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# *What is Soft Computing?* – Bridging Gaps for 21st Century Science![*]

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## Abstract

This contribution serves historical and philosophical reflecting cognitions on the role of Soft Computing in the 21st century. Referring to Magdalena's article in this issue, this paper considers the aspects of mixtures of techniques, the opposite pair "Hard Computing" and "Soft Computing", and Computational Intelligence. From the historical perspective the paper goes back to three articles by Warren Weaver that appeared after World War II. A concentrated study of these papers helps to understand that Soft Computing will be able to play a key role in the future development of science and technology.

*Keywords*: Soft Computing, Computational Intelligence, Artificial Intelligence, Communication, Interdisciplinary Mixtures, Bridging.

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## Introduction

This issue will appear early in 2010. Then Soft Computing will exist for already 20 years. “The concept of soft computing crystallized in my mind during the waning months of 1990”, wrote Lotfi Zadeh (born 1921) in a retrospective foreword to the then founded journal Applied Soft Computing in 2001 and in the same year the Berkeley Initiative in Soft Computing (BISC) was launched. Five years later, the Foundation for the Advancement of Soft Computing and its European Centre for Soft Computing (ECSC) started working in the Spanish city of Mieres. Recently (May 19, 2009), Zadeh repeated his former suggestion to establish the research field of Soft Computing (SC) to the BISC mailing list:† “As we move further into the age of intelligent systems, the problems that we are faced with become more complex and harder to solve. To address the problems, we have an array of methodologies – principally fuzzy logic, neurocomputing, evolutionary computing and probabilistic computing. In large measure, the methodologies are complementary; and yet, there is an element of competition among them. In this setting, what makes sense is formation of a coalition. It is this perception that motivated the genesis of soft computing – a coalition of fuzzy logic, neurocomputing, evolutionary computing, probabilistic computing and other methodologies.”(1) With his broadcast Zadeh intended “that steps be taken to include an undergraduate/graduate course on "Computational Intelligence and Soft Computing," in engineering curricula. A course on CI/SC would serve an important function; it would introduce students to the principal methodologies which are employed in the conception, design and operation of intelligent systems.”(2) More than 20 BISC-mailing list members followed Zadeh’s request to distribute their experiences on teachings courses on CI/SC until the end of May 2009. There exist already undergraduate and graduate courses on CI/SC/ in some countries and there were two announcements of Master courses in Spain for 2009/2010: the Department of Computer Science and Artificial Intelligence of the University of Granada organizes the “Master in Soft Computing and Intelligent Systems” and the ECSC in Mieres launched the “Master in Soft Computing and Intelligent Data Analysis”.‡ Luis Magdalena, the General Director of the ECSC, wrote the motivating article of the special issue at hand, titled “What is Soft Computing? Revisiting Possible Answers” (3)

Questions that start with “What is” often require philosophical cognitions. Thus, to discuss the question and Magdalena’s answers in his article, some philosophical and, in my judgement, historical reflections will be useful.

The initiation of the “Age of intelligent systems”, was in the middle of the 20th century when many of the scientific-technological achievements that were developed in research projects during the second world war became generally known by the public. At that time the influential American scientist and science administrator Warren Weaver (1894-1978) wrote three important papers:

- “Science and Complexity”[4]
- “The Mathematics of Communication”[5] §
- “Translation”[9] **

In the first paper of this list Weaver identified a “region” of problems “which science has as yet [1947/1948] little explored or conquered”. These problems, he wrote, can neither be reduced to a simple formula nor can they be solved with methods of probability theory. To solve such problems he pinned his hope on the power of computers and on interdisciplinary collaborating “mixed teams”. [3]

In the second paper he argued that Claude E. Shannon‘s “Mathematical theory of communication” did not even touch upon any of the semantic and effectiveness or pragmatic problems, but that the concepts of information and communication therefore must not be identified with the “meaning” of the symbols. But then he wrote “The theory goes further. Though ostensibly applicable only to problems at the

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† As the “backdrop” for his suggestion Zadeh used almost the same words that he wrote in 2001 in Ref. 1.

‡ As a consequence of Zadeh´s initiative the ECSC provides a comprehensible list of teaching activities in SC/CI and related fields on the web page http://docs.softcomputing.es/public/teaching/.

§ This is a re-interpretation of the article “A Mathematical Theory of Communication”[6] by the electronic engineer and mathematician Claude Elwood Shannon (1916-2001) for broader scientific audiences. Later, Weaver modified and accentuated this text with the new title “Recent Contributions to the Mathematical Theory of Communication”[7] that was published together with Shannon’s work in the book *The Mathematical Theory of Communication*.[8]

** This is a memorandum, circulated to some twenty or thirty acquaintances, which was to stimulate the beginnings of research on machine translation in the United States. Later, 1955 it appeared in a Collection of essays on *Machine translation of Language*, see Ref. 9.

technical level, it is helpful and suggestive at the levels of semantics and effectiveness as well."[5] Weaver added some ideas to these problems to Shannon's communication scheme and we will give an interpretation of these ideas in terms of fuzzification and defuzzification in the following chapter.

In the third paper, Weaver brooded whether it is unthinkable to design computers which would translate, Weaver speculated "that the way to translate from Chinese to Arabic, or from Russian to Portuguese, is not to attempt the direct route […]. Perhaps the way is to descend, from each language, down to the common base of human communication – the real but as yet undiscovered universal language – and – then re-emerge by whatever particular route is convenient."[9]

Weaver's midcentury expectations on the progress in science and technology seem to be anticipating important topics of CI/SC – vague, fuzzy or approximate reasoning, the meaning of concepts, and "to descend from each language, down to the common base of human communication—the real but as yet undiscovered universal language—"[9] that seems similar to Zadeh's concept of "precisiated natural language" – and obviously he perceived that there will be a big change in science and technology in the 20th century. However, there is no direct relation between the work of Weaver and Zadeh[††] but it seems to me that it is worth to study Weavers writings in this context.

In the first paragraph of "Science and Complexity" Weaver asked: "How can we get a view of the function that science should have in the developing future of man? How can we appreciate what science really is and, equally important, what science is not? It is, of course, possible to discuss the nature of science in general philosophical terms. For some purposes such a discussion is important and necessary, but for the present a more direct approach is desirable." Weaver then overviewed the "three and a half centuries" of modern science and he took "a broad view that tries to see the main features, and omits minor details."[4] For the following pages we will learn a lesson from Weaver's reflections on science illuminating various points of "What is Soft Computing?" from the historical and epistemic perspective.

