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Neurocybernetics and Artificial Intelligence

1. Objective

This lecture explores the evolution and content of Neurocybernetics, its relation to Artificial Intelligence and their interrelations with Computer Science and Knowledge Engineering.

We want to emphasize throughout the presentation the need to return in a systematic way to the original writings of the main authors, where one can find many of the basic ideas, which are still pending to be developed and which are a source of inspiration. We also want to emphasize the educational potentials these matters offer for computing research curricula.

In dealing with the relations of Neurocybernetics to Artificial Intelligence, we shall make generous use of some ideas shared with our former and very good friend and colleague, Prof. Jos´e Mira Mira, who passed away unexpectedly and too early. What is presented here is dedicated to his Memory, and to his lively, strong and serious way to make cybernetic and computing science.

1. The Original Components of Cybernetics

Neurocybernetics took off in the Forties although many of the basic ideas had been being managed in philosophic and scientific circles since the times of the Ancient Greeks. From 1943 to 1945, a kind of synergetic process was started up, triggered as the result of three basic pieces of work: Norbert Wiener, Arthur Rosemblueth and Julian Bigelow's study (1943) on the nature of teleological processes where the crucial idea was that the relevant in a homeostatic process is the information return and not the energy return via the feedback loops (see figure 1).

Following this, came the work of the young British philosopher, Kenneth Craick, published in the form of a small book called *On the Nature of Explanation* in 1943. He offered a pursuit of a Theory of Knowledge which would be contrastable like any other Natural Science. He was not completely successful in achieving this aim but he did, however, establish the rational bases upon which all the theories and models of systems of artificial behaviour have since been built. Craick offered a clear and powerful framework within which to express the acquisition, processing, storage, communication and use of knowledge (see figure 2).

And third, the work of Warren McCulloch and Walter Pitts, *A Logical Calculus of the Ideas Immanent in Nervous Activity*, which was also published in 1943. They elaborated the concept of a "formal neuron". Its response is, in fact, equivalent to a symbolic proposal with respect to the corresponding stimulus and which allows for a neural network to be considered as a logical system capable of handling symbols and elevating them to the level of the logic required for proposals. They came to the final conclusion that a network of formal neurons, with an effective infinite memory tape, can compute any number which is computable by a Turing Machine (see figure 3).

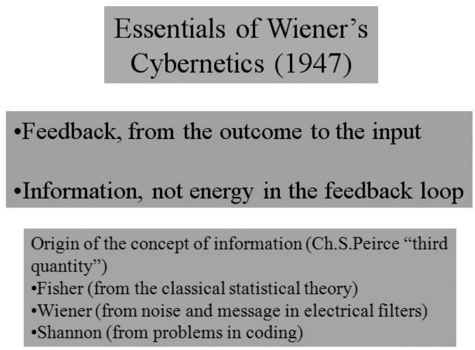

Figure 1. Fundamentals of homeostasis and reactive agents.

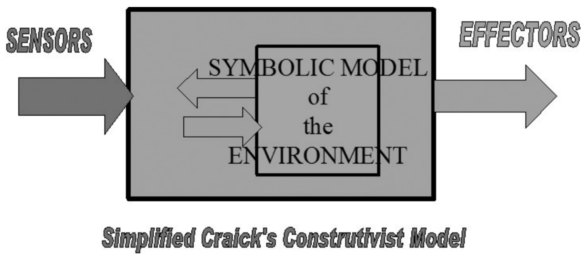

Figure 2. Basis of Symbolic A.I. Agents and Robotics.

In 1942 McCulloch met Norbert Wiener with their mutual friend Arturo Rosemblueth. The crucial paper for the emergence of Cybernetics was presented at the first Macy Foundation meeting in New York City: *Behaviour, Purpose and Teleology*, published the following year by Norbert Wiener, Arturo Rosemblueth and Julian Bigelow.

