a further question. Can intelligence be considered as a unique function, in the physiological sense, or is it the product of a set of independent mechanisms which, when combined, lead to intelligent activity? However, we must first lay down a general definition of a physiological function. It should be noted that since observed intelligent activity is a manifestation of intelligence, the science of psychology may be able to evaluate this activity by means of psychometric tests, but it can hardly be expected to provide a satisfactory definition of intelligence.

In the sections that follow, we propose to develop a theory (i.e. a conceptual framework) for the definition of intelligence and offer an interpretation of intelligent activity. However, intelligence should not be thought of as being restricted to the nobler aspects of abstraction, creation, and intuition mentioned above. Indeed, *physical* activity should also be considered as a manifestation of intelligence.

In a sense, the relationship between intelligence and *awareness* would appear to be evident since intelligent activity can only be envisaged at the conscious level. If this were not the case, the activity would be merely due to an instinctive reflex, independent of any mental representation.

The coupling of awareness and intelligent activity generates great difficulty in the interpretation of psychometric tests. Thus behavioral psychologists prefer to evaluate the manner in which a problem is tackled (e.g. by measuring response times, appreciating the techniques used, and so on) rather than the quality of the solution itself. Behaviorists have considerably modified conventional psychology to produce their theory—analogous to Darwin’s theory of natural selection—according to which only adapted behavior is reinforced and selected. Within this conceptual framework, what counts is not the objective but the behavior involved in attaining the objective.

Another interesting approach is due to Jean Piaget, the Swiss psychologist, who introduced the *structural theory* of intelligence. According to this theory, the set of *observable* intelligent actions is considered in terms of a system and the solution to the problem is obtained by determining the relations that govern the system. Piaget states that intelligent activity stems from action, the mental act being in fact an internalized action (i.e. an action executed at the virtual level). This implies a transformation from an initial state to the final state. The structural theory bears on the organization of mental acts and their development, assuming that these acts are elements of a mathematical *group* structure. Direct action and inverse action are treated by the group structure as a usual operation—as a neutral element—which could explain the acquisition of the notion of conservation. Within this framework, Piaget defines three stages: the stage of intuitive intelligence, with the absence of the notion of conservation; the stage of *concrete* operations, differing from the final stage; and the stage of *formal* operations, involving material objects rather than abstract objects. Without going into further details of Piaget’s theory, we may observe that it is not based on any neurobiological elements. In particular, it does not take into account the dynamics of the fundamental processes of cerebral activity: memory and learning.

It is true that psychometric methods have allowed the identification of certain factors of intelligent activity through the use of standardized tests submitted to statistical analysis. However, the common factor that emerged—the *intelligence quotient*—though still widely used, remains controversial and is often considered an unsatisfactory indicator of intelligent activity.

From a more general standpoint, we may conceive of intelligence as a process analogous to other mental processes, all constructed along the same neurobiological principles. In other words, we may extend Piaget’s theory and consider all mental acts, whether related to abstraction or locomotor activity, as governed by the same neurobiological principles. Piaget himself believed that eventually biology would have to explain how logico-mathematical structures are actually assembled in the brain and why they adapt so closely to the external environment.

3. The Neurobiological Bases of Intelligence

As we have seen above, the definition of intelligence poses a number of questions. Given that intelligence is a highly cognitive function from a neurobiological point of view, the study of the underlying physiological mechanisms could lead to a satisfactory definition. While this approach does not necessarily simplify the problem, it promises the advantage of a theoretical framework incorporating the major notions of memory and learning. It would even allow numerical simulations on the basis of appropriately constructed neurobiological models.