## 1. Mixtures and Hybridizations

"Soft Computing as the mixture of several pre-existing techniques" is the heading of the second section in Magdalena's article.[3] Of course, the areas of fuzzy sets and systems, of artificial neural networks and of evolutionary and genetic algorithms emerged as independent research disciplines in the decades between the 1940s and 1970s but beginning in the 1980s new developments arose that were hardly foreseeable: the theory of fuzzy sets and systems was combined with artificial neural networks, and later also with genetic or evolutionary algorithms or these algorithms could be successfully connected with artificial neural networks. The use of such "hybrid systems" became more and more common in all types of applications.

Hans Jürgen Zimmermann, the editor of the journal *Fuzzy Sets and Systems* at that time, foresaw in an editorial that the development of such hybrid systems would continue in the future. Therefore he deliberated about a name for the common field of research, which would then also become the subtitle of *Fuzzy Sets and Systems*: "Soft computing, biological computing and computational intelligence have been suggested so far." These concepts seemed to be attractive in different ways and also varied with respect to their expressive power. He suggested calling the field – and thus also the new subtitle of the journal – "soft computing and intelligence," since the other concepts seemed to place too much emphasis on "computing," "which is certainly not appropriate at least for certain areas of fuzzy set theory." The name "soft computing and intelligence" would be better defined than "artificial intelligence," but both have in common the word "intelligence," which Zimmermann found defined in Random House Dictionary as follows: "Capacity for reasoning, understanding and for similar forms of mental activity." This was exactly what the editors of this journal had considered to be central to fuzzy set theory in the first issue.[11] Thus since the first issue of 1995 *Fuzzy Sets and Systems* has appeared with the subtitle *International Journal for Soft Computing and Intelligence* (Fig. 1)

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[††] In a personal message Zadeh answered to the author's question whether he was familiar with Weaver's papers in the 1940s and 1950s that he did not read the papers in Ref.4 and Ref. 5. He also wrote: "It may well be the case that most people near the center [of the "world of information theory and communication" in that time] did not appreciate what he had to say. In a sense, he may have been ahead of his time."(Ref. 10)

There are, however, other examples of concoctions or compositions of pre-existing techniques in the history of 20th century science and technology – *General Systems Theory*, *Cybernetics*, *Information Theory*, and *Artificial Intelligence* – and these "fusions" are historically interconnected and interwoven with the historical genesis of CI/SC. Let us consider these historical scientific "confraternities"!

The biologist Ludwig von Bertalanffy's *General Systems Theory* and the mathematician Norbert Wiener's *Cybernetics* appeared in the first half of the 20th century. The history of the former was already 20 years old when Wiener (1894-1964) published his *Cybernetics* and subtitled the book with *communication and control in the animal and the machine*.[12]

As a natural philosopher and biologist, Bertalanffy (1901-1972) was familiar both with the mechanistic view, according to which living things were fragmented into their individual parts and life processes were considered in terms of their sub-processes, as well as with the newer philosophy of organism, which stressed the principles of organization and order by which they were joined as a whole.

Wiener's *Cybernetics* culminated in the hypothesis that the behavioural mechanisms in machines and in living organisms were – at least roughly – the same, although it was acknowledged that particularities might occur in one way or another. There were naturally functional differences, as well, between living beings and machines; if an engineer were to design a robot that was supposed to act like an animal, he would not be likely to build it out of proteins and other colloids, but would instead probably use metallic implements, a few dielectrics and a lot of vacuum tubes.

In the "transdisciplinary" *Cybernetics* the same principles were sought in different sciences and the feedback principle, which was central to cybernetics, constituted one of these principles: "We can not reduce the biological, behavioral and social levels to the lowest level, that of the constructs and laws of physics. We can, however, find constructs and possibly laws within the individual levels."[12]

Also Bertalanffy had stressed that the feedback principle could explicitly be found in Wiener's theory and could be presented as one of the principles that were found spanning the sciences. Beyond that he proposed a unified principle of sciences in the organizational structure of the individual areas which join together to form a whole, and this principle aimed to find it. (Fig. 2).

Fig. 1. Front pages of the volumes 68 (1994) and 69 (1995) of *Fuzzy Sets and Systems*; since 1995 the subtitle has been "International Journal for Soft Computing and Intelligence".

In the early 1950s, also an engineering-oriented *System Theory* was a rising scientific discipline "to the study of systems per se, regardless of their physical structure".[13] Engineers at that time were, in general, inadequately trained to think in abstract terms, but nevertheless, Zadeh, who was then assistant professor at Columbia University in New York, believed that it was only a matter of time before system theory attains acceptance.

In April 1963, when Zadeh was already for five years a professor at the University of California at Berkeley, he participated in the *Second Systems Symposium at Case Institute of Technology* in Cleveland, Ohio, where the organizers brought together, systems scientists in terms of the *General Systems Theory* and *Cybernetics* on the one hand and technical system scientists on the other hand. The proceedings were published by Mihaljo D. Mesarović (born 1928), entitled *Views on General Systems Theory*.[14] Indeed, this book contains some very different views and approaches and Mesarović emphasized in the preface: "Finally, it was expressed that a broad-enough collection of powerful methods for the synthesis (design) of systems of diverse kinds should be considered as constituting the sought-for theory and any further integration was unnecessary."[14] [‡‡]

Two years later, at the *Symposium on System Theory* that took place at the Polytechnic Institute in Brooklyn, Zadeh presented "A New View on System Theory"[12] where he defined for the first time a fuzzy system as a system $S$ such that input $u(t)$, output $y(t)$, or state $x(t)$ of

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[‡‡] Here, Zadeh introduced "The Concept of State in System Theory" into the system theoretical approach in electrical engineering.[15]

*S* or any combination of them ranges over fuzzy sets.[16] [§§]

There is also a historical link from the theory of *Fuzzy Sets and Systems* to *Information Theory*. Considering this aspect, let us start with Shannon's paper on "Mathematical Theory of Communication" that appeared – in the same year as Wiener's *Cybernetics* – in two parts in the July and October 1948 editions of the *Bell System Technical Journal*.[6] However, it is very likely that this article wouldn't have became famous without the help of Weaver, whose popular text "The Mathematics of Communication"[5] re-interpreted Shannon's work for broader scientific audiences. Later, Weaver modified this text a little and accentuated it with the new title "Recent Contributions to the Mathematical Theory of Communication" as a kind of "introduction" into Shannon's article and both manuscripts appeared in the one year later published book *The Mathematical Theory of Communication*.[8]

It was the parallel work on secret binary codes and ways to improve them in World War II that led Shannon, as it had Wiener, to employ statistical considerations: A source selects from a set of symbols with particular probabilities. The information conveyed by a symbol increases if its probability of occurrence increases.