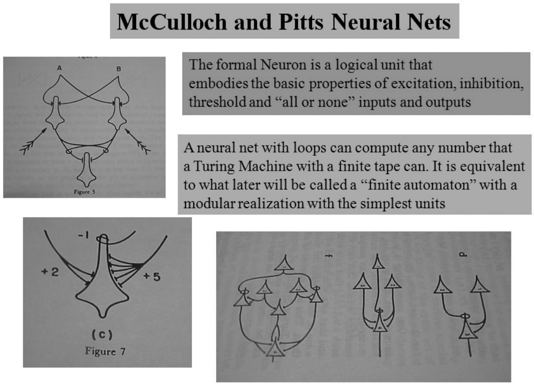

Figure 3. Origins of Connectivism.

Rosemblueth and McCulloch had reached with the Josiah Macy Foundation an important agreement to organize a yearly interdisciplinary meeting. Before they started, there was late in 1942 a meeting of engineers, physiologists and mathematicians at Princeton, referred by Wiener in the Introduction of his book of 1949 *Cybernetics*. There, McCulloch says, he met John von Neumann.

The Macy Foundation Conferences started under the name "*Conferences on Circular, Causal and Feedback Mechanisms in Biological and Social Systems*", which was changed to "Conferences on Cybernetics" in 1949. The series of stimulating and constructive Conferences run until 1953. They established a new conception for treating living and non-living machines, which with more or less successes, failures and redefinitions came to our days. It would be fruitful to dig into that remarkable source of ideas and inspiration, but only some of the Transactions are available. As Von Foerster said "The Conferences have became an oral tradition, a myth". Today, the consequences of that myth can be found in McCulloch and other attendants' essays. Many of the attendants to the Conferences may be considered the real foundations of Cybernetics. Some names: W. Ross Ashby, Y. Bar-Hillel, Julian

Bigelow, Jan Droogleever-Fortuyn, W. Grey Walter, Rafael Lorente de N ′ o, Donald MacKay, Warren McCulloch (Chairman of the Conferences), J.M. Nielsen, F.S.C. Northrop, Linus Pauling, Antoine Remond, Arturo Rosemblueth, Claude Shannon, Heinz Von Foerster, John Von Neumann, Norbert Wiener. From that time, McCulloch was advisor and friend of the operational research pioneer Stafford Beer.

From the Macy's Conferences on, there were a number of crucial subjects and problems, raised and discussed in the many sessions. Among them, there were the concepts of regulation, homeostasis and goal directed activity, the transmission of signals and communication in machines and nervous systems, the raise of Neural Nets and Automata Theory. In what refers to nervous systems organization, the ideas of reverberating and closing loops to explain brain activity were established there. These ideas generated concepts and theories on circular causality in Economics and in the polling of public opinion.

Table 1.

Neurocybernetics Subjects from the Macy's Conferences (1950's)
* Regulation, homeostasis and goal directed activity * Transmission of signals and communication
* Neural nets and automata theory * Closed loops in the central nervous system * "Circular causality" in economics and the polling of public opinion
* Conflict between motives in psychiatry (heterarchy of values)
* Reverberating and content addressable memories * Learning as changes in transition probabilities

The analysis of conflict between motives in psychiatry led to the developing of concepts like heterarchyof values in mental processes. Also, the ideas of content addressable memory, active or reverberating memories and the consideration of learning as changes in transition probabilities among states, were inspired from Biology to became terms applicable to machines. In sum, a considerable and rich flow of new ideas and concepts to be applied both to machine and to living systems (see a summary in table 1).

Neurocybernetics evolved with powerful input from the Theory of Communication of Shannon and key figures in the field of Computer Science such as Von Neumann, in the case of the latter, with application to questions of computability, performability, capacity for reproduction and reliability of functioning. McCulloch and Von Neumann were personal friends. McCulloch delighted a great deal in recounting the anecdote of how they began their work together on reliability of functioning, probabilistic logic and probabilistic computing.

Table 2.

