Abstract Booklet

1ª Edición del Simposio de Investigadores Noveles en Complejidad (SINC)

1st Edition of the Symposium of Novel Researchers in Complexity

Contents

1 Analytical techniques to tackle nonlinear oscillators

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Abstract. We present an analytical approach to solve a Duffing–van der Pol oscillator with cubic and quintic nonlinearities and time-dependent coefficients. Using a combination of the factorization method and integrability analysis, we identify classes of equations that admit exact solutions. The system,

$$\ddot{x} + \left[A(t)x^2 + B(t)\right]\dot{x} + C(t)x + D(t)x^3 + E(t)x^5 = 0,$$

is shown to be Painlevé integrable under certain conditions. These techniques yield explicit solutions and allow derivation of the Lagrangian and Hamiltonian via the Jacobi Last Multiplier. Results are illustrated with examples and stem from joint work with O. Cornejo-Pérez and J. Negro.

Keywords: *Duffing–van der Pol oscillator, Factorization method, Integrability, Jacobi Last Multiplier*

Reference:

1. O. Cornejo-Pérez, P. Albares, and J. Negro, *Physica D*, 476, 134675 (2025).

2 PageRank for Temporal Networks

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Abstract. The PageRank algorithm revolutionized relevance metrics in networks through a random surfer model. In this talk, we extend PageRank to temporal networks by allowing the adjacency matrix, damping factor, and personalization vector to vary with time. Both discrete and continuous-time formulations are explored, showing that continuous-time PageRank can be accurately approximated using discrete snapshots. We also derive sharp bounds on how much the personalization vector influences node rankings over time.

3 Predicting deterministic extreme events

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Abstract. In classical physics, knowing the initial conditions of a system allows us to determine its future state. This principle holds even for chaotic systems—although their sensitivity to initial conditions makes prediction extremely difficult. A particularly relevant feature of chaos is the emergence of extreme events, which have implications in domains like transport, climate, and cybersecurity. In this study, we investigate the predictability of such events in a solid-state laser with modulated cavity losses. Through bifurcation analysis, we uncover complex behaviors ranging from periodic states to fully chaotic regimes. Remarkably, we identify a precursor signal that arises 20 modulation periods before an extreme event, linking specific initial conditions to its onset. Experimental results confirm the theoretical predictions, offering a promising framework for forecasting deterministic extreme events.

4 Robustness and plasticity in biological systems

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Abstract. Biological systems exhibit both robustness—maintaining structure in noisy environments—and plasticity—the ability to remodel when prompted. Understanding how these contrasting properties coexist remains a fundamental open question. In this talk, I will present a series of research projects exploring mechanisms underlying this balance.

5 Two-Player Yorke's Game of Survival in Chaotic Transients

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Abstract. We present a novel two-player game within a chaotic dynamical system, where players have opposing goals concerning the system's evolution. Using the methodology of partial control—borrowed from chaos control theory—we explore how players can develop winning strategies even without full knowledge of their opponent's actions. Applied to the logistic map, one player attempts to keep the system within a transient chaotic region, while the other seeks to expel it. We identify the sets of initial conditions (winning sets) for each player, along with the optimal strategies. This framework highlights the potential of partial control in the context of game theory and strategic decision-making in chaotic environments.

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4. G. Alfaro, R. Capeáns, and M.A.F. Sanjuán. *Forcing the escape: Partial control of escaping orbits from a transient chaotic region.* Nonlinear Dyn., 104, 1603–1612 (2021).

5. J.R. Marden and J.S. Shamma. *Game Theory and Control.* Annu. Rev. Control. Robotics Auton. Syst., 1, 105–134 (2018).

6 Nonlinear delayed forcing drives a non-delayed Duffing oscillator

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Abstract. We present the study of two coupled systems, one playing the role of the driver system and the other one of the driven. The driver system is a time-delayed oscillator, and the driven or response system has a negligible delay. Since the driver system plays the role of the only external forcing of the driven system, we investigate its influence on the response system amplitude, frequency, and the conditions for which it triggers a resonance in the response system output. It results that in some ranges of the coupling value, the stronger the value does not mean the stronger the synchronization, due to the arise of a resonance. Moreover, coupling means an interchange of information between the driver and the driven system. Thus, a built-in delay should be considered. Therefore, we study whether a delayed-nonlinear oscillator can pass along its delay to the entire coupled system and, consequently, to model the lag in the interchange of information between the two coupled systems.