Shannon included "new factors" to the theory of "transmission of intelligence" – as it was called in the first decades of the 20th century and then changed to the name "transmission of information" with the work[18] of the Bell-engineer Ralph Vinton Lyon Hartley (1888-1970) in 1928 – "in particular the effect of noise in the channel, and the savings possible due to the statistical structure of the original message and due to the nature of the final destination of the information."[6]

When Weaver wrote his popularizing article on Shannon's "Mathematical Theory of Communication", he was apparently familiar with Charles William Morris' (1903-1979) 10 years old work on the *Foundations of the Theory of Signs*,[19] the *semiotics* that Morris had defined as a *universal* theory of signs and an *interdisciplinary* undertaking. In his view, the mission of semiotics as a science of signs which produces dispositions to social behavior, and in order to understand the uses and effects of signs we have to understand that and how signs influence social behavior.

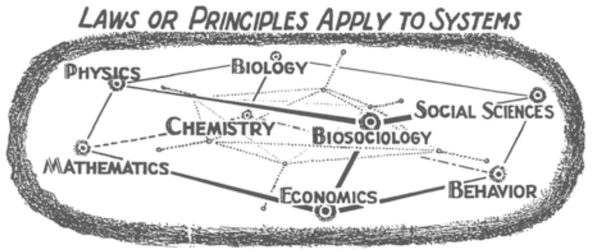

Fig. 2. Illustration of Bertalanffy's General Systems Theory.

Already in the third paragraph of his paper Weaver wrote: "In communication there seem to be problems at three levels: 1) technical, 2) semantic, and 3) influential. The technical problems are concerned with the accuracy of transference of information from sender to receiver. They are inherent in all forms of communication, whether by sets of discrete symbols (written speech), or by a varying two-dimensional pattern (television). The semantic problems are concerned with the interpretation of meaning by the receiver, as compared with the intended meaning of the sender. This is a very deep and involved situation, even when one deals only with the relatively simple problems of communicating through speech. […] The problems of influence or effectiveness are concerned with the success with which the meaning conveyed to the receiver leads to the desired conduct on his part. It may seem at the first glance undesirable narrow to imply that the purpose of all communication is to influence the conduct of the receiver. But with any reasonably broad definition of conduct, it is clear that communication either affects conduct or is without any discernible and provable effect at all."[5]

In the revised version of the paper Weaver explained the trichotomy of the communication problem in extenso and he divided it into three levels[7]:

- *Level A* contains the purely technical problem involving the exactness with which the symbols can be transmitted,
- *Level B* contains the semantic problem that inquires as to the precision with which the transmitted signal transports the desired meaning,
- *Level C* contains the pragmatic problem pertaining to the effect of the symbol on the destination side: What influence does it exert?

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[§§] The talk's printed version in the symposium's proceedings has the heading "Fuzzy Sets and Systems"[16]. In the same year Zadeh established his seminal paper "Fuzzy Sets" in the journal *Information and Control*[17] that appeared before Ref 16.

He underscored very clearly the fact that Shannon's theory did not even touch upon any of the problems contained in levels *B* and *C*, that the concept of information therefore must not be identified with the "meaning" of the symbols: "In fact, two messages, one of which is heavily loaded with meaning and the other of which is pure nonsense, can be exactly equivalent, from the present viewpoint, as regards information."[7]
Weaver stated, that Shannon's communication scheme (Fig. 3) "can, in all likelihood, be extended to include the central issues of meaning and effectiveness. […] One can imagine, as an addition to the diagram, another box labeled "Semantic Receiver" interposed between the engineering receiver (which changes signals to messages) and the destination. This semantic receiver subjects the message to a second decoding the demand on this one being that it must match the statistical semantic characteristics of the message to the statistical semantic capacities of the totality of receivers, or of that subset of receivers which constitutes the audience one wishes to affect.

Similarly one can imagine another box in the diagram which inserted between the information source and the transmitter, would be labeled "Semantic Noise" (not to be confused with "engineering noise". This would represent distortions of meaning introduced by the information source, such as a speaker, which are not intentional but nevertheless affect the destination, or listener. And the problem of semantic decoding must take this semantic noise into account. It is also possible to think of a treatment or adjustment of the original message that would make the sum of message meaning plus semantic noise equal to the desired total message meaning at the destination."[5]

However, there is plenty of fuzziness in the levels *B* and *C*. The interpretation of meaning of signs, e. g. linguistic signs, names, words, is obviously a fuzzy process, and influence or effectiveness exerted to the receiver's side is a fuzzy process, too. Thus, figure 4 shows *my* version of Shannon's diagram of a communication system with Weaver's two additional "boxes" that I designate as "fuzzy boxes" because in my view the "first coding" between the information source and the "Semantic Noise" is a *fuzzification* and the "second decoding" between the "Semantic Receiver" and the destination is a *defuzzification*.

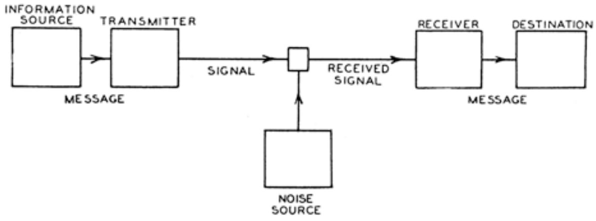

Fig. 3. Shannon's communication scheme.

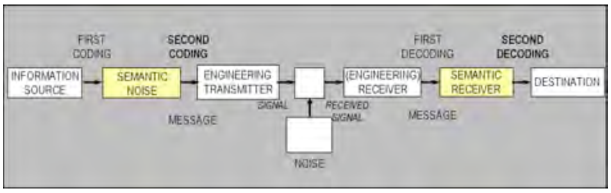

Fig. 4. Illustration of Weaver's additional "boxes" in Shannon's communication scheme.