3.1 What is a Neural Network? Hierarchy and Functional Units

The field of artificial neural networks has been extensively developed over the past few years (see *Neural Networks*). Each artificial neuron is a mathematical entity possessing two properties: Firstly, the output Y is the sum of the inputs X_i, weighted by the synaptic efficacies μ_i; secondly, the variation of the synaptic efficacy is proportional to the input signal X_i and the output signal Y. In the case of a network of n neurons connected to a given neuron, these properties are mathematically represented by the non-linear dynamic system:

$$\begin{aligned} Y &= \sum_{i=1}^{n} \mu_i X_i \\ \frac{d\mu_i}{dt} &= \alpha X_i Y \end{aligned} \qquad (1)$$

The second equation of this system is known as the *learning rule* of the neural network.

With a given connectivity between neurons, the problem is to determine the mathematical properties of the network related to the learning and memorization of patterns. In fact, several characteristics of neural networks play an important role in learning and memory: the number of neural layers in the network, particularly the inner or “hidden” layers, the number of neurons per layer, and the learning rule. Since the construction of the “perceptron” by Rosenblatt in the 1970s, various other neural networks have been developed, such as Hopfield’s supervised network with its internal dynamics, and Kohonen’s non-supervised, self-organizing network with its feedback and feed-forward loops. All these networks possess specific mathematical properties that unfortunately do not correspond to biological reality. The difficulty arises from the non-linearity of the mathematical systems and the impossibility of finding an analytic solution for a dynamic system involving synaptic weighting. The true complexity of the problem will be readily appreciated when we consider the fact that the artificial neuron and its corresponding network are extremely simple in comparison with the real neuron surrounded by nervous tissue.

Fortunately, from a biological point of view the complexity of the phenomena involved is essentially the same whether we consider a real, isolated neuron or a network of artificial neurons. This idea stimulated the search for a representation incorporating the properties of a real neural network. Early in the twenty-first century, much headway has been made in the mathematical description of a real biological system. The observed hierarchical organization of biological structural units from the cellular to the organismal levels (cell organelles, nuclei, neurons, synapses, neural groups, nervous tissue, and cerebral organs) naturally suggested a hierarchical representation. However, the hierarchical aspect of the corresponding functional organization is far from evident (see *Integrative Systems Methodology*). The novel three-dimensional representation of a biological system that we propose (see Section 4.1 below), with axes for space scales, timescales, and structural units, allows the visualization of the coupling between the structural and functional organizations. This representation is based essentially on the determination of the timescales of the dynamic systems describing physiological functions. The establishment of the functional hierarchy is very useful for the determination of the physiological functions associated with nervous structures. In the case of real neural networks, there are two physiological functions: the propagation of membrane potential on a timescale of the order of milliseconds, and the modification of the long-term synaptic efficacy on a timescale of the order of seconds or even hours. So the functional order observed has its origin in a functional hierarchy that is evidently a manifestation of molecular mechanisms.