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7 Cluster synchronization of identical chaotic oscillators

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Abstract. The field of dynamical systems explores how complex phenomena emerge from relatively simple equations, with a prime example being the chaotic behavior observed in the Lorenz equations. This complexity is further amplified when considering dynamical systems with non-trivial underlying topology, such as systems where interacting units are connected in a network-like structure. In these cases, the importance of the underlying network structure in determining the dynamical features has been demonstrated repeatedly [1]. A key objective in the theory of networked dynamical systems is to understand the relationship between the structural properties of the network and its synchronous state, i.e., whether the entire network can operate in unison. The Master Stability Function [2] approach stands as a landmark in these studies, providing a precise and quantitative characterization of this relationship. In recent years, significant research has focused on understanding a more intricate phenomenon: cluster synchronization, where groups of nodes synchronize with each other but not with the rest of the network. Until very recently, there was only numerical evidence and hints about when this phenomenon might occur. In our study, a complete characterization of cluster synchronization has been provided, elucidating not only which groups of nodes will synchronize but also the specific coupling strength values at which this transition will happen.

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8 Lasers, ants, tsunamis and the structure of the universe

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Abstract. What do lasers, ants, tsunamis, and the structure of the universe have in common? The answer is *branched flow*—a phenomenon where waves or rays propagating through weakly refracting media spontaneously form branching intensity patterns. These structures are central to diverse scientific domains. This talk explores the fundamentals of branched flow, its semiclassical dynamics, and emerging implications in fields such as AI and developmental biology.

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9 Dissipation effects in a Lorentz gas

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Abstract. Research on particle dynamics has had a significant impact on society, not only as a physics theory but also as technological improvement. The development of new materials and nanomaterials, as well as advances in nuclear fusion reactors and electronic systems, is characterized by nonlinear dynamics and out-of-equilibrium transport, which often lead to chaotic and complex behavior. This study investigates the influence of dissipation on particle dynamics in a Lorentz gas with a soft Fermi-type potential, arranged on a square lattice. The Lorentz gas model was originally conceived to describe the dynamics of electrons in metallic bodies through elastic collisions with hard scatterers. In recent times, the model has evolved into more sophisticated versions using soft potentials, allowing the study of complex phenomena such as anomalous diffusion and chaotic scattering.

For this investigation, numerical simulations were implemented in MATLAB to analyze particle trajectories, calculate the diffusion coefficient, and visualize the phase space structure through Poincaré sections, KAM islands, and escape and parameter basins. For the calculations, integrators such as Verlet (in the conservative case) and fourth-order Runge-Kutta (for dissipative systems) were used.

The results show that dissipation reduces diffusion and destroys KAM islands, altering the structure of the phase space. The resulting basins reveal sensitivity to initial conditions and fractal structures, which are typical of chaotic scattering. Furthermore, it is observed that the final distance is also affected by some dissipation parameters.This research confirms previous results in a conservative system and opens new lines of investigation in the dissipative system, with applications in statistical physics, transport and chaos theory.

10 Metaheuristic optimization for the Three-Stage Remanufacturing System Scheduling Problem

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Abstract. The Three-Stage Remanufacturing System Scheduling Problem (3T-RSSP) is an NP-hard optimization problem central to advancing circular economy practices. It focuses on minimizing makespan in a hybrid flow shop with unrelated parallel machines for disassembly and reassembly, and dedicated flow-shop lines for reprocessing. We propose an enhanced GRASP metaheuristic featuring a highly efficient cost function evaluation that reduces computational effort. Parameters were fine-tuned using the `irace` package. Experimental results on benchmark instances show that our algorithm outperforms existing approaches, achieving more best-known solutions and cutting execution times by up to two orders of magnitude.