Shannon and Wiener, both were members of the editorial board of the *IRE Transactions on Information Theory* in the 1950s and each wrote an editorial for an issue in 1956. Shannon called for readers to bear in mind that, despite all of the popularity information theory had enjoyed over the previous few years, it was not a "universal remedy" and that they should thus return to serious research and development at the highest scientific levels. The fact that information theory had been applied successfully in so many fields, even in psychology, economics, and the social sciences, was good news, but it also obscured the abstract meaning of these terms: "Indeed, the hard core of information theory is essentially a branch of mathematics, a strictly deductive system."[20] Shannon was pushing back against the interdisciplinary expansion of his mathematical theory, and thus naturally against Wiener's cybernetics, as well. Three months later, Wiener took the opportunity to respond: "What I am here entreating is that communication theory be studied as one item in an entire context of related theories of a statistical nature, and that it should not lose its integrity by becoming a special vested interest attached to a certain set of slogans and clichés." Wiener was clear in his dismissal of Shannon's "purism": "I hope that these *Transactions* may encourage this integrated view of communication theory by extending its hospitality to papers which, why they bear on communication theory, cross its boundaries, and have a scope covering the related statistical theories. In my opinion we are in a dangerous age of overspecialization.[21]

Therefore, one can say that Shannon pleaded for the restriction of *Information Theory* to the technical problems whereas Wiener advocated scientific research of information theory in all other scientific disciplines.

Finally, when *General Systems Theory*, *Cybernetics*, the new *System Theory* in engineering sciences and *Information Science* melded in North America in the 1950s Bertalanffy presented his "über-science" as one member of a "group of modern currents, which also included the theory of information, cybernetics, game theory, operational research theory and others"[22] and in the mid-1970s, the editors of an anthology on *System Theory and System Technology* found that it was "not sensible to attempt here and now to define precise delimitations between the individual schools, whose findings, axioms and instruments can be used imaginatively as a great box of tools". However, the "large field of system theory/cybernetics"[23] – a scientific tool box! – made the scientists see very plainly the ivory towers in which they had primarily been sitting and continued to sit, as the computer scientist George Klir (born 1932) summed up in his 1991 overview of the "facets" of the "system sciences". Generally speaking, the arguments put forth for decades had made the scientists increasingly sensitive to the boundaries of their disciplines, and they were becoming more aware of the fact that the important real-world problems could be understood only if they transcended the boundaries of the individual sciences to study those problems.[24]

In 1956, a new view on the research field of complex information processing (CIP) appeared during the *Dartmouth Summer Research Project on Artificial Intelligence* in Hannover, New Hampshire, which symbolizes in today's historiography of informatics a changing of the guard from one generation to the next and from the individual scientific and technological mixtures of *Cybernetics*, *General Systems Theory* and *Information Theory* to the new mixture Artificial Intelligence (AI). This name was enforced by the mathematician John McCarthy (born 1927), one of the project founders among Shannon, the mathematician and neurologist Marvin L. Minsky (born 1927), and IBM-Manager Nathaniel Rochester (1919-2001) but it was not consent of all protagonists, e.g. in Shannon's view this was a non-scientific designation. However, "AI" attracted the military and non-military investor's interests. Since that time the interdisciplinary research field AI has the goal to describe aspects of learning and other abilities of intelligence with big exactness which should enable suitably built machines to simulate these abilities.[25]

From the beginning to our days AI is a research field of many scientists in various different disciplines – mathematicians, physicists, engineers, biologists and psychologists and also social scientists, linguists and philosophers – working together and creating hybrid technological systems and some of them seem to be intelligent, seem to think, seem to have mind.

In 1980 the Berkeley-philosopher John Searle (born 1932) initiated to distinguish *strong* AI from *weak* AI. In *weak* AI the computer (program) is a tool to simulate some of the human mind's properties and therefore weak AI is suitable to study the human mind itself. In contrast, *strong* AI is the view that a computer (program) may have *its own* mind and cognitive states. Then, Searle attacked strong AI making the point that simulations of states are not identical to the state itself. And to equalize both is an error in categories. Searle emphasised that computer programs do not have minds and therefore they are not able to think.[25]

This differentiation in AI research marks the limit of the analogy observation on "Control and Communication in the Animal and the Machine" that was the subtitle of Wiener's *Cybernetics* and that was also behind John von Neumann's thinking when he adopted the neuron model of the mathematician, psychologist and neurologist Warren McCulloch (1898-1969) and his co-worker Walter Pitts (1923-1969) that considered the network system of neurons in a natural brain as a computer[27] and drew the inverse conclusion: If the neural network of a natural brain is essentially a computer, then it must also be possible to describe computers with the help of elements similar to nerve cells.[28]

In 1957/1958, the psychologist Frank Rosenblatt (1928-1969) developed together with the engineer Charles Wightman at the Cornell Aeronautical Laboratory at Cornell University a machine for pattern classification, called *Mark I Perceptron*. It was the first model of an artificial neural network which was capable of learning and in which it could be shown that the proposed learning algorithm was always successful when the problem had a solution at all. It appeared to be a universal machine and Rosenblatt had also heralded it as such when he wrote: “For the first time, we have a machine which is capable of having original ideas. [...] As concept, it would seem that the perceptron has established, beyond doubt, the feasibility and principle of nonhuman systems which may embody human cognitive functions.”[29]

The general euphoria came to an abrupt halt when about 10 years later Marvin Minsky and his co-worker Seymour Papert completed their study of perceptron networks and published their findings in a book.[30] The results of the mathematical analysis to which they had subjected Rosenblatt’s perceptron were devastating: Artificial neural networks like those in Rosenblatt’s perceptron are not able to overcome many different problems! For example, it could not discern whether the pattern presented to it represented a single object or a number of intertwined but unrelated objects. The perceptron could not even determine whether the number of pattern components was odd or even. Yet this should have been a simple classification task that was known as a “parity problem”

As a consequence, the whole research on artificial neural networks suffered a setback and therefore did not play an important role until the 1980s when the research group of the psychologist James L. (Jay) McClelland (born 1938) presented an enlarged neural network with “hidden layers” that is able to overcome the problems and is suitable to represent all logical propositional combinations. Thus, these “Multi-Layer-Perceptrons” were the starting point of the research project of *Parallel Distributed Processing* as a new direction in AI research that was also the name of the later so-called “bible for cognitive scientists”, published in 1986, *Parallel distributed processing: Explorations in the microstructure of cognition*[31] by the psychologists James L. (Jay) McClelland (born 1938) and David Rumelhart (born 1942).

The field experienced a renaissance in the 1990s and artificial neural networks have developed to be one of the main disciplines in AI and also in SC/CI at the present day. We will accent in the next section that SC as a new interdisciplinary mixture of scientific research with new goals of hybrid systems in the last decade finally opened the doors to AI.

