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Special Issue on Unsolved Problems of Noise in Physics, Biology and Technology

Introduction: Unsolved Problems on Noise[3]

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Abstract. This paper is an introduction to the special issue of the *7th Int. Conf. on Unsolved Problems on Noise* (UPoN) that took place at Casa Convalescència in Barcelona (Spain) in July 2015. The aim of the UPoN conferences is to provide a forum for researchers working on different fields of noise, fluctuations and variability, where they present their scientific problems which resist solutions. The papers of this Special Issue reflect the interdisciplinary topics (physics, biology, circuits, financial markets, psychology, technology, etc) presented at the UPoN conference. Noise is not only a hindrance to signal detection, but it is indeed a valuable source of information (not present in the signal) that help us to get a deeper understanding on how Nature works.

Keywords: fluctuation phenomena, large deviations in non-equilibrium systems, nonlinear dynamics, stochastic processes

[3] This special issue of the 7th *International Conference on Unsolved Problems on Noise* (UPoN) is dedicated to Laszlo Kish in the occasion of his 60th birthday. He organized the first edition of these UPoN conferences in Szeged (Hungary) in 1996. Many of us have greatly benefited from his 'volcanic imagination in tackling new problems from unconventional points of views'.

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Contents

1. Introduction

This paper is an introduction to the special issue of the *7th Int. Conf. on Unsolved Problems on Noise* (UPoN) that took place at Casa Convalescència in Barcelona (Spain) during July 2015.

1.1. A bit of history

The UPoN conferences aim to provide a forum for researchers working on different fields of noise in physics, biology, circuits, psychology, technology, etc. The first conference, organized by Kish, was held in Szeged (Hungary) in 1996 and was mostly devoted to high technology devices. The second one, organized by Abbott, was hosted in Adelaide (Australia) in 1999 and focused mainly on mathematical aspects and paradoxes in noise and fluctuations. The third one, organized by Bezrukov, was held in the National Institutes of Health campus in Bethesda, Washington (USA), in 2002, and focused mainly on biology, biophysics, and biomedical engineering aspects. The fourth one, organized by Reggiani, was held in Gallipoli (Italy) in 2005, and was devoted to noise and fluctuations at the nanometric scale-length in electron-devices, bio-materials, and mesoscopic systems. The fifth one, organized by Ciliberto, was held in Lyon (France) in 2008, and had a special section on crackling noise that appears in many physical, biological, geological and technological problems. The sixth UpoN conference, organized by Bardhan, took place in Kolkata (India) in 2012, having a

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large impact on spreading the interest on noise in the Indian scientific community. In this latest edition, the conference was organized by Oriols and took place in Barcelona (Spain). The number of summited papers in this 2015 edition was 101 abstracts, whose authors came from 21 different countries all around the world [1]. Let us specify that, for different reasons, not all the papers presented at the 2015 conference are finally included in this Special Issue.

1.2. Why unsolved problems on noise?

In general, our society is fascinated by new scientific developments. We always see newspapers highlighting the latest achievements on physics, genetics, robotics, etc. However, to be honest, our scientific knowledge is much less complete than our society believes. Noise is, repeatedly, a reminder of our scientific ignorance or of our incapacity to perfectly predict the future. Even for fully deterministic theories (like classical mechanics), noise or unpredictability can appear because of the unknown environment, the extreme sensitivity to initial conditions, or due to the complexity of the system. There are even fundamental models (like those for the quantum world) that are intrinsically noisy, where only average values can be predicted. In general, predicting or understanding the behavior of the signal (or average values) is much easier than predicting its noise.

Due to the difficulties in properly understanding noise and its role in Nature, the study of random fluctuations, and their effects on systems, have always been an interdisciplinary subject that has attracted some of the best scientists. The UPoN conferences deal with unsolved problems on noise that are starting to become understandable. At such frontiers of research, our knowledge is still unstable, somehow immature and, certainly, not free from controversies. In this Special Issue many attempts devoted to better understand noise phenomena in different scientific fields can be found, ranging from physics till financial markets, including biology, circuits, psychology, technology, etc.

2. Outlook of the present special issue

The papers in this Special Issue are grouped in six different sections. In the following sections, we introduce and briefly summarize the specific works that can be found in the rest of this Special Issue.

2.1. Theoretical trends in noise and fluctuations

As indicated in the introduction, most of the time our ignorance is due to the complexity (i.e. the large number of microscopic degrees of freedom involved) in most systems of interest. A direct mechanical explanation of such system is really difficult, if not impossible. Statistical mechanics appears then as a really powerful formalism that introduce some probabilistic elements and allows us to understand such complex systems in terms of new macroscopic quantities. One of the theoretical subjects of research in the conference was the fluctuations of complex systems far from their (thermodynamic) equilibrium state. For example, a great experimental and theoretical activity is devoted to the fluctuation theorem, that gives a precise mathematical expression for determining which is the probability that entropy could flow in a direction opposite to that dictated by the second law of thermodynamics. An example for electric circuits and micro devices was presented in [2]. An experimental realization of a Carnot engine was described in [3]. Another relevant topic of research present in the conference was quantum thermodynamics, that tries to provide a deeper quantum mechanical understanding of the (classical) thermodynamic laws. Again the main interest is devoted to systems out of equilibrium [4, 5]. The reconciliation (or not) of a quantum explanation for well-known classical results on noise is another topic of debate [6].

On the other hand, in spite of being a very old problem whose investigation started in the 19th century, the diffusion of particles is still a very active field of research since such transport phenomena is present in many physical and biological systems of current interest. The study of anomalies on the typical diffusion models is of particular relevance [6, 7].