Later Classical Neurocybernetics Problems
Reliable computation in nets (McCulloch, von Neumann) Adaptive Systems and Learning (Ashby, von Foerster, Caianiello)
McCulloch's Programs I and II (Logical Synthesis: Neuronal Counterparts of Logical Machines) ("Automata" Synthesis of Nervous Structures)
Connections Neurocybernetics-Artificial Intelligence

McCulloch then held (in the Fifties) the chair of Psychiatry at the University of Chicago. One night, he, Von Neumann and some colleagues drunk too much whisky. McCulloch suddenly stopped the conversation dead and commented something on its effect: "The thresholds of neurones are now very, very low. Nevertheless, neurons are still computing reasonably reliably. What can there be in the brain, in its modular structure and links, which makes it such a reliable piece of machinery in spite of failure in threshold levels and components?"

A magnificent piece of work called *Agathe Tyche*: The lucky reckoners offers a fair overview of muchof his philosophy with respect to ways of building reliable machinery from unsafe components. The classic by Cowan called *Reliable Computation in the Presence of Noise* and almost all of his later work on reliable computing was the result of McCulloch's expansion of Von Neumann's original concept.

Master contributions in the 50's and 60's include among other Ross Ashby, Heinz von Foerster and Eduardo Caianiello. Ashby's concept of homeostatic machines is fundamental for the development of mathematical Cybernetics, as well the ideas developed in his classical book "*Design for a Brain*". Von Foerster, was a physicist who became cybernetician after serving as secretary to the Macy's Foundation Conferences and editor of the Transactions. His contributions on second order cybernetics or cybernetics of observing systems, are crucial to understand complex non trivial machines and systems. Third, there are Eduardo Caianiello's neuronic and mnemonic equations for neural dynamics and for learning.

Around 1965, some forty four years back, the office of McCulloch in the Electronic Research lab at the MIT was a kind of breathtaking classroom both for the quality of the science produced and for the incredible people who filed through it. All of the greats of Cybernetics were there: Colin Cherry, Donald McKay, Patrick Meredith, Von Foerster, Gordon Pask, Eduardo Caianiello, to name only a few. Marvin Minsky and Seymour Papert set up the MAC project in Artificial Intelligence in a nearby lab. It was a young mathematician, Manuel Blum, who had discovered the theory of neural networks with the interaction of afferents, together with another young mathematician, Michael Arbib.

After the problems with respect to the reliability of functioning, which reached some acceptable solutions, the theory of neural networks faced up to the question of dynamic memory. This problem refers to oscillations in networks, expressly constructed to provoke controlled oscillations, which serve as a support to the dynamic storage of information. The initial logical problem was to find the maximum theoretical number of ways of oscillation in a non-linear, discrete and arbitrary network of N formal neurons. Schnabel calculated it and he found it was a number which grows extraordinarily when the number of formal neurons is increased. For example, for two neurons, there are twenty oscillation modes: for three, there 6.024 ie, three neurons could "store" 6.924 different models, each of which could be evoked by different external inputs. We say, "it could" because we still have to show that a network of fixed anatomy could be designed that incorporates all the modes of oscillation. This was proved in 1966 via the theorem of synthesis, using formal neurons with afferent interaction introduced by Blum.

By the year 1969, the theory of formal Neural Networks was considered, from the logical perspective, to be a closed matter mainly due to the introduction of the so-called functional matrices. They allowed, transparently, the demonstration of equivalence between determinist and probabilistic robots and networks of formal neurons with feedback, via constructive theorems. There was only one formal gap, discovered in 1977 by a student at the University of Zaragoza and it consisted in the fact that certain probabilistic machines had no counterpart in the logical networks of formal neurons unless an additional probabilistic codifier was incorporated into the network, previous to the input to the networks if unless the "outside" world (outside the neural) had a non-deterministic nature and, what is worse, a nature which depends on the structure of the network of formal neurons. In other words, that there are probabilistic robots which cannot be duplicated in the networks of formal neurons with afferent interaction. In fact and in the practical totality of the applications, the subject is not completely relevant. But from the theoretical perspective, it is inadmissible since we could not defend that the logical model of McCulloch and Pitts was an appropriate model to represent the activity of the brain at the computational level of coding and communication.