## 2. Hard Computing versus Soft Computing

The history of AI is a story of several successes but has yet lagged behind expectations. AI became a field of research to build computers and computer programs that act “intelligently” although no human being controls those systems. AI methods became methods to compute with numbers and find exact solutions. However, not all problems can be resolved with these methods. On the other hand, humans are able to resolve such tasks very well, as Zadeh mentioned in many speeches and articles over the last decades. In conclusion, he stated that “thinking machines” do not think as humans do. From the mid-1980s he focused on “Making Computers Think like People”.[32] For this purpose, the machine’s ability “to compute with numbers” was supplemented by an additional ability that was similar to human thinking.

In 1990 he began to formulate a new scientific concept when he wrote that “what might be referred to as *soft computing* – and, in particular, fuzzy logic – to mimic the ability of the human mind to effectively employ modes of reasoning that are approximate rather than exact. In traditional – hard – computing, the prime desiderata are precision, certainty, and rigor. By contrast, the point of departure in soft computing is the thesis that precision and certainty carry a cost and that computation, reasoning, and decision making should exploit – wherever possible – the tolerance for imprecision and uncertainty. [...] Somewhat later, neural network techniques combined with fuzzy logic began to be employed in a wide variety of consumer products, endowing such products with the capability to adapt and learn from experience. Such neurofuzzy products are likely to become ubiquitous in the years ahead. The same is likely to happen in the realms of robotics, industrial systems, and process control. It is from this perspective that the year 1990 may be viewed as a turning point in the evolution of high MIQ-products[***] and systems. Underlying this evolution was an

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[***] MIQ means “Machine Intelligence Quotient”; Zadeh wrote: “In retrospect, the year 1990 may well be viewed as the beginning of a new trend in the design of household appliances, consumer electronics, cameras, and other types of widely used consumer products. The trend in question relates to a marked increase in what might be called the Machine Intelligence Quotient (MIQ) of such products compared to what it was before 1990. Today, we have microwave ovens and washing machines that can figure out on their own what settings to use to perform their task optimally; cameras that come close to professional photographers in picture-taking ability; and many other products that manifest an impressive capability to reason, make intelligent decisions, and learn from experience.”[32]

acceleration in the employment of soft computing – and especially fuzzy logic – in the conception and design of intelligent systems that can exploit the tolerance for imprecision and uncertainty, learn from experience, and adapt to changes in the operation conditions."[32]

Luis Magdalena comes from these considerations when he distinguishes between "Soft Computing as opposite to Hard Computing" in his fourth chapter[3], where he argues that the "conventional approaches" of Hard Computing (HC) "gain a precision that in many applications is not really needed or, at least, can be relaxed without a significant effect on the solution" and that the "more economical, less complex and more feasible solutions" of SC are sufficient. He points out that using sub-optimal solutions "that are enough" is "softening the goal of optimization" to be satisfied with inferring "an implicit model from the problem specification and the available data". Inversely we can say that without an explicit model we will never find the optimal solution. But this is not a handicap! – SC makes a virtue out of necessity because it is a "combination of emerging problem-solving technologies" for real-world problems and this means that we have only "empirical prior knowledge and input-output data representing instances of the system's behavior. As Magdalena quotes the computer scientist Piero Bonissone: In these cases of "ill-defined systems", that are "difficult to model and with large-scale solution spaces" "precise models are impractical, too expensive, or non-existent". Bonissone continued: "Therefore, we need approximate reasoning systems capable of handling such imperfect information. Soft Computing technologies provide us with a set of flexible computing tools to perform these approximate reasoning and search tasks.[33]

In the 1990s Zadeh established *Computing with Words* (CW) [34, 35] instead of exact computing with numbers, as a method for reasoning and computing with perceptions based on the theory of fuzzy sets. He stated that "the main contribution of fuzzy logic is a methodology for computing with words. No other methodology serves this purpose"[34] and his new *Computational Theory of Perceptions* (CTP) is based on the methodology of CW (Fig. 5).

In CTP, words play the role of labels of perceptions and, more generally, perceptions are expressed as propositions in natural language."[35]

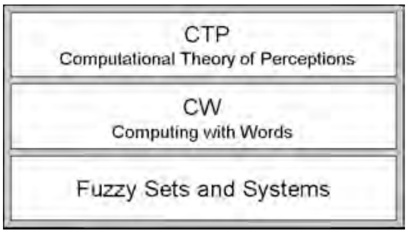

Fig. 5. Zadeh's hierarchical stack of SC methodologies.

He was inspired by the "remarkable human capability to perform a wide variety of physical and mental tasks without any measurements and any computations. Everyday examples of such tasks are parking a car, playing golf, deciphering sloppy handwriting and summarizing a story. Underlying this capability is the brain's crucial ability to reason with perceptions – perceptions of time, distance, speed, force, direction, shape, intent, likelihood, truth and other attributes of physical and mental objects."[36]

Zadeh intended to establish a new dimension of AI. His thesis was "that progress has been, and continues to be, slow in those areas where a methodology is needed in which the objects of computation are perceptions – perceptions of time, distance, form, direction, color, shape, truth, likelihood, intend, and other attributes of physical and mental objects." Thus, he created the new view of "perception-based system modeling", where the input, the output and the states are assumed to be perceptions.[37]

He received an opportunity to propose these considerations concerning "A New Direction in AI" to the AI community, when his manuscript was accepted for the *AI Magazine* issue in the spring of 2001.[38]

## 3. Complexity and Science

Warren Weaver's paper "Science and Complexity" based upon material for a series of radio talks, presenting aspects of modern science, given as intermission programs during New York Philharmonic-Symphony broadcasts. They appeared in print in the book *The Scientists Speak*[39] and one year later the "Science and Complexity", which arose from the book's first chapter, was published in the *American Scientist*[4]. Regarding the history of sciences, Weaver said "that the seventeenth, eighteenth, and nineteenth centuries formed the period in which physical sciences learned variables, which brought us the telephone and the radio, the automobile and the airplane, the phonograph and the moving pictures, the turbine and the Diesel engine, and the modern hydroelectric power plant." Compared to that, he assessed the development of life sciences elsewise: "The concurrent progress in biology and medicine was also impressive, but that was of a different character. The significant problems of living organisms are seldom those in which one can rigidly maintain constant all but two variables. Living things are more likely to present situations in which a half-dozen or even several dozen quantities are all varying simultaneously, and in subtly interconnected ways. Often they present situations in which the essentially important quantities are either non-quantitative, or have at any rate eluded identification or measurement up to the moment. Thus biological and medical problems often involve the consideration of a most complexly organized whole."[4]

