SURF@IFISC 2025 Proposals

1. Network Geometry and Path Lengths

Advisor: Antonio Fernández Peralta

The structure of complex networks shapes how phenomena like epidemics and information spread. Path-length distributions measure distances between nodes and offer insights into network dimensionality and connectivity. They also reveal recurring patterns and allow comparisons with reference models.
Many real networks display small-world properties, typically characterized by short average path lengths. By studying networks that deviate from this model in transportation, social, and biological systems, we can uncover alternative organizational forms and compare them with frameworks beyond the small-world paradigm.

2. Ordinal language of Non-Gaussian distributed data

Advisor: Felipe Olivares

Temporal sequences of measurements are essential for studying natural phenomena and often represent the only information available associated with the dynamics of complex systems. In particular, understanding deviations from Gaussianity in these measurements is crucial for making reliable inferences, enhancing predictive models, and gaining deeper insights into complex systems [1]. While the Normal distribution is a convenient statistical model, many empirical datasets display deviations from it, exhibiting characteristics such as skewness, heavy tails and extreme events, as seen in financial [1] and turbulence datasets [2].

Rather than forcing real-world data into Gaussian assumptions, this project aims to embrace its true statistical nature by using ordinal patterns [3] to characterize departures from Gaussianity. To achieve this, we will analyze numerical sequences sampled from various distributions, including q-Gaussian, stable distributions and other Non-Gaussian noise models. Furthermore, we will conduct experimental analyses of (i) non-isotropic atmospheric turbulence data—specifically, the fluctuations of a laser beam wandering through laboratory-synthesized optical turbulence [4]— and (ii) financial data [1], to evaluate the classical Kolmogorov turbulence model, and the so-called efficient-market hypothesis, respectively. The student must have knowledge of MatLab (or alternatively Python).

[1] F. De Domenico, G. Livan, G. Montagna, and O. Nicrosini. Physica A 622 (2023).
[2] J.G. Jones, G.H. Watson and G.W. Foster. AIAA JOURNAL vol.42 No.12 (2004).
[3] C. Bandt and B. Pompe. Phys. Rev. Lett. 88 (17) 174102 (2002).
[4] G. Funes, F. Olivares, C. Weinberger, Y. Carrasco, L. Nuñez, D.P. Pérez. Optics Letter Vol. 41(24) (2016).

3. Transport Properties of Quantum Anomalous Hall and QAH-Superconductor Junctions
Advisors: Javier Osca and Llorenç Serra

A student working on topological insulators will be tasked with exploring the unique electronic properties of these fascinating materials, which lie at the frontier of condensed matter physics. Topological insulators exhibit robust edge states protected by topology, allowing for dissipationless transport even in the presence of disorder. These properties make them highly promising for next-generation electronic and quantum technologies. The student will focus on theoretical transport models to investigate charge and spin transport in these systems, aiming to unveil new physical phenomena with potential technological applications.

In particular, the research will delve on quantum anomalous Hall (QAH) systems and QAH-superconductor (QAH+S) junctions, which provide an exciting platform for realizing exotic quantum states. QAH insulators exhibit quantized Hall conductance without an external magnetic field, enabling novel ways to engineer robust edge currents. By integrating superconducting elements, QAH+S junctions can host Majorana bound states—key candidates for fault-tolerant quantum computing. The student will employ transport simulations and theoretical modelling to explore these systems, contributing to a deeper understanding of topological superconductivity and its potential role in future electronic and quantum devices. This research will not only enhance our fundamental knowledge of topological phases of matter but also pave the way for practical advancements in quantum technologies.

4. Spatiotemporal dynamics of vegetation patterns
Advisors: Daniel Ruiz-Reynés and Damià Gomila

Vegetation self-organizes as a result of spatially-extended interactions to form regular patterns extending over large areas, often spanning kilometers. Vegetation patterns have been identified as an essential mechanism of resilience in front of environmental changes providing adaptability under the influence of climate change.
The goal of this project is to investigate the spatiotemporal dynamics of vegetation patterns using mathematical models based on partial differential equations that describe vegetation growth. The student will learn concepts of dynamical systems, bifurcation theory and pattern formation applying both analytical techniques and numerical methods to explore and characterize the dynamic behavior of vegetation under varying conditions.

5. Exploring a Simple Neural Network Inspired by the Brain
Advisor: Silvia Ortín

In this project, we will explore a type of artificial neural network called **Reservoir Computing**, which can be used to recognize patterns and process information efficiently. Instead of using many interconnected nodes like typical neural networks, we will simulate a system that relies on a **single nonlinear node** with a feedback loop (a delay line).

The goal is to understand how adjusting this feedback loop can improve the system's performance and whether this approach could be useful in real-world applications, such as **optoelectronic devices**. During the project, the student will run computer simulations, analyze results, and gain insights into how simple systems can perform complex computations.

6. Decoding the Brain: How Neuronal Morphology Shapes Dynamics and Function
Advisor: Leonardo Gollo

Neurons serve as the fundamental building blocks of the brain. With billions of neurons in the human brain, it remains uncertain whether any two neurons are truly identical. These distinct morphological features of neurons are essential in shaping their dynamics and function. Understanding how these unique structures influence neural behavior is a key question in neurophysics. This project seeks to deepen our understanding of how neuronal morphology affects dynamics and function. By utilizing biologically plausible computational models, we will explore how neuronal morphology influences energy consumption, firing rates, intrinsic timescales, and dynamic range.

Through active participation in this research, students will gain valuable insights into brain modeling and develop a comprehensive understanding of the critical role neurons play within the brain's intricate network.

What You Will Learn:

- Techniques for modeling and interpreting brain dynamics

Skills Required:

- Proficiency in Matlab or Python
- (Desirable) Knowledge of nonlinear dynamical systems

7. Spatiotemporal Dynamics of a Two-Species Model in a Flowing Environment
Advisor: Nathan Silvano

This research project focuses on studying the spatiotemporal dynamics of a two-species interaction model under environmental flow. The goal is to model a simple river ecosystem and understand how external flows influence the existence or coexistence of steady states when compared to the same static system.

To achieve this, we propose using a competition-diffusion-advection model, such as a two-species Lotka-Volterra system. In this project, we will explore:
(i) the analytical implications of incorporating an external flow into the partial differential equations,
(ii) the numerical simulation of the two-dimensional system, initially with periodic boundary conditions in both directions,
(iii) the effects of introducing physical boundaries to better approximate a river-like environment.