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SOME REFLECTIONS ON CYBERNETICS AND ITS SCIENTIFIC HERITAGE

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Abstract. The scientific research program of Cybernetics, originated by Norbert Wiener, was mainly concerned with the communication and control whether in living organisms or machines. The main aim was to get useful and essential information on the functioning of the brain on which to construct later a science of the mind. This requires methods and knowledge borrowed from different disciplines including Physics, Biology, and Humanities. The great novelty of Cybernetics was the introduction of a new entity called 'information' of fundamental importance in the theory of communication. However, several different formalizations of the intuitive notion of information exist which depend on the 'context', i.e., the characteristic features of the 'source', of the 'channel', and of the 'receiver'. The context is of a particular relevance in the study of biological systems where there exist sophisticated coding mechanisms which are essential to the information processing, and underlie the high level functions of human mind. At present, still lacking is a theory of information and coding that could be usefully employed for the study of complex biological systems. This was the main reason for the decline of Cybernetics.

1 Introduction What Cybernetics is or was ? In the book "Introduction to Cybernetics" by Luigi Ricciardi and myself [1], at the beginning of the seventies, we refrained from giving a *definition* of Cybernetics and went straight onto some topics of the book which was meant to be only an *introduction* to Cybernetics itself.

In his Preface our maestro Eduardo Caianiello grouped the sciences into three classes, having as their subjects of study respectively Matter, Life, and Intelligence. According to Eduardo, Cybernetics plays among the sciences concerning intelligence a role similar to that of Physics among the sciences studying inanimate nature (see also[2]). For Norbert Wiener Cybernetics is the science of the communication and the control whether in living organisms or machines [3].

Successively, several definitions of Cybernetics were proposed. I remember that the last session of a meeting on Cybernetics held at Namur at the end of sixties, was specifically devoted to propose some acceptable definitions of Cybernetics. In the Website of the American Society for Cybernetics (ASC) more than 40 definitions of Cybernetics are reported[1]. The term Cybernetics, derived from the Greek $\kappa\upsilon\beta\epsilon\rho\nu\acute{\eta}\tau\eta\varsigma$ (meaning *steersman*), was introduced, about one century before Wiener, by the French scientist André-Marie Ampère to mean the art of governing a Society or the *science of government*.

Actually, Cybernetics was more a scientific research program than a science like Physics, Chemistry, or Biology, all having their own language, methods, and basic assumptions. Indeed, the main goal was to apply the powerful methods of Mathematics, greatly successful

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[1] In the Website of ASC it is also reported that C. Shannon has suggested to Wiener in a letter of 1940's to use the word Cybernetics because nobody knows what it means. This would always give him an advantage in arguments.

in theoretical Physics, to the description of highly complex systems, such as neuronal nets. This in order to get useful and essential information on the functioning of the *brain* on which to construct later a science of the *mind*. This project was followed, for instance, by Warren McCulloch and Walter Pitts[4], and by Caianiello[5] in their formalizations of neural networks.

In its very nature the scientific program of Cybernetics was interdisciplinary, in that it involves languages, methods, and knowledge borrowed from different disciplines including natural sciences and humanities. For instance, our group of Cybernetics at the Institute of Theoretical Physics, directed by Caianiello, was of a real interdisciplinary nature, consisting of Physicists, Chemists, Mathematicians, Logicians, Engineers, and Biologists, including collaborators expert in the humanities such as natural languages. Every week we had a very interesting general meeting where research projects were discussed by all of us, each one giving a contribution on the base of its own experience and competence.

The interdisciplinary research program of Cybernetics set the Man at the center of its investigations. This attitude was very similar to that of scientific research at the time of Leonardo, i.e., before the specialization of Science into several distinct disciplines. This is the reason why Eduardo often referred to Cybernetics as to the "new scientific Humanism".

In a way in some respects analog to what occurred to Science after the Renaissance, from Cybernetics several scientific disciplines were originated and, successively, separated. For instance, the theory of finite automata was generated by the pioneering work on neural networks by McCulloch and Pitts. At the present, Automata Theory is an autonomous very well developed discipline strongly related to Algebra (semigroup theory) and Computer Science. Other disciplines, more or less related to the initial program of Cybernetics, are Information Theory- originated from the basic works of Claude Shannon [6] and Wiener[7]-, Formal Language Theory- that stemmed out of automata theory and the works of the linguist Noam Chomsky and the mathematician Marco Schützenberger[8]-, Systems and Control Theory, Bionics, Artificial intelligence, Robotics, and Informatics.