2.2. Quantum noise and coherence

The quantum theory, contrarily to most physical theories like classical mechanics, has an intrinsic source of randomness inside. Even after perfectly fixing all initial conditions of an experiment, the final output is still random, unpredictable. Therefore, the quantum noise of very simple (not complex) systems is still very intriguing. For example, the quantum noise in simple two-particle systems with tunneling and exchange is actually a relevant topic of research [8, 9]. The measurement itself is an unavoidable source of randomness that has to be carefully taken into account in quantum systems [10], specifically when the measurement (collapse of the system) is repeated many times to get information on the high frequency dynamics [11]. As other relevant examples, the effect of noise sources on the transient dynamics of long Josephson junctions is analyzed in [12] and finite-frequency quantum noise in a non-interacting quantum dot is studied in [13].

How to properly include the environment in a open quantum system and its effect on noise is another constant subject of debate. Particularly attractive nowadays is the discussion of heat and temperature interchange between the system and the environment. As indicated in the previous section, when lowering the dimensions of a system, quantum fluctuations become crucial and classical thermodynamics cannot be applied. A rigorous description of heat exchange in quantum systems is presented in [14] and a particular example in quantum dots is studied in [15]. Finally, a quantum particle strongly interacting with a bath is developed in [16].

2.3. Fluctuations in materials and devices

From an engineering point of view, understanding the sources of noise is a mandatory requirement to avoid or minimize interferences with the signal. On the contrary, from a physical point of view, the noise itself contains new physical phenomena that help us to get a better understanding on how Nature works. This dichotomy is clearly present in all sections of this Special Issue and, in particular, in this section devoted to noise in materials and devices.

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As expected, noise in graphene materials and devices had a relevant repercussion in the conference [17–19]. Similarly, investigations on the plasmonic noise in terahertz electronic devices were also discussed [19, 20]. In [21] the occurrence of noise reduction effect in semiconductors embedded in sub-THz electric fields is studied. This is an example of the well-known phenomena of stochastic resonance, where the system performance *resonates* at a particular noise level.

The ubiquity of $1/f$ noise is one of the oldest puzzles of contemporary physics and science in general. After almost a century of study, it is still a controversial topic of discussion on its origins [22] and on how it can be minimized in graphene structures [17], ultrathin gold nanowires [23], doped manganite crystal [24] and in bulk acoustic wave resonators [25]. Finally, how to treat the (local) spatial distribution of electrical power and its fluctuations in quantum devices is presented [26].

2.4. Fluctuations in biological systems

This section has a specially broad scope. Biology is a natural science concerned with the study of life and living organisms. The complexity of such systems runs from cells as the basic units of life, till attempts to provide a physiological understanding of conscious and unconscious human behavior. In the former, biology meets physics (the so-called biophysics) and typical noise models of inanimate systems (such diffusive models [28] or Coulomb blockade [27]) are extrapolated to simple biological systems [27, 28]. The fluctuations in such small biological systems can also be used to defined an effective temperature [29]. Specially interested is the study of fluctuations in molecular motors (proteins that are able to do work and subjected to stochastic dynamics because of thermal fluctuations) that can provide information, for example, on the length of DNA [30] or on the complex molecular dynamics [31].

Fluctuations in much more complex biological systems, like our brain, require however more phenomenological rules. A paradigmatic example of the usefulness of noise models in our own health is shown in [32] where the role of fluctuations on cancer growth dynamics is presented. As another example, the role that noise plays in the transmission of information in the brain is studied in [33]. Spontaneous human activity is not free from stochastic behavior whose modeling can provide useful rules about human condition [34].

2.5. Noise in complex systems

In this section, the reader will find research on mathematical models dealing with noise. As in many other disciplines, the mathematical language used to study the fluctuations of physical systems is becoming increasingly sophisticated. The solution of exotic stochastic differential equations like those in [35], the Van der Pol type oscillator [36], or eigenvalues and eigenvectors of random matrices [37] are some relevant examples.

The reader can also find in this section a study on how absolute negative mobility in classical systems can be enhanced by noise [38]. Finally, the spectral power density of the coordinates of particles in an infinitely deep rectangular well is analyzed in [39]. All these types of abstract mathematical models of noise find, later, very relevant practical applications in many different research fields, such as biology, chemistry, financial markets, etc.

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2.6. Applications of noise

As repeatedly stressed throughout this paper, the knowledge of a whole performance of a system beyond its signal behavior provides a deeper understanding (with multiples advantages) of the whole system behavior. For example, the fluctuations in the periodic motion of kayak-paddlers can be used to better estimate their performance [40]. Another example is the Allison mixture to study how unintuitive correlations (or autoinformations) can be obtained from a random sampling of two uncorrelated parent processes [41]. Browian motion can be used to develop optimal search strategies in our everyday life [42]. Similar arguments can be employed to develop winning strategies by switching in a sequence of Parrondo games (in which two losing games can be combined to become a winning one) [43]. An example on how the addition of noise can even improve the contrast between two states of the signal in a resistive switching device is presented in [44]. The latter is another practical example of the stochastic resonance mentioned in a previous section. A paradigmatic example of how relevant the random fluctuations are in the dynamics of (very) big natural systems is mentioned in [45] where the phytoplankton dynamics in the Tyrrhenian sea is studied.

3. Final remarks

As a final remark, we want to sincerely thank all the participants of the UPoN conference for their fruitful cooperation in the conference. During one week, all participants contributed to the success of the conference by promoting discussions on noise, asking and answering questions, in a friendly atmosphere. As an overall summary of this brief introductory paper of the Special Issue, as indicated in the abstract, noise is not only a hindrance to signal detection, but it is indeed a valuable source of information (not present in the signal) that help us to get a deeper understanding on how Nature works. Paraphrasing Peter McClintock in a previous UPoN conference [46], we conclude that: 'noise is starting to look altogether friendlier and more useful than it did in earlier times'.

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