This gap was acknowledged, but the subject was parked due to the fact that neural networks suffered a fall in scientific interest from the end of the Seventies through to the mid Eighties. In 1983, a doctorate student in Maths, took up the subject again and proved that, if interaction between axons was admitted - the output channels of the neurons - in an intercommunication process which may take place through the medium, in a network of hierarchizised formal neurons, then the theory was complete i.e., a network of formal neurons with feedback would duplicate any arbitrary robot, be it deterministic, probabilistic or non-deterministic. This effect of output interaction was added elegantly to the interaction of afferents (inputs) of Blum dating back to 1962. This finishes the so called McCulloch's Program 1, the Logical Program.

McCulloch's Program II is more realistic and can be considered as brain theory at the level of Systems Sciences. The prototype paper is the 1947 paper by McCulloch and Pitts entitled "How we know Universals", as well as his and Kilmer's subsequent work on modelling the reticular formation. Actually, as Norbert Wiener says in the Introduction to his book Cybernetics, McCulloch was after an apparatus to read aloud a printed page, which, because the necessary invariances, was a definite analogue to the problem of Gestalt's form perception. He designed a device that made von Bonin ask if it was a diagram of the fourth layer of the visual cortex. A typical neurocybernetic solution.

Program II can be simply stated as follows: from a subsystem of the nervous system, define the most precisely its functions and try to find a cooperative, reliable granular structure to perform said functions. That will be a true theoretical neural net. Program II can be formulated for the artificial as well, so that it provides for systematic reasonable ways to solve problems by means of artificial "neural nets" of computing modules (see figure 4).

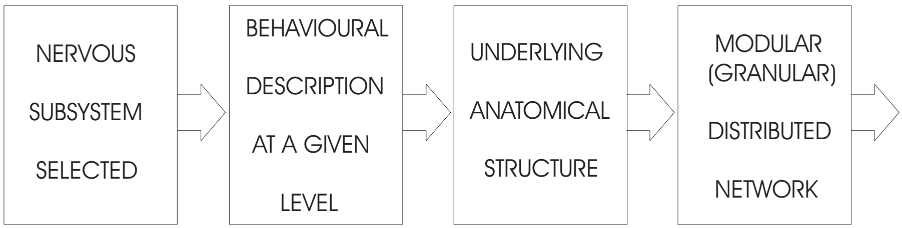

Figure 4. Proceeding according McCulloch's Program II

As it is known, in the Eighties, there was an upsurge in neural computing which, I believe, was due to one basic cause: the growing availability of microcomputers at a very low cost so that hundreds and even thousands of them could be linked up in parallel processing networks each with functions much more complex than the formal neurons of McCulloch and Pitts and the addenda. Anyway, we should not forget the fact that the classic theory is complete at a logical level and by offering greater computing potential to the basic units, the maximum we arrive at is a reduction in the number of units needed for the practical working of an artificial system apart from an increase in the speed of design. The only crucial element which had not been contemplated and which was easy to incorporate - and was incorporated in the famous Perceptrons of the 60s - was the capacity of modification of synaptic weighting through learning.

As it is well known, this resurgence of neural networks as systems of distributed granular computing is finding application in technological fields ranging from processing and treatment of signals (voice, image), systems of artificial vision, in robots and in control. We however believe that most works on artificial neural nets are irrelevant ways of solving problems using non-optimal tools. It is our believe that significant progress in artificial neural net theory (or modular distributed computation) requires to proceed strictly according McCulloch's Program II.

3. From Neurocybernetics to Bioinspired Artificial Intelligence

The aims of Neurocybernetics are essentially the understanding of neural behaviour at different levels, by constructing models and theories. If we add the obvious condition that these models and theories are computable, in order to embody them in a physical structure, we can conclude that these are also the aims of the so more recently called Computational Neuroscience. Thus the range in what Neurocybernetics acts goes from membrane phenomena to perceptual and cognitive, and to behavioural and social processes.