It is noteworthy that in these new formalized disciplines the initial motivations of the problems, of great importance and interest in the original research program, were lost and often completely disappeared. This is the case, for instance, of neural nets in the case of theory of Automata after the work of Stephen Cole Kleene [9].

Cybernetics was quite vital and developed in Italy up to the middle of the seventies. I was lecturer of Cybernetics at the Faculty of Sciences of the University of Naples from 1968 to 1973. Ricciardi became full professor of Cybernetics in 1975. However, since the beginning of seventies the term Cybernetics was less and less used and often replaced by the term Computer Science or by the new term Informatics. At the present, practically no one in Italy and only a few in the world uses the term Cybernetics, neither are there much of university courses or professorship positions, or research groups focusing on this discipline. A noteworthy exception is the CNR Istituto di Cibernetica "Eduardo Caianiello" (Pozzuoli) founded by Caianiello himself in 1969 and presently directed by my friend Settimo Termini.

Why this decline of Cybernetics? Can Cybernetics be considered dead? In my opinion the main reason for decline is that the original research project was much too wide and ambitious, and the results obtained on the main problems (understanding high mental functions like intelligence) were very modest and often far from the effective and practical needs of science and technology.

As stressed by Vittorio Somenzi [10], the difficulties encountered in the realization of the projects of Cybernetics announced at the middle of the fourties have to be attributed in part to their too much interdisciplinary character. Indeed, only towering personalities such as Alan Mathison Turing, John von Neumann, and Wiener were able, on the base of a complete domain of contemporary Mathematics and Logic, to deal with the very rich phenomenology offered by a variety of sciences such as physics, electronics, genetics, chemistry, psycology, economy, linguistics, apparently lacking a common background. Moreover, the tendency to specialization typical of the major part of structures of research and teaching, was an obstacle to the training of professionals who could be full time devoted to subjects originating from several different disciplines.

Some more intrinsic difficulties encountered by Cybernetics in the realization of its research program will be analyzed in more details in the following sections.

In the history of Science, an example of a quick decline of a discipline that, however, arose again after some centuries, is offered by Logic. Born in the ancient Greece, considered as very important and much developed in Middle Ages, it almost vanished during the Humanism and the Renaissance. Still, after about two centuries, Logic underwent new and great developments.

Can Cybernetics, or at least its interdisciplinary research program, rise again? I believe that this will occur. Indeed, there is at present a revival of interest by scientists and philosophers in the main problems left open by Cybernetics; moreover, due to the great and rapid developments of sciences and new technologies that will produce enormous changes in the conditions of the life of human beings in our planet, it will become very important and indispensable to put again, as Cybernetics did, Man at the center of scientific investigation.

2 Information and coding The great novelty of Cybernetics was the introduction, in the setting of the physical sciences, of a new entity called *information* of fundamental importance in the communication of human beings and machines.

Information and its measurement are, however, intuitive concepts which have a wide 'semantic halo' so that several formalizations are possible. Intuitively, information means *minimum amount of 'data' which are required to 'determine' an 'object' within a given class.*

Several approaches have been proposed in order to formalize and quantify the notion of information[2]. Any definition of information requires a suitable specification of the terms 'data', 'determine', and 'class of objects' used in the intuitive definition. These approaches, called *technical, semantic, pragmatic, descriptive, algorithmic, logic, structural, etc.*, are conceptually very different in spite of some analogies, even though often only formal, between the considered quantities. Moreover, some formalizations of the concept of information, though meaningful and interesting, lack a solid mathematical frame in which to evaluate the actual implications of these concepts or find deep theorems.

There exist two main conceptions about the notion of information. The first, that can be called 'entropic', is based on a global 'measure of ignorance' about the state of a system. This measure is called 'entropy' in analogy to the physical entropy[3]. Any determination of the state of a system yields an (average) information proportional to its entropy. The second, that we call 'logic', is essentially based on 'formal logic'. In this case information is related to the 'complexity' required to compute or generate an object of a given class.

Shannon's theory of communication is a beautiful mathematical theory of information originated from the research program of Cybernetics at the end of the fourties. It is based on an entropy measure $H(S)$ that can be associated with any information source S emitting symbols according to some probability rules. The source S is usually described by an ergodic Markov chain. The entropy $H(S)$ can be interpreted as the *average amount of uncertainty in making a prevision* on the event which will occur in a random experiment

[2]A general view of the author on the conceptual aspects of the different approaches to a quantitative definition of the notion of information is in [11].

