Preface

The main problem addressed in this book came out during a Fulbright research fellowship stage at U.C. Berkeley (California, USA, 1996–1998). Then, I had the opportunity to work in the research group of Leon Chua on a subject called CNN (cellular neural/nonlinear network). The CNN, developed in the end of the 1980s was an important step ahead in getting cellular computing closer to practical applications. The CNN is actually a cellular array made of many identical elements interconnected in a neighborhood. But unlike the cellular automata (CA) the CNN was designed as a circuit-oriented architecture being developed up to the point where it serves as a low-power smart sensor or visual microprocessor capable to acquire and process images or multi-dimensional signals in general with processing speeds of the order of 10^{12} (Tera) operations per second. Today, there are several academic and industrial groups providing CNN-based solutions for various practical problems, particularly when high speed processing at low power is needed. Also, researchers in the area of nano-technology recognize cellular computing as a suitable computing paradigm to the specific of these technologies where many identical active elements are available on a mass proportion. Researchers in biology also recognize the cellular paradigm as a well-suited paradigm for models of natural systems. Indeed there is a similarity, as biological systems essentially are functionally meaningful aggregates of mostly local interconnected cells. A brief review of the cellular computing paradigm, its relation to natural computing in general and the state of the art of its use in applications are given in Chaps. 1 and 2 of this book.

At the moment of my arrival at Berkeley a well-established theory of the standard CNN architecture was already developed, and many researchers worked on finding novel applications. Still several problems were recognized as needed to be solved. A first one was to define universal cells, i.e. to find a general nonlinear system describing any arbitrary local interaction (e.g. a Boolean function) within a family of similar functions. A set of parameters of the nonlinear system, called a gene, is supposed to prescribe any particular "individual" from the family of functions. The parallelism with biology is obvious: Here, the DNA string represents the gene while the unfolding mechanism producing and multiplying biological cells may be associated to the cellular nonlinear system and its dynamics. A theory of piecewise-linear representation of cells was then developed and briefly recalled in this book in Chap. 3 since later it turned out to be relevant in a consistent framework for predicting emergence, or as we will call it often throughout this book, for the "design for emergence" of cellular systems.

Indeed, a second problem posed in the mid 1990s for the CNN researchers was to develop a consistent theory of emergence, or in other words to find a way to anticipate how the cellular array (CA) will behave without extensively running the entire CA system. It is a crucial design problem since the space of possibilities in choosing the cells' gene is huge and looking exhaustively to cellular systems behaviors associated with each and all of them is impossible. Researchers in biology face a similar problem in the attempt to "decode" the genome i.e. to understand how different biological behaviors (disorders, diseases, etc.) emerge from a known genome.

A great step towards a theory of emergence is Leon Chua's theory of local activity (published in 1997) as it is able to predict, to a certain degree, the nature of the emergent phenomena within the cellular array, while investigating only the simple nonlinear system associated to the isolated cell. A series of papers were published on this topic providing clues and practical methods for locating the "edge of chaos" as a narrow region within the cells' parameter (or gene) space. Such widely known nonlinear systems as Fitz-Hugh Nagumo model of excitable nervous membranes, the Brusselator and the Gierer-Meinhard's model for morphogenesis were considered, and it was verified that indeed local activity is powerful enough to locate previously reported emergent behaviors but also to discover new ones.

Still, the theory of local activity has some limitations in that it relies on some circuit theory theorems and therefore assumes that the model to be investigated shall be cast into a circuit specific framework. Therefore, the theory can be applied and was done so far solely for Reaction–Diffusion systems. However, there are many other cellular or network-based computing paradigms, as briefly recalled in Chap. 3, that may benefit from a general theory of emergent computation.

Here comes the novelty of this book, which reports recent results aiming to establish a global theory and practice for a "design for emergence" framework.

The first step in designing for emergence was to recognize that one needs to measure emergence. This is the aim of Chap. 4, where several scalar measures were introduced and defined as algorithms operating during the running of a cellular system. Some hints on how to associate various values of these measures to various categories of emergent behaviors were also given.

Chapter 5 comes with an additional measure which later proved to be very interesting in that an equivalent form of it could be determined without running the CA but solely based on the cells' structure.

With accurately defined measures of emergence the next step towards a "design for emergence" framework was to recognize and define tools to select among the entire space of possibilities only those genes related to desired emergent behaviors, described often in a fuzzy natural language. Their definition and some practical aspects of their use are the subjects of Chap. 6.

The most interesting result comes in Chap. 7 where the grounds for a general theory of emergence are provided, using tools from the information theory.

Here, we provide analytic formulae to determine a measure of emergence solely based on cell's structure (its gene) and its neighborhood. Comparisons with the experimentally determined (during the CA running) similar measure confirmed the validity of this new theory called a theory of the probabilistic exponents of growth, for reasons to be detailed within the chapter.

As its name anticipates, probabilities and other notions from information theory play a crucial role in its development. Unlike the theory of local activity, this new theory is rather general and it does not depend too much on the specific cellular system. Although we exemplify it for discrete-time binary-state cellular automata, hints are provided on how to expand it to any type of system. Also, the neighborhood and its parameters are included in the theory, improving its predictive value, when compared with theories such as local activity where emergence is predicted with some degree of uncertainty left on the behalf of the interconnectivity. It can also explain many situations that were previously observed empirically in cellular systems.

While doing several research stages at Institute of Microelectronic Systems at T.U. Darmstadt, Germany in a research group oriented towards solving many practical problems, it turned out that there is a huge demand from the industry to build low power intelligent systems. It later turned out that natural computing approaches like the use of cellular automata systems for various signal processing tasks may dramatically reduce the implementation complexity when compared to traditional solutions. What was needed, were the CA design tools. Once they have been introduced in the previously mentioned chapters, the last chapter of this book presents three different innovative applications of cellular automata in signal processing.

As cellular systems are part of the natural computing systems and the focus of many interdisciplinary research groups, and since myself was formed as an electrical and computer science engineer I wrote the book in an easily to understand style, without too much mathematical formalism. Some programs are also provided within the text to facilitate a faster access of the interested reader to the design for emergence tools. Although mathematicians may not like the lack of formal proofs I encourage readers from this area to browse the book, and I hope that they may extract some useful ideas for a more formal treatment.

Much of the work reported here was done with the support of an Alexander von Humboldt research fellowship, during a stage at T.U. Darmstadt between 2005 and 2006. Some of the chapters in the book were taught as lectures in a course on Natural Computing systems I gave at Darmstadt during this stage. I am deeply indebted to Professor Manfred Glesner, the director of the research group and to many members of his team for their continuous support and hospitality during this stage, as well as for the opening they gave me to seek not only theoretical sides of cellular systems but also to look for convincing practical applications of them. I acknowledge the steady support of Professor Leon Chua who sparkled and stimulated my interest for the fascinating research area of cellular computing systems and shaped deeply my way of thinking. Other sponsors such as the Volkswagen Stiftung are also acknowledged here, particularly for their role in shaping my interest for solving some practical signal processing problems. I am also indebted to colleagues and my former professors from the Applied Electronics and Information Engineering as well as to many friends and colleagues, anonymous reviewers and other persons familiar to my work who gave me some critic feedback in various stages.

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