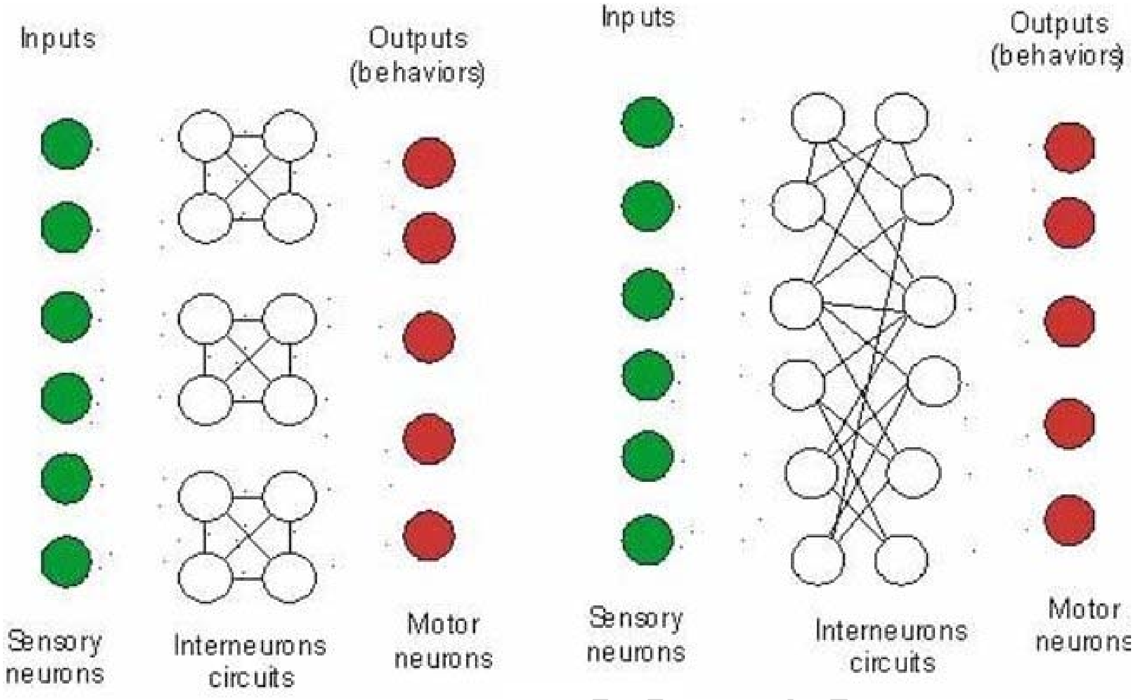

Figure 1. Dedicated (left) and distributed (right) networks (After G. A. Chauvet and P. Chauvet; in *Advances in Synaptic Plasticity*, eds. Baudry M., Davis J. L., and Thompson R. F. (1990). Cambridge, MA: MIT Press, Chap. 12, pp. 277–298).