[3]It was observed by Boltzmann in 1896 in the framework of Thermodynamics, that physical entropy is a measure of the total amount of the 'missing' information about the (miscroscopic) state of a physical system while knowing all the macroscopic information about it.

(the letter which will be emitted from the source). Equivalently, the entropy of S measures the *average amount of information* that one receives from the realization of an event in a random experiment (i.e., the letter emitted from the source). We shall not enter into the mathematical details of Shannon's theory. We limit ourselves only to stress the following general features.

- The importance of the Shannon information theory is doubtless due to the possibility of proving, by making use of the theory of 'ergodic processes', some fundamental theorems (*coding theorems*) on communication and information transmission.
- There is a relation with Thermodynamics. The Shannon entropy is formally similar to the physical entropy. However, there is no equivalent of physical energy.
- The validity of Shannon's theory, or better the meaningful application of it, is confined to *statistical communication theory* which is based on probability theory. Many questions of a great intuitive appeal from the information point of view, do not make sense in the frame of Shannon's theory.
- As stressed by W. Weaver [12], in Shannon's theory only the 'technical problems' of communication are considered while the 'semantic' and 'pragmatic' aspects are not taken into account.

A different approach to information, based on a non-probabilistic entropy, was introduced by Termini and myself in [13, 14, 15]. The 'entropy' gives a certain kind of global 'distance' of a non-Boolean universe (described by *fuzzy sets*) from a Boolean one. It can be interpreted as the *total amount of uncertainty in taking decisions*, where a decision can be viewed as an operator transforming a non-Boolean object into a Boolean one. It is noteworthy that the uncertainty measured by this entropy is not of a probabilistic nature.

As we previously said the concept of 'information' can be based on the notion of 'complexity' of a certain 'mechanical system' able to 'produce' an object belonging to a given fixed universe. A formalization of this notion requires a formal specification of the terms 'mechanical system', 'complexity', and 'produce'. By mechanical system one can mean an 'algorithm', that is a finite list of instructions (or *program*) for an (abstract) machine, or a set of derivation rules of a *formal system*. In the first case the mechanical system makes a 'computation', i.e., if it stops, then produces a unique object after a finite number of steps. In the second case, by using the rules of the system, one can generate at each step more objects. In other terms there is a sort of a 'non-deterministic computation' usually called 'derivation'.

As regards 'complexity', one can refer either to a 'static' or to a 'dynamical' measure. A static measure of complexity is related to the 'size' of the program or of the input in the case of an algorithm and to the 'size' of the set of axioms in the case of a formal system. A dynamical measure of the complexity is related to the 'length' of computation or derivation.

The trade-off between 'information' and 'complexity' requires that one specifies exactly what 'algorithm' and 'complexity' of algorithms mean[4].

In the approach of A.N. Kolmogorov[16] and G.J. Chaitin[17] (see also [18]) 'information' is defined in terms of the algorithmic static complexity (*program complexity*)[5] as follows.

[4]We recall that at about the same time (1936) Alan Turing, Alonzo Church, and Emil Post, mostly independently of one another, provided different formalizations of the intuitive notion of algorithm. They all have been proved to be equivalent to that of *Turing machine* in the sense that they yield the same class of 'effectively computable' functions (*partial recursive functions*) (see [20]). A solid mathematical theory of algorithmic complexity was developed in the frame of the theory of algorithms (see, for instance, [21]).

[5]A similar but different approach based on dynamic complexity measures in the framework of the theory of formal systems is outlined in [19].

The objects are identified with strings (or words) on a finite alphabet and the algorithms with Turing machines. The *program-complexity* of an object x given the object (input) y is the minimal size (length) of a program p of a (universal) Turing machine U able to compute x starting from the input y, i.e., $U(p, y) = x$. This quantity is denoted by $K_U(x/y)$ and interpreted as the amount of 'additional information' needed to obtain x starting with the input y (the subscript U denotes the dependence on the universal machine U). If the input y is the empty string ε, then $K_U(x/\varepsilon)$ is called the (absolute) program complexity of x and is simply denoted by $K_U(x)$. The difference

$$K_U(x) - K_U(x/y)$$

is interpreted as the *quantity of information* conveyed by y about x. We stress the following features of the Kolmogorov-Chaitin approach.