The neural function is a really complex phenomenon and its characterization requires, as a norm, meticulous approaches both at the level of tools and methods to be applied as in accepting or choosing the parameters which are considered necessary when describing and trying to explain this function. Also care should be taken when considering the scope of possible validity of conclusions reached via the theoretical and experimental approaches adopted. This is equivalent to saying that any theory with respect to the nervous system is limited a priori by the conceptual tools. To exaggerate, we should not attempt to explain the capacity for resolution of problems of the nervous system using, for example, non-linear differential-integral equations. Nor can we delve deeper into the properties of the neural membrane using the logic of relationships.

Thus, we cannot deny the historic role played of action potential registration from the Fifties since they have allowed for a physical knowledge of the carrier substratum of messages. But it is illegitimate to work from them to deduce high level properties or to try to build functional models of the brain. It would be, albeit an unfair comparison, like using statistics of the pulses which appear in a data bus or computer commands to deduce the algorithmic base of the programme solving a problem in RAM.

We can sum up this structure of Neurocybernetics levels in a way which indicates what are the appropriate tools for each level, keeping in mind that a notable change in level cannot be allowed in the theory without changing tools. But, if prudent, in the practical research into the brain and artificial machines which we wish to make work like the brain, we can skip the level slightly.

The most basic level (where computational machines still do not appear, strictly, apart from as tools) is the level of the neurotransmitters, membrane phenomena and action potentials. Tools present in this level are Biochemistry and Biophysics. Then comes Biophysics of Neural codes and multiple codes, where this is a word used in neurophysiology to indicate multiplex. Then we move onto Biophysics and Signal Processing. We continue through sensorial codes, decodification in effectors - motor and glandular action - and the code of advanced peripheral neurons such as the ganglion cells in the retina. We are now in the realm of Signal Theory almost at the level of logic. Then, we have the neural net level, the interaction of input and output of the neurons themselves, and the coordination of the output -effectors. We are now at the level of the Language of Logic bordering on Symbolic Languages and, finally, we come to the central cortex neural code, the cooperative processes between masses of brain tissue, the extraction of Universals and the social processes of interaction between neuron masses. We are at the level of Symbolic language. The structure in levels is summarized in table 3. Upper square bounds the more classical formal tools of computational neuroscience. Lower square bounds techniques close to Artificial Intelligence tools.

Following Mira and Delgado three main subdomains can be distinguished in the broad domain of Artificial Intelligence (AI), as shown in figure 5. The actions of Neurocybernetics and Computational Neuroscience show up in going to and from Bioinspired AI, that is the understanding of cognitive processes, from and to the more practical knowledge engineering techniques, dealing with tasks and methods. Influencing both are the more classical Artificial Intelligence concepts and methods, an optimistic line of thought originated in 1956, when the term Artificial Intelligence was coined. Some times it is

Table 3.

LEVEL	FORMAL TOOLS
Neurotransmitters, membrane phenomena, action potentials	Biochemistry, Biophysics
Biophysics of neural codes and multiple codes	Biophysics, Signal Processing
Sensorial codes, decoding in motor and glandular effectors, coding in the Retina	Space-time System Theory
(Integro-differential & difference equations, Statistics, Fuzzy)	
Neural nets, input output interaction and coordination. Brain subsystems	Algorithmic (Logic, Symbolic) Connectivistic A.I.
Central neural code, cooperative processes, perception of universals, social-like behaviour	Symbolic, Methods and Techniques of Scientific A.I.
(Formal tools close to A.I. tools)	

called Good Old Fashion AI Representations (GOFAIR). This diagram provides for a clarifying picture of the place and role of Neurocybernetics and Computational Neuroscience in a modern post-graduate educational plan for Artificial Intelligence.

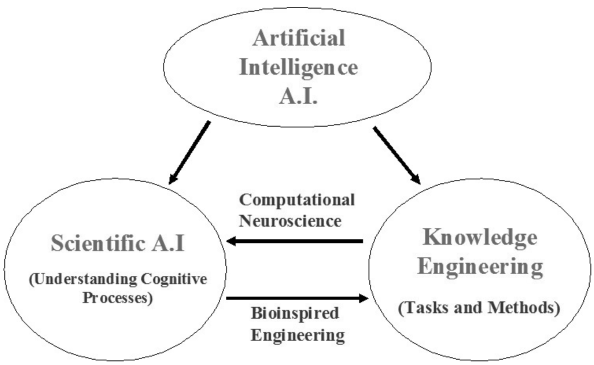

Figure 5. Subdomains of the domain Artificial Intelligence and the place of Neurocybernetics as a link.