In summary, Weaver distinguished here between "problems of simplicity" that "physical science before 1900 was largely concerned with", and another type of problems that "life sciences, in which these problems of simplicity are not so often significant", are concerned with. The life sciences "had not yet become highly quantitative or analytical in character", Weaver stated in the late 1940s. Then, he enlarged on the new developed approach of probability and statistics in the area of exact sciences at around 1900: "Rather then study problems which involved two variables or at most three or four, some imaginative minds went to the other extreme, and said. »Let us develop analytical methods which can deal with two billion variables.« That is to say, the physical scientists, with the mathematician often in the vanguard, developed powerful techniques of probability theory and statistical mechanics to deal with what may be problems of *disorganized complexity*", a phrase that "calls for explanation" as he wrote, and he entertained this as follows: A problem of disorganized complexity "is a problem in which the number of variables is very large, and one in which each of the many variables has a behavior which is individually erratic, or perhaps totally unknown. However, in spite of this helter-skelter, or unknown, behavior of all the individual variables, the system as a whole possesses certain orderly and analyzable average properties."[4]

Weaver emphasized that probability theory and statistical techniques "are not restricted to situations where the scientific theory of the individual events is very well known" but he also attached importance to the fact that they can also "be applied to situations […] where the individual event is as shrouded in mystery as is the chain of complicated and unpredictable events associated with the accidental death of a healthy man." He stressed "the more fundamental use which science makes of these new techniques. The motions of the atoms which form all matter, as well as the motions of the stars which form the universe, come under the range of these new techniques. The fundamental laws of heredity are analyzed by them. The laws of thermodynamics, which describe basic and inevitable tendencies of all physical systems, are derived from statistical considerations. The entire structure of modern physics, our present concept of the nature of the physical universe, and of the accessible experimental facts concerning it, rest on these statistical concepts. Indeed, the whole question of evidence and the way in which knowledge can be inferred from evidence are now recognized to depend on these same statistical ideas, so that probability notions are essential to any theory of knowledge itself."[4]

But there is more to this paper than that! In this article at the end of the 1940's Weaver mentioned – may be for the first time at all – a trichotomy of scientific problems: In addition to, and in-between, the "problems of simplicity" and the "problems of disorganized complexity" he identified another kind of scientific problems: "One is tempted to oversimplify, and say that scientific methodology went from one extreme to the other—from two variables to an astronomical number—and left untouched a great middle region. The importance of this middle region, moreover, does not depend primarily on the fact that the number of variables involved is moderate—large compared to two, but small compared to the number of atoms in a pinch of salt. The problems in this middle region, in fact, will often involve a considerable number of variables. The really important characteristic problems of this middle region, which science has as yet little explored or conquered, lies in the fact that these problems, as contrasted with the disorganized situations which statistics can cope, show the essential feature of organization. In fact, one can refer to this group of problems as those of *organized complexity*."[4] (Fig. 6) He listed examples of such problems:

- What makes an evening primrose open when it does?
- Why does salt water fail to satisfy thirst?
- Why can one particular genetic strain of microorganism synthesize within its minute body certain organic compounds that another strain of the same organism cannot manufacture?
- Why is one chemical substance a poison when another, whose molecules have just the same atoms but assembled into a mirror-image pattern, is completely harmless?
- Why does the amount of manganese in the diet affect the maternal instinct of an animal?
- What is the description of aging in biochemical terms?
- What meaning is to be assigned to the question: Is a virus a living organism?
- What is a gene, and how does the original genetic constitution of a living organism express itself in the developed characteristics of the adult?
- Do complex protein molecules "know how" to reduplicate their pattern, and is this an essential clue to the problem of reproduction of living creatures?

Although these problems are complex, they are not problems "to which statistical methods hold the key" but they are "problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole". All these are not problems of disorganized complexity but, "in the language here proposed, problems of organized complexity."[4] Weaver specified some more of these questions:

- On what does the prize of wheat depend?
- How can currency be wisely and effectively stabilized?
- To what extend is it safe to depend on the free interplay of such economic forces as supply and demand?
- To what extend must systems of economic control be employed to prevent the wide swings from prosperity to depression?
- How can one explain the behavior of pattern of a group of persons such as a labor union, or a group of manufacturers, or a racial minority?
- With a given total of national resources that can be brought to bear, what tactics and strategy will most promptly win a war, or better: what sacrifices of present selfish interest will most effectively contribute to a stable, decent, and peaceful world?

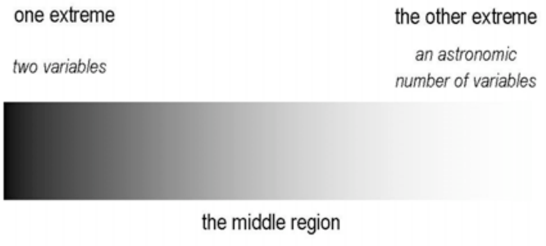

Fig. 6. Weaver's trichotomy of scientific problems.

With regard to these problems Weaver stressed that the involved variables are "all interrelated in a complicated, but nevertheless not in helter-skelter, fashion" that these complex systems have "parts in close interrelations", and that "something more is needed than the mathematics of averages."[4]

"These problems—and a wide range of similar problems in the biological, medical, psychological, economic, and political sciences—are just too complicated to yield to the old nineteenth-century techniques …" and "these new problems, moreover, cannot be handled with the statistical techniques so effective in describing average behaviour in problems of disorganized complexity." "These new problems – and the future of the world depends of many of them, requires science to make a third great advance, an advantage that must be even greater than the nineteenth-century conquest of problems of simplicity or the twentieth-century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of organized complexity."[4]

In my judgment science performed this task in fact with some new concepts and theories, which have – of course – their roots in earlier decades or centuries, but have got developed in the second half of the 20th century, e.g. *self-organization*, *synergetic*, *chaos theory*, *fractals*, and the technologies of SC with the central theory of fuzzy sets and systems! Already in the beginning of Zadeh's call for a non-probabilistic and non-statistical mathematical theory of fuzziness it is understood that he kept sets of problems at the back of his mind, that are very similar to Weaver's trichonomy, when he described problems and applications of System Theory and its relations to network theory, control theory, and information theory in the paper “From Circuit Theory to System Theory” in 1962. He pointed out that “largely within the past two decades, by the great progress in our understanding of the behaviour of both inanimate and animate systems—progress which resulted on the one hand from a vast expansion in the scientific and technological activities directed toward the development of highly complex systems for such purposes as automatic control, pattern recognition, data-processing, communication, and machine computation, and, on the other hand, by attempts at quantitative analyses of the extremely complex animate and man-machine systems which are encountered in biology, neurophysiology, econometrics, operations research and other fields”[40]