- The algorithmic approach is based on the theory of recursive functions that is a very solid and well developed mathematical theory.
- There is the possibility of defining 'random' objects as those for which the program complexity is approximately equal to the size of the object. Random objects pass all conceivable statistical tests.
- There are many analogies often only at the formal level, with Shannon's information theory.
- The theory is an asymptotic theory. Indeed, the program complexity $K_U(x)$ is defined for a single object only up to an additive constant (depending on the universal machine U).
- Even though it is very important from a conceptual point of view (trade-off between information and complexity) the program complexity is not much utilizable in practice.

We remark that the interpretation of the program complexity as an information measure is completely different from the notion of information of Shannon's theory. For instance, in the probabilistic setting of this latter theory, a question like "what is the content of information conveyed by a string y about the string x?" is meaningless.

The notion of 'information' thus possesses several different facets so that, differently from physical entities, there is not a unique definition of it. Moreover, it seems that this notion cannot be independent of the 'context'. Here, the term context is used in its most comprehensive acceptation. It includes the 'source', the 'channel', and the utilization of information and thus it strongly depends on the characteristic features of the 'receiver'.

This dependence on the context is of particular relevance in the study of biological systems where there exist 'sophisticated mechanisms' that are essential to the information processing. These mechanisms are sometimes 'coding processes'. The most famous is the genetic coding mechanism. By means of this a sequence of bases of DNA (gene) written over an alphabet containing the four bases A (*adenine*), T (*thymine*), C (*cytosine*), and G (*guanine*), is transformed into a protein, i.e., a sequence over a 20-letter alphabet (*amino-acids* alphabet). As is well known the genome contains all 'genetic information' about a living organism and, moreover, it is able to control the activity of different genes by this coding mechanism. As we shall discuss in more details in the next section, also the 'brain' and especially the 'cortical areas' have complex and specialized mechanisms in order to analyze and process information.

It seems that 'Life' is the only known case, in the great variety of phenomena of the physical world, in which there exist some 'natural' coding mechanisms such as the genetic code. The natural origin of these mechanisms is very surprising and extraordinary since the coded objects are often very different from the uncoded ones (for instance, genes and proteins) and coding is an operation which, in general, implies the existence of an 'intelligent' mechanism, or an entity, that makes the coding map. Moreover, Biology seems to show that any definition of information cannot be independent of the 'semantic' and 'pragmatic' aspects of communication, which are strongly related with its utilization[6]. However, at present there does not exist a theory of information and coding that could be usefully employed for the study of complex biological systems.

3 The mind as a 'mechanism' of the brain As is well known the central nervous system, both of humans and of animals, with very few exceptions, is a hugely complex system. The aim of this section[7] is to give at an intuitive rather than formal level, some general ideas and to formulate some hypotheses on the very sophisticated mechanisms of functioning of the brain. From this will stem out, I hope, the reason for the profound difficulty encountered by Cybernetics in its attempt to provide an effective model of human brain and its functions by using whether the mathematical techniques that work so well in Physics and in System theory, or Information theory as up to now developed.

The main thesis that will be sustained is that if one regards the human brain as a machine, then the high level functions of the mind, such as *abstraction, consciouness, intelligence, learning, memory*, that are at the base of the *human thinking*, are of fundamental importance for a very efficient behavior of the cerebral machine. For this reason the title of this section inverts the traditional and usual roles of the *brain* and of the *mind*, i.e., the mind is not like a program or software running in the brain-machine that is the hardware of the human computer, but, on the contrary, the mind is an essential part of the 'mechanism' of the brain.

The nervous system of human beings is a collection of about 10 billion neurons occupying a volume of about 1 liter. Each neuron can receive stimuli from a few or many other neurons through the *synaptic junctions* and can send electrical stimuli (excitatory or inhibitory) to other neurons. In some respects the structure of a neural net can be considered similar to that of a digital computer[8]. However, the diversity between the functioning of the brain and that of a digital machine is huge. In fact, only some kind of neurons, dislocated mainly in peripheral areas of the nervous systems, such as *eye, ear, cerebellum, spinal cord*, have a behavior in some respects similar to that of the logical elements of a computer. This similarity vanishes if one considers the behavior of *cortical neurons*. Indeed, each of these neurons, such as *pyramidal cells*, can receive stimuli coming from more than a hundred thousand neurons and can stimulate a large number of other neurons[9]. The behavior of these neurons appears to be more analogic than digital.

