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Introduction

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Criticality in Neural Systems

Neuroscience is currently experiencing a revolution in the area of monitoring brain activity at ever higher spatial and temporal resolutions. The simultaneous recording of the activity of hundreds or thousands of nerve cells and the observation of averaged activity of large fractions of the whole human brain with ever-increasing precision is leading to a new generation of Big Data. The complexity of the myriads of observed neuronal interactions promises deep insights into how real brains work – how brains assure the survival of the species in highly complex and dynamically changing environments. At the same time, this complexity poses an enormous challenge to our analytical skills and our willingness to break traditional approaches to explore and explain brain function. The nearly century-old and still highly successful approach to neuroscience that maps single neuron responses to select sensory, motor, or associative processes is challenged by the view that it is activity from wide-spread organized neuronal populations that underlies the computational operations of the brain. The view that brain circuits are analogous to both precisely and permanently wired electronic circuits is making way to a picture in which circuit elements continuously change affiliations leading to the emergence of complex spatio-temporal patterns. Yet, will these metaphors provide us with the precision and manipulative potential that is ultimately required to understand brain functions? Are we forced to leave the realm of precise biophysical laws at the single neuron level to enter a level of description in which insights can be expressed only in terms of probabilistic patterns that loosely correlate with brain operations?

In fact, there is a theoretical framework that allows for more than just that, a framework in which precise rules and laws govern the interactions of many elements in distributed, complex systems. It is the theory of criticality that has transformed the study of complex systems in physics and other areas, but has been neglected for a long time in the study of the most complex system in biology – the brain. This volume provides the first comprehensive account of the recent cross-fertilization between neuroscience and the interdisciplinary science of criticality.

Criticality in Neural Systems, First Edition. Edited by Dietmar Plenz and Ernst Niebur.

The firework of insights that this interaction has sparked ranges from studies of isolated neuronal networks to a deep understanding of results of the most advanced imaging of the human brain.

The origins of this book lie in a series of experimental findings predicted by criticality theory, of which the discovery of 'neuronal avalanches' at the National Institute of Mental Health in 2001 was particularly influential. Avalanches are cascades of events that emerge in systems at a critical point, where order and disorder are perfectly balanced. At criticality, the sizes of avalanches in the brain are distributed according to a power law, which establishes a direct link to the theory of critical branching processes and the theory of self-organized criticality introduced by Per Bak and his co-workers in the early nineties. These experiments also tied together earlier work by Arnold Mandell, Scott Kelso, Walter Freeman, Dante Chialvo and others on neuronal phenomena such as critical slowing down in motor program switching, intermittency/variability in neuronal populations, and learning by mistakes at the network level. Over the past decade, the field has experienced rapid expansion with a flurry of new results, both experimental and theoretical. These results, coming from a correspondingly increasing number of researchers, have been published in a variety of journals, as might be expected for a topic at the intersection of two very different fields (the theory of critical phenomena on one side, and neuroscience on the other), both of which are interdisciplinary by themselves. There was, however, not a single place where these various results are shown in context and related to each other.

It was in these circumstances that the editors decided that a compendium summarizing the current state of criticality in nervous systems would be helpful. This is the perfect time to *faire le point* of the field: An impressive body of work has been compiled but it can *just* fit in one book. When contemplating potential chapter authors, we realized that something similar is true for the primary workers in the field: they could *just* fit in one (largish) room. As many of them knew of each other only through their publications, we felt that an in-person meeting and ensuing discussions would contribute considerably to the coherence of the book as well as to the field as a whole. We therefore decided to organize a workshop in 2012 on the NIH campus where nearly all contributors to the book would meet for two days of talks and intense discussions. This workshop was made possible by funding from the National Institute of Mental Health and from the Office of Naval Research. In particular we would like to acknowledge support of this project by Dr. Thomas McKenna from ONR. Because of unavoidable conflicts we could not include some important contributors to the field, but we feel that those left out are a small minority and that we have the field covered nearly completely. That first meeting also spawned a series of annual follow-up conferences, one taking place in Capri, Italy, in 2013, and the next planned for 2014 at the HRL laboratories in Malibu, California.

The book's target audience consists of graduate students and advanced scholars seeking to understand the impact of the paradigm-shifting application of criticality theory on the understanding of neural systems. The first half of the book summarizes current experimental evidence on criticality in the brain, ranging from the discovery of neuronal avalanches, to spatial correlation functions and long-term temporal relationships covering small networks, all the way to observations of critical phenomena in the human brain. A rich mixture of experimental and modeling approaches that include graph theory and neuronal modeling at various levels of detail, from realistic network simulations to more formal and abstract network analysis, introduces the reader to a multitude of modeling approaches regarding criticality and neuroscience. Chapters toward the end of the book expand the theory of criticality formally and conceptually to levels beyond neuronal networks and the brain.

This book fills an important need in the rapidly rising interdisciplinary field of criticality in systems neuroscience. It establishes a solid compendium of current research in this field and we are confident that it will serve as an important entry point for students and future scholars.