Then, in this paper he used for the first time the term “fuzzy” without exact knowing, what kind of theory he would create two years later:

“In fact, there is a fairly wide gap between what might be regarded as „animate“ system theorists and „inanimate“ system theorists at the present time, and it is not at all certain that this gap will be narrowed, much less closed, in the near future. There are some who feel that this gap reflects the fundamental inadequacy of the conventional mathematics – the mathematics of precisely-defined points, functions, sets, probability measures, etc. – for coping with the analysis of biological systems, and that to deal effectively with such systems, which are generally orders of magnitude more complex than man-made systems, we need a radically different kind of mathematics, the mathematics of fuzzy or cloudy quantities which are not describable in terms of probability distributions. Indeed, the need for such mathematics is becoming increasingly apparent even in the realm of inanimate systems, for in most practical cases the a priori data as well as the criteria by which the performance of a man-made system is judged are far from being precisely specified or having accurately-known probability distributions.”[40]

Of course when Zadeh called for this “fuzzy mathematics” in 1962 he could not know what fuzzy sets and systems would be when he would create this theory two and a half year later.

## 4. SC and Computational Intelligence

The concept of *Computational Intelligence* (CI) was introduced by the computer scientist James C. Bezdek in 1994: “A system is computationally intelligent when it: deals with only numerical (low-level) data, has pattern recognition components, does not use knowledge in the AI sense; and additionally when it (begins to) exhibit 1) computational adaptivity, 2) computational fault tolerance, 3) speed approaching human-like turnaround and 4) error rates that approximate human performance.” The adjective “computational” was intended to refer to subsymbolic problem representation, knowledge aggregation and information processing. Bezdek pointed out that the concept “CI” is, however, only seductive as long as the concept of intelligence is no better defined than it currently is. [41]

However, in the 1990s CI was a collection of methods but meanwhile there exist attempts to characterize this research area explicitly. Considering the problems CI is concerned with, the computer scientist Włodziław Duch wrote in 2007: „CI studies problems for which there are no effective algorithms, either because it is not possible to formulate them or because they are NP-hard and thus not effective in real life applications!”[42]

As opposed to artificial (or inanimate) systems, animate systems like living brains are able to solve problems for which there are no effective computational algorithms: „extracting meaning from perception, understanding language, solving ill-defined computational vision problems thanks to evolutionary adaption of the brain to the environment, survival in a hostile environment.“[42] Here, we reach the basics of *natural* intelligence but – as a matter of course – it is important to distinguish between *natural* intelligence and *artificial* intelligence (AI). Duch surmises that “the idea that all intelligence comes from symbol manipulation has been perhaps misunderstood by the AI community.” When the psychologists Alan Newell (1927-1992), Herbert A. Simon (1916-2001) and John Clifford Shaw (1922-1991), the so-called NSS-group[†††] of the Carnegie-Rand[‡‡‡] group, presented on the 1956 founding AI workshop in Dartmouth the *Logical Theory Machine*, that could proof mathematical theorems in elementary logic, and also when they presented three years later the *General Problem Solver*,[42] they dealt with formal symbol manipulations. However, Duch stressed that these authors “wrote about physical symbols, not about symbolic variables. Physical symbols are better represented as multi-dimensional

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[†††] NSS was the name of a chess program, the initials of its authors.

[‡‡‡] Carnegie-Mellon University and Rand-Corporation.

patterns representing states of various brain areas. Symbolic models of brain processes certainly do not offer accurate approximations for vision, control or any other problem that is described by continuous rather then symbolic variables. Approximations to brain processes should be done at a proper level to obtain similar functions. Symbolic dynamics […] and extraction of finite state automata from recurrent networks […] may provide useful information on dynamical systems, and may be useful in modelling transition between low-to high level processes."[42]

He noticed that the problems that "are at present solved in a best way by the AI community using methods based on search, symbolic knowledge representation, reasoning with frame-based expert systems, machine learning in symbolic domains, logics and linguistic methods, are "non-algorithmizable problems involving systematic thinking, reasoning, complex representation of knowledge, episodic memory, planning, understanding of symbolic knowledge". To solve these problems "higher level cognitive functions are required".[42] On the contrary, "a good part of CI research is concerned with low-level cognitive functions: perception, object recognition, signal analysis, discovery of structures in data, simple associations and control. Methods developed for this type of problems include supervised and unsupervised learning by adaptive systems, and they encompass not only neural, fuzzy and evolutionary approaches but also probabilistic and statistic approaches, such as Bayesian networks or kernel methods."[42]

Duch states that there is "little overlap between problems solved using low and high-level mental functions, although they belong to the same broader category of non-algorithmizable problems." From this perspective he accentuates distinctly: "*AI is a part of CI* focusing on problems that require higher cognition and at present are easier to solve using symbolic knowledge representation.[§§§] It is possible that other CI methods will also find applications to these problems in future. The main overlap areas between low and high-level cognitive functions are in sequence learning, reinforcement and associative learning, and distributed multi-agent systems. All tasks that require reasoning based on perceptions, such as robotics, automatic car driving, autonomous systems, require methods for solving both low and high-level cognitive problems and thus are a natural meeting ground for AI experts with the rest of the CI community."[42]

These problems Warren Weaver would have ranked among the "problems of organized complexity" but – of course – they have not been known in the last 1940s. Nevertheless, these problems are complex, their parts are in close interrelations, they are just too complicated to yield to the old nineteenth-century techniques to solve the "problems of simplicity" and also they cannot be handled with the methods of probability theory and statistical techniques, thus these problems are to find in Weaver's "middle region". As we quoted already in chapter 4, he wrote at the end of the 1940s in force that "something more is needed than the mathematics of averages" and: "Science must, over the next 50 years, learn to deal with these problems of organized complexity."[4] Well, from my point of view, science learned to deal with these problems in the last 50 years of the 20th century when scientists developed the theories and methodologies of CI and SC.