Neuroanatomy and neurophysiology, by using powerful modern tools[10], have led to a great increase of our knowledge of the nervous system. However, up to now they are still

[6] A recent, very intriguing, analysis of the semantic of "information", mainly in regard to biological systems, has been done by Valentino Braitenberg in [22]

[7] The material of this section is a part of an unpublished manuscript (in Italian) of the author, written in 1982[23].

[8] An analysis of the analogies and differences existing between computing systems and living organisms was made by von Neumann in 1958 in a delightful booklet written just before his death [24].

[9] An excellent book by Braitenberg and Almut Schütz [25] is a precious reference for the statistics and geometry of cortical neurons.

[10] At present neurophysiology uses powerful instruments for the analysis of the activity of the brain such as the PET (positron emission tomography) and the functional magnetic resonance.

unable to give meaningful answers to the understanding of brain's activity mainly concerning the 'location' and the 'mechanisms' of high mental functions. Indeed, the cerebral cortex is a tremendously complex system with an enormous flux of information across its elements that interact according to non-linear laws. From the mathematical point of view any quite realistic model of its activity is not easily dealt with and hence it is not effective; from the experimental point of view it is very difficult to establish a precise correspondence between some external stimuli (conveyed by sensorial neurons, or by electrodes) and the activity of single neurons or small portions of the central nervous system.

If one limits oneself to considering only some peripheral areas of the brain, the above correspondence can, to a certain extent, be established. For instance, in the cases of ear and eye, starting from sensorial neurons and following the nervous fibers up to a certain level, it is possible to find some correspondence (often a one-to-one map) between the characteristic features of the stimulus and the activity (frequency) of single neurons or "neural pools".

The attitude of making a correspondence between an input (stimulus) and an output (electrical activity) is typical of a system analyst. Conceptually, it does not differ too much from the point of view of René Descartes[11] who tried to explain the human vision by making the simple correspondence between a 'burning candle' and its image in the eye's retina as in a camera [26]. (Since the image on the retina is turned upside down, Descartes attributed to the particular anatomy of optical fibers the capability of rotating the image of the candle). The human vision mechanism is much more complex; the cortical area devoted to this process is located in the back of the brain (area 17). Moreover, vision cannot be separated from other processes such as the 'recognition' of the object itself. This recognition activity is quite independent of the physical characteristics of the stimulus.

From the informational point of view we observe that, passing from the peripheral to central areas, the information is subject to various transformations and codings. Moreover, it seems that there exist some preordered schemes (of genetic origin) for filtering and selecting the information itself. However, the activity of the cortex is only partly conditioned by external stimuli. In fact, a large amount of its activity is autonomous (as, for instance, in sleeping or in dreaming) and seems to be related to very deep inner mechanisms of (successive) codifications of the information associated with neuronal activity.

Coding is a one-to-one map between two sets of objects. The nature of the objects of the two sets can be very different. For instance, in the Morse telegraphy the letters of the alphabet are coded by sequences of dots and dashes corresponding to electrical pulses of different duration, in the DNA coding mechanism a gene is transformed into a protein, in Mathematics a *set* is a code for a collectivity of objects and it is an entity different from the objects that it represents; moreover, it can be an element of other sets.

The human mind very often identifies some real or abstract objects with their codes. For instance, a natural number may be identified with its decimal representation and the word *pipe* with the object pipe[12]. This identification is a very powerful (and sometime dangerous) tool in the activity of the mind; in fact, it produces a considerable reduction in the amount of information required to represent the objects themselves. Moreover, it is at the base of capacity of abstraction and of the human language.

Another fundamental function of the human mind is *consciousness*, that is the deep and mysterious capability of the human machine to 'see itself' as reflected by a mirror. In my opinion, the famous statement of Descartes "*Cogito ergo sum (I think, therefore I am)*" essentially means that consciousness allows one to recognize one's own existence.

[11] In the conception of Descartes brain and mind (soul) are two entities, created by God, of a very different nature. The soul is immaterial and joined to the human body through the Pineal Gland

[12] The Belgian artist René Magritte in several of his surrealistic paintings emphasizes some paradoxes deriving from the identification, or not, of an object with its name.