In return, there are at least three paradigms of AI which are incident in the concepts and methods of Neurocybernetics. This paradigms project back to the three basic original components of Neurocybernetics cited in section 2. First, there is the Symbolic Paradigm, which is actually an updated view of Craick's proposal, corresponding to Symbolic Agents AI. Here, a Knowledge Base houses the model of the environment, which is to be updated with data coming from the sensory lower level representations and from the coded motor actions prior to the executions on the environment. Planning and inferences are operated by the sensory representations and by the present model of the environment, to act on said model and the coding of output actions. This is illustrated in figure 6.

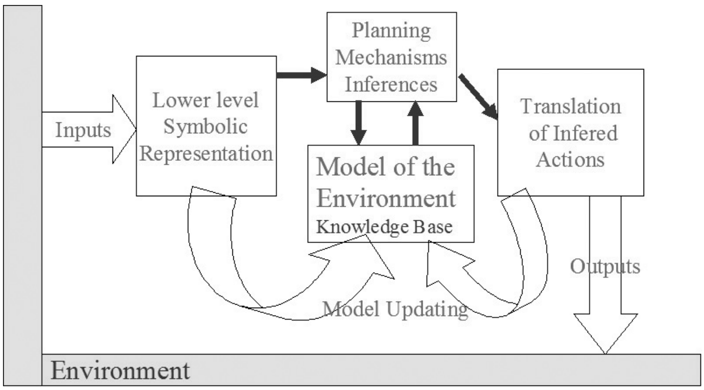

Figure 6. Updated view of Craick's proposal (Symbolic Agent A.I.)

The second AI paradigm incident in Neurocybernetics is the situated AI paradigm which corresponds to the so called Intelligence Agents. Its basic concepts can be traced back to Wiener's purposive behaviour cited in section 2. Here, the kernel of the situated intelligence agent is a kind of finite learning automaton, holding association tables, capable of reactive and conditional coding of elementary actions. The inputs to this association computer are the results of perceptual transforms of the sensory data. The output feeds the computation of chains of actions to go to the effectors. Notice that the main feedback loop controlling the system is an external one, determined by the situation of the agent in the environment. This type of architecture is illustrated in figure 7.

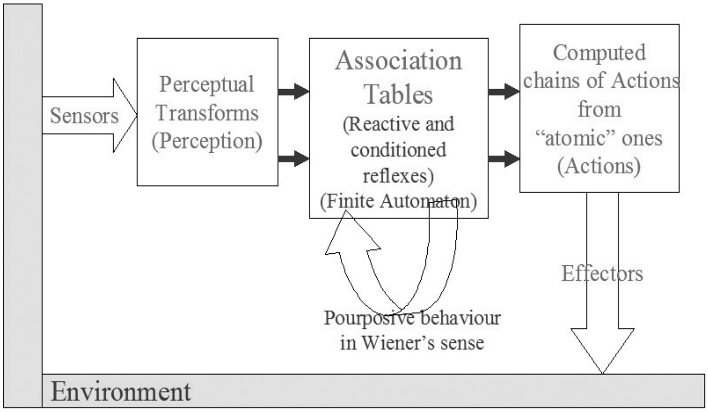

Figure 7. Architecture of a Situated I.A.System (Intelligent Agent).

Finally, there is the Connectivistic Paradigm, which sprung from the original McCulloch and Pitts paper and the later Perceptrons and Artificial Neural Nets. Here, though we are far from the original meaning given to formal neurons in 1943 and to posterior work of McCulloch and collaborators, it is typically accepted that networks of artificial neurons (many of them, variants of Perceptrons) are capable of solving classes of Artificial Intelligence problems in a distributed, granular way. This claim is actually based on the two basic and very important translating operations performed by the human operator, external to the net: an abstraction of the observed data to generate numerical labelled variables (or input lines) and a re-translation of numerical solutions on output labelled lines or variables into a subset of the natural language, to provide classes in which fit the original observed data. In between, an ANN (Artificial Neural Network) is actually a parametric numerical associator which can learn (modify weights), having the nature of a multilayer Perceptron. The typical connectivistic Artificial Intelligence architecture is shown in figure 8.

