Acceptance speech on receiving an
Honorary Degree from the University of Bologna

The Nature of Computation and Computation in Nature

I feel very honored to receive the Honorary Degree from the famous University of Bologna.

I would like to reflect on this occasion on the historical development of the science of computation and on natural computing.

The classic notion of computation is firmly rooted in the notion of an algorithm that informally speaking is a set of rules for performing a task. The quest for formalizing the notion of an algorithm so that it could be "mechanised" dates back at least to the work of Gottfried W. Leibnitz. Leibnitz (1646-1716) wanted to formalize human reasoning in such a way that it could be described as a collection of rules, which then could be executed in a mechanistic way.

The motivation for his passionate research was stated by Leibnitz as follows: "it is unworthy of excellent men to loose hours like slaves in the labor of calculation which could safely be relegated to anyone else if the machine was used". Thus the motivation was rooted in the specific "negative idea" that the task of performing calculations is a waste of time. This however can be turned into a positive motivation, viz., the need to understand which mental processes can be formalized so that they can be automated - this point of view is closer to the current thinking in computer science.

This research into the understanding of the notion of an algorithm was carried on by many outstanding scientists and it culminated in the works of Kurt Gödel, Alonzo Church, Alan Turing and Emil Post approximately in the period 1930-1940.

The formalization of the notion of an algorithm by these four giants, and especially the work by Alan Turing, led to the construction of the first computers, and to the beginnings of Computer Science. In formalizing the notion of an algorithm, Turing has focussed on what a person performing calculations did when following a set of rules, hence following a given algorithm. Thus the beginnings of computer science were rooted in human-designed computing.

The scope and importance of computer science grew tremendously since its beginnings. In fact, the spectacular progress in Information and Communication Technology (ICT) is very much supported by the evolution of computer science which designs and develops the instruments needed for this progress: computers, computer networks, software methodologies, etc. Since ICT has such a tremendous impact on our everyday life, so does computer science.

However, there is much more to computer science than ICT: it is the science of information processing, and as such it is a fundamental science for other scientific disciplines. As a matter of fact, the only common denominator for research done in all so diverse areas of computer science is thinking about various aspects of information processing. Therefore, the frequently used (mostly in Europe) term "Informatics" is much better than "Computer Science" - the latter stipulates that a specific instrument, viz., computer, is the main research topic of our discipline. On the other hand, one of the important developments of the last century for a number of other scientific disciplines is the adoption of Information and Information Processing as their central notions and thinking habits - biology and physics are beautiful examples here. For these scientific disciplines informatics provides not only instruments but also a way of thinking.

I am convinced that one of the Grand Challenges of informatics is to understand the world around us in terms of information processing. Each time progress is made in achieving this goal, both the world around us and informatics benefits. Since nature is a dominating part of the world around us, one way to understand this world in terms of information processing is to study computing taking place in nature. Natural Computing is concerned with this type of computing as well as with its main benefit for informatics, viz., human-designed computing inspired by nature. Research in natural computing is genuinely interdisciplinary, and therefore natural computing forms a bridge between informatics and natural sciences. It has already contributed enormously to human-designed computing through the use of paradigms, principles and mechanisms underlying natural systems. Some disciplines of this type of computing are relatively old (in the young history of computer science) and are well established by now. Well known examples of such disciplines are evolutionary computing and neural computing. Evolutionary algorithms are based on the concepts of mutation, recombination and natural selection from the theory of evolution, while neural networks are based on concepts originating in the study of the highly interconnected neural structures in the brain and the nervous system. On the other hand, molecular computing and quantum computing are younger disciplines of natural computing: molecular computing is based on paradigms from molecular biology, while quantum computing is based on quantum physics and exploits quantum parallelism. Human-designed computing inspired by nature includes also other subdisciplines and paradigms.

Thus research in natural computing had already a big impact on the development of informatics, and in particular it contributed to our understanding of the nature of computation. Since the understanding of the nature of computation is the main task of theoretical computer science, it is important to point out here that the interaction of theoretical computer science and natural sciences dates back to the very beginnings of computer science and has continued since then. Here are some examples of this interaction.