The reflection mechanism underlying consciousness can be activated if some predicates (or relations) involving the human 'brain-machine' and a certain inner representation of the external world, are suitably coded into the neural activities of its cortical areas. This process is some respects similar to the projection of the *meta-language* of a theory into the *language* of the theory itself. We shall illustrate this by giving an example taken from the theory of computable functions.

A very famous theorem (*normal form theorem*) due to Kleene states that any partial function computable by a Turing machine is partially recursive (cf.[20]). The proof, very special in the setting of Mathematics, is obtained as follows. First one gives a suitable coding of the language of Turing machines (Gödel numberings) so that any Turing machine, as well as its associated partially computable function, is coded by a natural number. Moreover, a predicate $T(z, x, y)$ is introduced that is true if and only if the Turing machine coded by z starting with the input x makes a computation coded by y. Kleene was able to prove that the predicate T is a suitable composition of several elementary predicates that are (primitive) recursive, so that T is itself (primitive) recursive. This implies that there exists a primitive recursive arithmetical function f such that $f(z, x, y) = 0$ if and only if $T(z, x, y)$ is true. From this it is quite easy to prove that the function computed by the Turing machine coded by z is a (partial) recursive function.

The singular feature of Kleene's beautiful proof lies in the projection of the meta-linguistic predicate T describing the behaviour of Turing machines (and then of partially recursive functions associated with them) inside the theory of partially recursive functions, so that within this class of objects some of them can codify relations or predicates concerning themselves.

Turning back to the brain and to the reflection mechanism of consciousness, it is noteworthy that the number of relations or predicates that can be projected inside the brain strongly depends on the size of cortical areas and it is in any case quite limited with respect to the number of all possible relations. This would explain why the animals, also at a high level of the philogenetic scale, have a very limited consciousness and why, also at the level of humans, a complete knowledge of themselves is impossible.

This fact could originate what in psycology is called the *unconscious.* Even though psycology is not a hard science like Physics or Chemistry, it has collected such a large series of experiments, facts, and results that there is no doubt that human beings are not able to have a complete knowledge of themselves. In other words in the human mind there are some zones which cannot be explored or analyzed by the mind itself.

The problem whether it is possible to design a machine having a certain *degree of consciousness* excited, in the past two decades, the interest of many researchers from different cultural areas such as Neurobiology, Physics, Cybernetics, Philosophy, and Psycology (among these I recall the names of D. Dennet, J. Horgan, D.J. Chalmers, J. Searle, F. Crick, and G. Trautteur). I shall not try to enter into the details of the different points of view [13]. I limit myself to mentioning that some positions are decidely negative whereas other are more optimistic. In my opinion the answer can be positive if one could be able to understand the deep coding and decoding mechanisms of the brain underlying the consciousness.

A question that naturally arises is why the brain-machine (or an artificial automaton) needs consciousness. In other words why the human brain has consciousness if it could perform its functions and reach its main goals without it.

Let us observe that, as a consequence of coding mechanisms inside the functioning of human brain, one has to expect that the following occurs. First, the rise of some *ambiguity* and *uncertainty* due to the fact the activity of some neurons (or neuronal areas) is originated

[13] See, for instance, [27, 28, 29, 30] and references therein.

by stimuli conveyed either by sensorial neurons or by the coding mechanism. Therefore, the same object can play a double (or multiple) role.

An analogy with this is offered again by the recursive functions theory. As is well known [20] a set of non-negative integers is *recursively enumerable* if it can be generated by a Turing machine. Since Turing machines can be enumerated, so will be recursively enumerable sets. Let $K_1, K_2, \ldots, K_n, \ldots$ be such a numbering, so that the integer i is a code for the set K_i. A recursively enumerable set can contain or not its code among its elements. Now consider the set K of all i such that $i \in K_i$. It is not difficult to prove that K is recursively enumerable but it is not recursive, because its complementary set $K' = \{i \mid i \notin K_i\}$ is not recursively enumerable. This implies that there is no algorithm for deciding whether an integer belongs or not to K. The essential reason of this result is due to the double role played by an integer as a *number* and as a *code-number* of a set. The above result, of fundamental importance in computation theory, is in fact an 'abstract formulation' of the very famous *Gödel uncompleteness theorem*. The same kind of argument is at the base of *Russel's paradox* of set theory.

An essential feature related to the consciousness coding mechanism, is then the possibility of using the same objects (neurons) for more functions. This would considerably increase, with the eventual rise of some ambiguity, the capability of representation of the brain. Moreover, from the cybernetical point of view, consciousness is by itself a formidable system for controlling the activity of the brain.