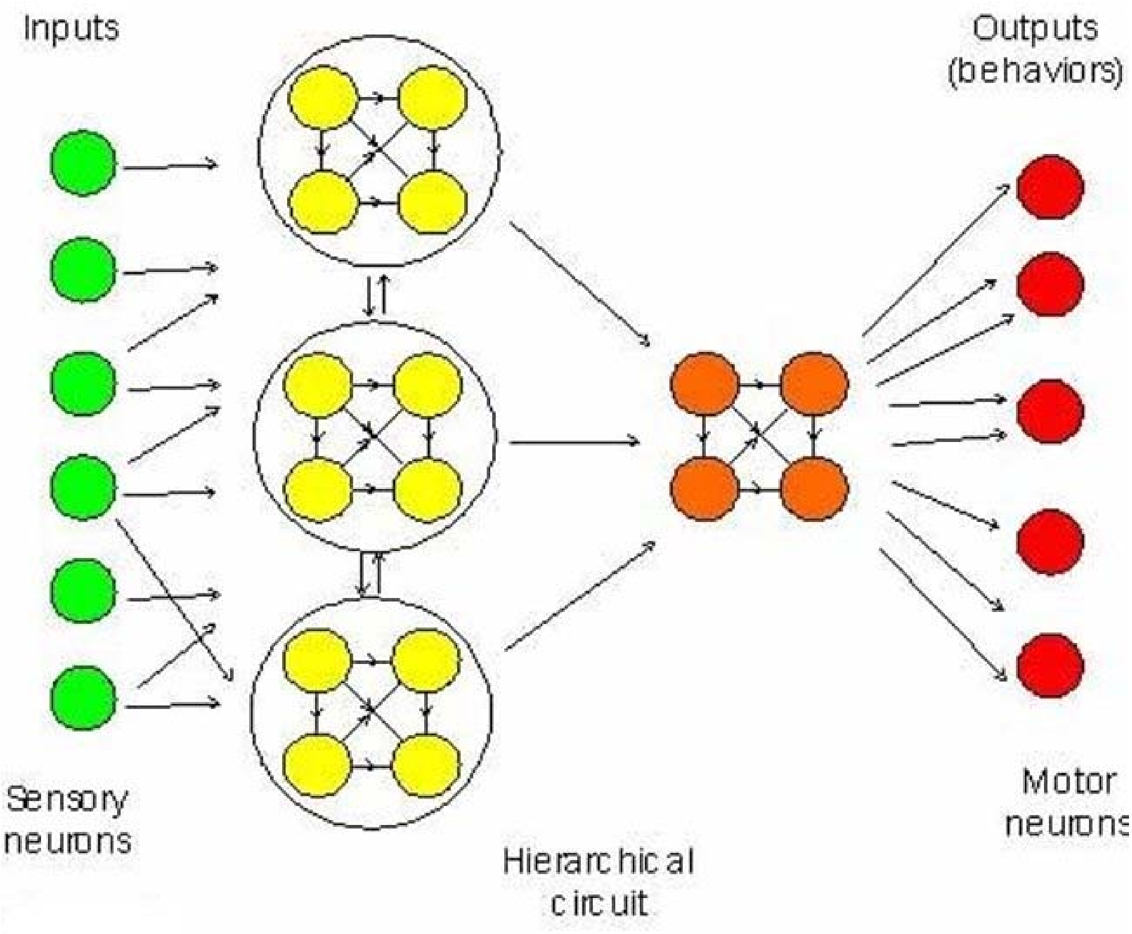

Figure 2. A hierarchical network. Properties emerge from the lower level and appear at the higher level inside a new structure. This new structure is called a functional unit if, and only if, it has a specific (After G. A. Chauvet and P. Chauvet; in *Advances in Synaptic Plasticity*, eds. Baudry M., Davis J. L., and Thompson R. F. (1990). Cambridge, MA: MIT Press, Chap. 12, pp. 277–298).

Typically, the artificial neural networks generally studied have several neuron layers. Figure 1 shows two types of neural network: the so-called “dedicated” network and the “distributed” network. The main difference between these networks is that the structure-function relationship is more evident in the latter. In contrast, the hierarchical network shown in Figure 2 is fundamentally different in nature and, in particular, possesses specific *emergent properties* (properties that appear at a higher level in a new structure). An important advantage of the hierarchical representation is that it offers a rigorous approach to the notion of a *functional unit*, which may now be defined as a structural unit with a specific function at a higher level of organization.

The functional unit, possessing its own timescale, incorporates a new function that can be deduced mathematically from the lower levels of organization in a biological system. For example, a *neuro-mimetic circuit* could be considered a *functional unit*.

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Biographical Sketch

Gilbert A. Chauvet received his B.Sc. degrees in Pure and Applied Mathematics from the University of Poitiers in France in 1964 and 1965, and M.Sc. and Ph.D. degrees in Solid Physics in 1966 and 1968 respectively; he also gained a Ph.D. in Molecular Theoretical Physics in 1974 from the University of Nantes in France. He then obtained his M.D. degree in 1976 from the University of Angers in France. The same year, he obtained the position of Professor of Biomathematics at the University of Angers, and in 1984 was made Director of the Medical Computing Department at the Regional Hospital Center of

Angers. In 1988, he became the Director-founder of the Institute of Theoretical Biology at the University of Angers; he is presently the co-Director of the Integrative Biology Research Center at Tarnier-Cochin Hospital in Paris. Before joining the faculty at USC in 1995, Dr. Chauvet worked as a Research Professor of Theoretical Neuroscience in the University of Pittsburgh from 1989 to 1993, then in USC at Los Angeles (Department of Biomedical Engineering) since 1994. During the fifteen last years, Dr. Chauvet has worked in all the fields of physiological modeling using a “bottom-up” approach, specifically in neurosciences, developing Integrative Physiology, a recent field, the development of which poses difficult and specific theoretical problems for mathematics, physics, and biology. He has proposed a synthesis (“up-down” approach) of his specific models into a theory of functional organization in a series of three books entitled *Theoretical Systems in Biology: Hierarchical and Functional Integration* (1996, Elsevier). This mathematically-based theory is derived from basic biological concepts which are different from the concepts used in physics. Professor Chauvet is currently working in various theoretical functional systems in order to validate the general theory. A specific computing system, VFS Physio*Logicals™*, has been developed on these bases for education.