11 Hydrodynamic quantum analogs and the Lorenz mill

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Abstract. We present a macroscopic wave–particle entity: a walking droplet on a vibrating liquid bath, exhibiting numerous hydrodynamic quantum analogs. These pilot-wave systems mimic quantum behaviors such as eigenstate quantization, tunneling-like transitions, diffraction, interference, spin-like states, time crystals, and quantum statistical features. We explore their dynamics via an integro-differential time-delayed equation linked to Lorenz-like chaotic systems. Finally, we introduce the "Lorenz mill" and investigate its thermodynamic efficiency, entropy generation, and exergy destruction, connecting chaos theory with far-from-equilibrium thermodynamics.

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12 Scalar embedding of temporal network trajectories

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Abstract. A temporal network—represented as a series of snapshots capturing the dynamic formation and dissolution of links—can be viewed as a trajectory within graph space. Embedding the trajectory into a low-dimensional Euclidean space is crucial for effectively examining its complex dynamics with methods drawn from time series analysis and signal processing. In this contribution, we propose that preserving the relative distances between snapshots, rather than their individual topological features, is crucial when performing this embedding. Consequently, we have used dimensionality reduction techniques explicitly focused on maintaining relative distances, such as Multidimensional Scaling (MDS), or treating the distance matrix itself as a feature space suitable for Principal Component Analysis (PCA). We present a straightforward methodology to implement this strategy, demonstrating through applications to both synthetic network trajectory models and empirical datasets that meaningful dynamic characteristics of network trajectories are retained even in scalar embeddings. This result facilitates the application of standard time series analytical techniques to the study of temporal networks.

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   `https://doi.org/10.1016/j.chaos.2025.116599`.

13 A Machine Learning enhanced Variable Neighborhood Search approach for the Uncapacitated Facility Location Problem

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Abstract. The Uncapacitated Facility Location Problem (UFLP) arises in domains such as logistics, telecommunications, and resource allocation, aiming to minimize the total cost of facility opening and customer assignment. Due to its NP-hard nature, solving large-scale instances exactly is computationally prohibitive. This work presents a novel Variable Neighborhood Search (VNS) algorithm enhanced with machine learning techniques, which guide the search toward promising regions of the solution space. Tested on standard benchmarks, the method achieves near-optimal results with significantly improved computational efficiency, outperforming many existing approaches. These results highlight the effectiveness of combining VNS with learning-based strategies for complex combinatorial problems like the UFLP.

14 On the iteration of the PageRank vector

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Abstract. We analyze the behavior of the PageRank vector when used iteratively as the personalization vector in successive applications of the matrix $X(\lambda) = (1-\lambda)(I-\lambda P_A)^{-1}$, where P_A is the row-normalized adjacency matrix of a directed graph. For irreducible P_A, we study the convergence of the recursive sequence $x_{k+1}^T = x_k^T X(\lambda)$. When P_A is reducible, we examine the dynamics under a block upper-triangular transformation, considering diagonal, zero-block column, and general cases. We show that the sequence converges to a non-zero vector related to the Perron vectors of the irreducible components, offering insights into the long-term behavior of PageRank under recursive application.

Acknowledgements. This work has been supported by INCIBE/URJC Agreement M3386/2024/0031/001 within the framework of the Recovery, Transformation and Resilience Plan funds of the European Union (Next Generation EU).

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15 Vector field theory in motion: Revealing latent potentials in football dynamics

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Abstract. We introduce a vector field framework to study team behavior in professional football. Using high-resolution tracking data from 100 LaLiga matches, we reconstructed player and ball flow fields and derived their conservative scalar potentials. These fields, satisfying Gauss's theorem and irrotational properties, were analyzed across offensive and defensive phases to reveal empirical potential functions unique to each team. Our method provides a physical, field-theoretic perspective on match dynamics, enabling comparison of strategic organization and performance. This represents a novel application of vector field theory to collective sports.

16 Computational Challenges in Facility Location Problems

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Abstract. Facility Location Problems aim to determine optimal locations for placing facilities in a given space—whether continuous or discrete. These problems are NP-complete, making exact solutions computationally intractable for large instances. To overcome this, researchers employ approximate algorithms and metaheuristics capable of efficiently producing high-quality solutions. This talk introduces the core principles of facility location problems, outlines their computational complexity, and reviews some of the most effective metaheuristic strategies for addressing them.