Some of the most important foundational research in automata theory was inspired by the work of W.S. McCulloch and W. Pitts which considers neurons as binary transmitters of information. The theory of L-systems initiated by A. Lindenmayer was motivated by modelling the development of simple organisms and it had a fundamental impact on formal language theory, as well as a significant impact on the modelling of plants. The DNA revolution which in the last 50 years had such tremendous impact on biology and many other areas of science (as well as on our everyday's life) had also a big influence on theoretical computer science. For example, the overwhelming success in sequencing of the human and other genomes was to a large extend based on the development of pattern matching and other string processing algorithms. The whole area of design and analysis of pattern matching and editing algorithms benefited enormously from the intense research concerned with sequencing of genomes.

As clear from the above, interdisciplinarity is a key feature of research in natural computing, and an important ingredient of evolution of the whole field of informatics.

I consider myself to be an interdisciplinary scientist. The support for this classification is given by my education and my research. My first degree is an engineer of electronics, my second degree is a Master in Computer Science, and my third degree is a Ph.D. in Mathematics. Then, for over 30 years, a big part of my research was concerned with the understanding of the principles of biological information processing. A considerable part of this research involved an intense cooperation with biologists. Therefore I would like to say a few words now about interdisciplinary research, and in particular about research in natural computing. Since my interdisciplinary research involves theoretical computer science on one hand and biology on the other, my reflections concern this specific research interaction.

Research on formal modelling of biological phenomena requires an a priori realization that the value or utility of the obtained models may be quite temporary. A formal model will at best reflect the biological knowledge at the time of its formulation. Biological knowledge is very dynamic, and new important facts are discovered all the time - some of these findings may change, sometimes dramatically, our understanding of the nature and working of certain biological phenomena. If they involve a phenomenon that we model, then often the model must be adapted, changed, or even totally discarded. Therefore one should strive, whenever possible, that the formal model is also solid and interesting from the formal point of view. In this way, during an often long trajectory of creating, adapting, and modifying a formal model, one may get an interesting and lasting contribution to theoretical computer science.

Another advice based on my experience is that the formulation of the model should begin with an understanding of the biological nature of the problem, and then continue with a very critical assessment of the tools that we have available (as specialists in theoretical computer science). Very often such a critical assessment will lead to the conclusion that one needs to formulate a genuinely new model, and then develop tools for its study as one goes along. This is definitely a preferred way of proceeding, rather than to bend (and often distort) biological knowledge in such a way that it fits one's tools!!

Finally in developing a formal model one should not forget that such a model consists of two parts: (1) a mathematical formal construct, and (2) its interpretation in the modelled domain. The second part is too often forgotten, while it is often really crucial in the choice of a "good model": among all models that are equivalent (in some formal sense) the only relevant models are those with good interpretability.

Natural computing is a fast growing and dynamic research area. When I introduced this name more than 25 years ago, it was considered as a sort of science fiction, but by today it is really popular and flourishing. There are institutes, journals, book series, conferences, professorships, ... of/on natural computing.

I am myself especially fascinated by Molecular Computing which is a good example of a research area that evolves in a very interesting way. It really begun as DNA Computing with the initial goal of providing a computing technology that will be a competition to the current silicon technology for computers. However, it has evolved into a science of molecular programming concerned with problems of the following type: "How to design a set of initial molecules so that a certain type of molecular complexes will be formed". In this way a large stream of research in molecular programming became a part of nanoscience and nanoengineering, where, e.g., in human-designed self-assembly one considers the same type of problems. The combination of nanoscale science and engineering with nanoscale computing is certainly an exciting development which will have tremendous impact on the science and technology of computing.

Now if we return to the part of natural computing that studies computing taking place in Nature, then the large question is "How does Nature compute?" In order to answer this question we have to consider and study various processes taking place in Nature as computational processes. But what does "computational" mean here? We will have to redefine the notion of computation, which must be able to accommodate also information processing taking place in nature. This is an exciting adventure which has only just begun. I have no doubts that it will lead to a new science of computation which will provide a broader and deeper understanding of what "computation" is about.

Let's now conclude by going back to informatics with all its facets. The attractiveness and beauty of informatics as a science is that while it is a fundamental science for a number of scientific disciplines, it is also the main force behind the development of ICT, and through this development it influences and revolutionizes our everyday life. Natural computing is an important vehicle of progress for both of these facets of informatics. Let's propagate and develop the science of informatics, and present it to "the outside world", using this framework. Both informatics, viewed as above, and natural computing have a great future!!!