Duch emphasized two years ago: "Computational Intelligence is certainly more than just the study of the design of intelligent agents, it includes also study of all non-algorithmizable processes that humans (and sometimes animals) can solve with various degree of competence, and the engineering approaches to solve such problems using hardware and software systems."[42]

Magdalena, expresses in the present paper at hand "the idea of CI being the branch of science considering those problems for which there is not an exact model, plus those cases where the model exists but its consideration is not computationally effective, i.e., *when we need to reduce the granularity or soften the goal.*" He also brought out that these ideas describe also "SC as the opposite to hard computing or based on its essential properties. So, apparently there is no significant difference between Soft Computing and Computational Intelligence." [3]

## 5. Soft Computing – the Bridge

As we have seen in the last chapters, SC is a new and interdisciplinary mixture of modern technologies, it solves problems of "organized complexity" that Weaver classified as a "middle region" between the "problems of simplicity", which can be solved by the analytical techniques that have been developed during the period from the 17th to the 19th century, and the "problems of

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[§§§] Italics are not in the original paper.

disorganizes complexity" that are handled by the methods of probability theory and statistics. Furthermore SC is the opposite of hard computing (HC) and it is almost equipollent to the also new scientific field of Computational Intelligence (CI) that comprises Artificial Intelligence (AI). AI and CI (and SC) meet in the fields of the different kinds of learning, distributed multi-agent systems and "reasoning with perceptions" and thus, we can say that SC/CI is a bridging of HC and brain processes. "The division between low and high-level cognitive functions is only a rough approximation to the processes in the brain"[42] wrote Duch; in this amount of space, in this "middle region" Zadeh intends to place the "Computational Theory of Perceptions" (CTP) as the top of the hierarchy of methodologies in SC (see Fig. 3). We will find also in this region learning processes that are modelled with artificial neural networks and optimization methods that result from evolutionary algorithms and CTP may use these techniques to approximate the natural processes and optimization strategies.

SC is also a bridging of the brain, natural languages and their man-made mathematical models: In his invited lecture for the AGOP 2009[****] the mathematician Enric Trillas said: "As one of the brain's activity, language appeared after brain is actually commanded through some brain functions and, in this sense, perhaps language is no less complex than brain functioning is. In addition, there is a relevant aspect that makes language less known than brain is. This lies in the amount of specific knowledge expressed in scientific terms neurobiologists do have on the functioning of the brain, something that is not the case with language since it is not currently treated as a natural experimental discipline concerning a special type of living being. Such a new discipline, provided it was created, could result in an upmost interest for the advancement of Computing with Words and Perceptions (CWP). At the end, brain functioning is closely related with the electro-chemical processing of perceptions, and language with the representation and communication, or spreading of such processing. […] Concerning the mathematical modelling of language, and the possible benefits that can follow from some results in fuzzy logic, it could be interesting to recall, for instance, the presence of symmetry in the way of obtaining the membership function on an antonym, or opposite, of a linguistic term *P* from a membership function of *P*.

Antonymy is an important feature of language, and since symmetry is a pervasive concept in the world, and also in the brain, possibly it should play some relevant role in language, and hence it could deserve to be studied for a deeper characterization of language. This is a challenging subject for mathematicians and computer scientists interested in CWP. "[44]

To bridge the gap between natural and artificial languages there is also Zadeh's concept of "Precisiated Natural language" (PNL) that he introduced already in his 2001 *AI-Magazine* article.[38] In 2004 he described the conceptual structure of PNL as a basis for CTP in greater detail.[45] However, we mentioned already in our introduction that we see an affinity between Zadeh's PNL and the "as yet [1948] undiscovered universal language" that Weaver's assumed to be the "common base of human communication"[9] and in chapter 2 we stressed the fuzziness of the semantic and the pragmatic level of the communication problem that Weaver described in connection with Shannon's communication scheme – sure enough without using the term "fuzzy".

## 6. Conclusions

We like to portray SC in two more aspects of SC as a bridging! Firstly, SC is a bridge of internationality. Zadeh wrote in 1991 that the creation of SC was also intended to inhibit nationalistic thinking in science: "Its genesis reflected the fact that in science, as in other realms of human activity, there is a tendency to be nationalistic – to make an exclusive commitment to a particular methodology and proclaim that it is superior to all others. It is this mentality that underlies the wellknown hammer principle: when the only tool you have is a hammer, everything looks like a nail."[2]

When Weaver was looking for "invariant properties which are, again not precisely but to some statistically useful degree, common to all languages" his diction sounds very similar: "All languages—at least all the ones under consideration here—were invented and developed by *men*, whether Bantu or Greek, Islandic or Peruvian, have essentially the same equipment to bring to bear on this problem. They have vocal organs capable of producing about the same set of sounds (with minor exceptions, such as the glottal click of the African native). Their brains are of the same general order of potential complexity. The elementary demands for

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[****] First International Summer School on Aggregation Operators.

language must have emerged in closely similar ways in different places and perhaps at different times. One would expect wide superficial differences; but it seems very reasonable to expect that certain basic, and probably very nonobvious, aspects be common to all the developments."[9]

Secondly, SC is a bridging of the two cultures which the scientist and novelist Charles Percy Snow (1905-1980) described in his Rede lectures[46] in 1959, *sciences* at one hand and *humanities* at the other. At that time, Snow claimed that in the "modern society" the communication between these two scientific cultures broke down and that this breakdown hindered the solving of the world's problems. This reminds us (see chapter 2) of the four years later organized *Second Systems Symposium* where researchers from science and engineering, and also from social sciences, economics and humanities came together to start a cooperation – and that this activity was a flop!

How can we override this situation? – Zadeh recommended that instead of "an element of competition" between the complementary methodologies of SC "what the coalition that has to be formed has to be much wider: It has to bridge the gap between HC and SC, it has to bridge the gap between the different communities in various fields of science and technology and it has to bridge the gap between science and humanities and social sciences! SC is a suitable candidate to meet these demands because – as we saw in the last chapters – it opens the fields to philosophy and social sciences, to linguistics and semiotics and also to other areas of mankind activities.

From his experience in the World War II, Weaver found among the "wartime development of new types of electronic computers" a second wartime advance, the "mixed-team" approach of operational analysis: "Although mathematicians, physicists, and engineers were essential, the best of the groups also contained physiologists, biochemists, psychologists, and a variety of representatives of other fields of the biochemical and social sciences. Among the outstanding members of English mixed teams, for example, were an endocrinologist and an X-ray crystallographer. Under the pressure of war, these mixed teams pooled their resources and focused all their different insights on the common problems. It as found, in spite of the modern tendencies toward intense scientific specialization, that members of such diverse groups could work together and could form a unit which was much greater than the mere sum of its parts. It was shown that these groups could tackle certain problems of organized complexity, and get useful answers."[4] Not only in wartimes but also in times of peace Weaver considered possible that mixed teams that bridge the gaps between natural sciences, engineering sciences, computer sciences, social sciences and humanities could achieve solutions of the world's problems. Continuing this thinking SC plays a key role in science and technology of the 21st century.

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