Another aspect of the human mind, related with its capacity of abstraction, is its capability to deal with unprecise and vague (or *fuzzy*) concepts. Therefore, the brain machinery can execute computations in the presence of uncertainty and vagueness, a behavior that is fundamentally very different from that of usual automata. This capability is also related to *reliability* of the functioning of the human brain which is very high if it is compared with that of a computer. In fact, if in a computer there are some defects in the hardware, or errors in the software, its functioning is irremediably compromised. On the contrary, one can remove some regions of cerebral cortex and still the brain continues to work reasonably well[14].

Further important functions of the brain are learning and memory. The first is the process of acquiring new knowledge and the second is the process of saving and recalling the previously learned knowledge. It seems that learning is originated by suitable actions on synaptic junctions of neurons. As is well known, there exist more than one kind of memory (associative, working memory, long and short term memory); however, their mechanisms, as well as the nervous circuits devoted to this activity, are only partially known. Learning and memory are somehow strictly related to all other mental functions, and are essential for the activity of the brain.

The human brain, viewed as a computer, has then quite limited physical capabilities (limited volume, power of its elements, etc.) but extraordinary and sophisticated mechanisms to process information such as coding and decoding, which, in my opinion, embody the high functions of the mind like abstraction and consciousness, and considerably increase its efficiency and reliability. In other words, if an engineer should design a machine that optimizes its behavior in terms of capability and efficiency, having at its disposal a large but quite limited amount of resources, he could not avoid inserting in his design some functions similar to those of the human mind.

[14]von Neumann considered in [31] the problem of the synthesis of reliable organisms or systems having unreliable components. He proved, in a probabilistic setting, that this synthesis is possible under a suitable assumption on error probability of the components. However, his construction is very complex and himself considered his treatment of error unsatisfactory and *ad hoc*. The conviction of von Neumann was that error, as well as the probabilistic logic, should be treated by methods similar to those of Thermodynamics.

As regards the simulation of high mental functions by a machine we observe that even though it is quite clear what a *machine* is, it is not so clear what an high mental function like *intelligence* is, in the sense that it is not so easy to define it in a precise way; moreover, some of these functions are not easily separable as all contribute in some measure to the *thinking activity* of the human mind. Actually, if one were able to formalize exactly a particular function, then it would be possible in principle to reproduce it in a suitable machine.

A way to avoid this serious difficulty was suggested by Turing who introduced [32] a purely operational, or in the psycologists' term 'behavioristic', test universally known as the *Turing test*. One can state that a machine (for instance, the computer *Hal* in the Kubrick's picture *2001: A Space Odyssey*) exhibits one or more mental functions (i.e., overcomes positively the test) if it has a behavior, relatively to a series of questions of external interlocutors which involve the intervention of the above functions, that does not allow them to distinguish it from that of a human being.

Several criticisms have been made of the Turing test which originated many disputes and heated debates. The truth is that the sophisticated mechanisms of the major part of high mental functions performed by the human brain are still unknown. This is the essential obstacle that prevents their implementation in an artificial machine, and the main reason for the failure of the initial research program of Cybernetics. However, such an obstacle will hopefully be overcome by the development of neurosciences and by unexpected pathways along which the new *Cybernetics* of the third millennium will probably start and grow.

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I.B Second-Order Cybernetics. Cybernetics had from the beginning been interested in the similarities between autonomous, living systems and machines. In this postwar era, the fascination with the new control and computer technologies tended to focus attention on the engineering approach, where it is the system designer who determines what the system will do.Â The observer too is a cybernetic system, trying to construct a model of another cybernetic system. To understand this process, we need a â€œcybernetics of cybernetics,â€ i.e., a â€œmetaâ€ or â€œsecond-orderâ€ cybernetics. Cybernetics, control theory as it is applied to complex systems. Cybernetics is associated with models in which a monitor compares what is happening to a system at various sampling times with some standard of what should be happening, and a controller adjusts the systemâ€™s behaviour accordingly. The term cybernetics comes from the ancient Greek word kybernetikos (â€œgood at steeringâ€), referring to the art of the helmsman.Â Wiener defined cybernetics as â€œthe science of control and communications in the animal and machine.â€ This definition relates cybernetics closely with the theory of automatic control and also with physiology, particularly the physiology of the nervous system.