SURF@IFISC 2024 Proposals

1. The effects of delay on stochastic evolutionary games

Advisor: Tobias Galla

Evolutionary game theory models the interaction of individuals in a population. These can be "players" in a society, who receive payoffs and update their actions through learning. Evolutionary game theory is also used to describe biological populations. Different "species" interact, compete and reproduce based on payoff. There is a well established formalism for evolutionary games, either through deterministic replicator equations (describing infinite populations), or stochastic individual-based models for finite populations.

In this project, you will investigate the effects of delayed learning and/or delayed payoffs on the outcome of evolutionary dynamics. To do this you will use tools from nonlinear dynamics and statistical mechanics, in particular numerical integration of delay differential equations (modified Runge-Kutta methods) and stochastic simulations of individual-based systems (e.g., Gillespie algorithm — prior knowledge not expected). Where possible we will also try to proceed analytically (e.g., stability analysis).

A genuine interest in theoretical aspects of nonlinear dynamics and statistical physics is required to carry out the project. At the same time strong programming skills are assumed as well. For example, one of the first task for the student would be to integrate differential equations of the form dot x = x(1-x)(ax+b) numerically (with a and b constants), and to analytically determine fixed points and their stability. I would normally expect the student to be able to do this (with some initial guidance), or to be able to learn the required methods independently at the beginning of the project.

2. Using Deep Learning to outperform network science

Advisor: Massimiliano Zanin

Two of the most interesting concepts that have been shaking science in the last couple of decades are complex networks and Deep Learning. While they may seem completely different, several works have started exploring the possibility of merging both theories, up to the point of showing that Deep Learning models can be trained to recover classical topological metrics (1, 2). Yet, one major question is still in the air: which one is better? In this project we will build upon models of complex networks with known topological characteristics, and compare the capacity of Deep Learning models for detecting such characteristics against what standard network metrics can achieve. The student must have a good knowledge of Python and of its standard libraries; previous experience in data analysis and concepts of Deep Learning will also positively be evaluated.

(1) Wandelt, S., Shi, X., & Sun, X. (2020). Complex network metrics: Can deep learning keep up with tailor-made reference algorithms?. IEEE Access, 8, 68114-68123.
(2) Liu, C., Cao, T., & Zhou, L. (2022). Learning to rank complex network node based on the self-supervised graph convolution model. Knowledge-Based Systems, 251, 109220.

3. Maxwell demon at the nanoscale
Advisor: Rosa López

The research project consists of dealing with a quantum system under the action of a feedback mechanism that is able to generate useful work. Such feedback mechanism is the modern version of a Maxwell demon formulated by James Clerk Maxwell in 1867. The quantum substance is an electronic conductor inserted in an Aharanov-Bohm interferometer and coupled to two thermal reservoirs. Heat and charge fluxes are driven by electrical and thermal biases. Due to the presence of the demon it is generated useful power against the thermodynamical forces as mentioned. In this project we will explore (i) the role of coherence and time-reversal symmetry in the performance of the demon and therefore in the engine efficiency, and (2) the behavior of dissipation and current fluctuations with respect of the quantum coherence exhibited by this system.

4. Power grid stability in scenarios of large penetration of variable renewable energy sources penetration
Advisor: Pere Colet

The power grid, the largest socio-technical system in the world, can be viewed as a network of nonlinear oscillators operating synchronously. Stable operation requires a to balance generation and consumption at any time. This balance is not easy to achieve due to the random character of (part of) the load and the increasing use of variable renewable sources which are subject to uncontrollable factors, such as wind or sunlight. Any unbalance translates into frequency fluctuations which, if large enough, may trigger a blackout. This project addresses the modelling of the dynamics of power grid dynamics power grids in which a large fraction of the generation comes from variable renewable sources to analyze the stability of the synchronous state and the resilience to overcome large perturbations, such as a line failure. The use of storage systems as well as demand-side control techniques may also be considered.

5. Entanglement classification with quantum reservoir computing
Advisors: Gianluca Giorgi and Ricard Ravell

Reservoir computing (RC) is a neuro-inspired machine-learning approach especially suited for online time series processing. Its generalization, quantum reservoir computing, holds the promise to generalize the power of RC to quantum systems and efficiently solve purely quantum tasks on quantum input sequences. A prototypical example of a quantum task is entanglement classification or recognition: given an unknown multipartite state, we want to establish whether it is factorizable or not [1]. In this project, using a spin network as a reservoir [2], we propose to analyze the requirements a quantum reservoir must possess to solve this eminently nonlinear task, with special reference to the presence of internal memory, which distinguishes reservoir computers from extreme learning machines [3].

[1] S. Ghosh, A. Opala, M. Matuszewski, T. Paterek, T. C. H. Liew, npj Quantum Information **5**, 35 (2019).
[2] R. Martínez-Peña, G. L. Giorgi, J. Nokkala, M. C. Soriano, R. Zambrini, Physical Review Letters **127**, 100502 (2021).
[3] P. Mujal, R. Martínez-Peña, J. Nokkala, J. García-Beni, G. L. Giorgi, M. C. Soriano, R. Zambrini, Advanced Quantum Technologies **4**, 2100027 (2021).

6. Spatiotemporal Dynamics: applications to vegetation population dynamics
Advisors: Damià Gomila and Daniel Ruiz-Reynés

The spontaneous formation of vegetation patterns is a natural phenomena that provides resilience to ecosystems under the effects of Global Change. In this project landscape-level dynamical models of vegetation leading to the formation of localized spatial structures and patterns will be studied. These models are described by partial differential equations, and their dynamics will be analyzed using both analytical techniques and computational methods. Concepts of dynamical systems and bifurcation theory will be applied.