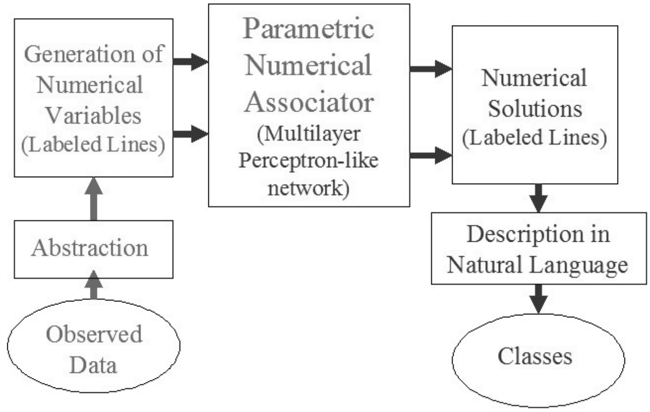

Figure 8. Typical Connectivistic A.I. Application Architecture of an Artificial Neural Net.

As it can be immediately concluded, artificial neural nets as they are nowadays understood do not provide for theories or models of the nervous systems, but rather are a pure computing tool, that should always be compared with other for for the solution of specific problems.

As a synthesis of the aims of neurocybernetics and of Bioinspired AI, we shall refer to a diagram which reflects Jos ́e Mira's desires of bringing together Neuroscience and AI, in an effort to clarify and to increase our understanding of the nervous system. And also, to develop better and more sophisticated computing tools in our benefits. The diagram is shown in figure 9. On the left, there are the different levels of description corresponding to the structures and components. At the right, a similar representation for the same levels corresponding to neural processes. In both cases, arrows coming down mean reductionistic approaches, while arrows up would reflect emergent properties. Notice that each reduction and apparent emergency requires a change in the formal language and in the interpretations by the external observer. Much care must be taken in the jumps between levels, as it was also the case for the levels and formal tools in Neurocybernetics (Table 3). Trying to describe and explain cognitive processes in terms of neurons and neural nets languages is too irrealistic, a jump similar to trying to describe the Theory of Computation or Data Structures and Algorithms in terms of hardware.

Bridging the formal tools and concepts of the two columns of the diagram at each level is an important task ahead for neuroscience and computing researchers. This was the aim of Jos ́e Mira; it is the aim of the congresses IWINAC (International WorkConference on the Interplay between Natural and Artificial Computation) that Mira initiated, and are the aims of many of us. We hope that the brilliant past of Neurocybernetics will project into a brilliant and useful research and educational future.

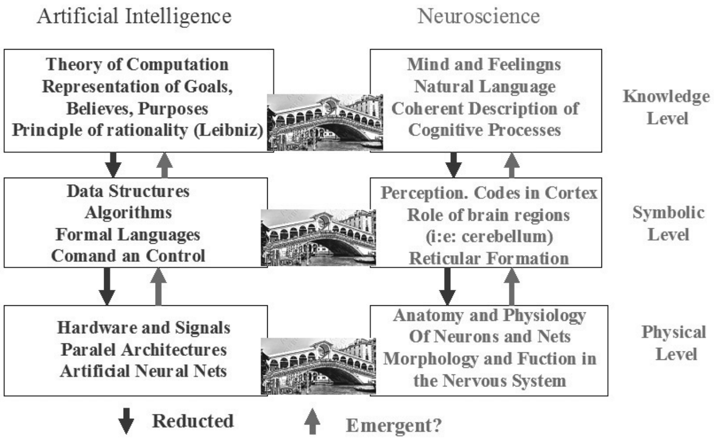

Figure 9. Bridging Computing Science and Neuroscience.

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