IEEE COMPENG 2026

Castel Ivano
July 8–10, 2026

2026 IEEE WORKSHOP on COMPLEXITY in ENGINEERING

Book of Abstracts

The electronic version of this book of abstracts can be found at:
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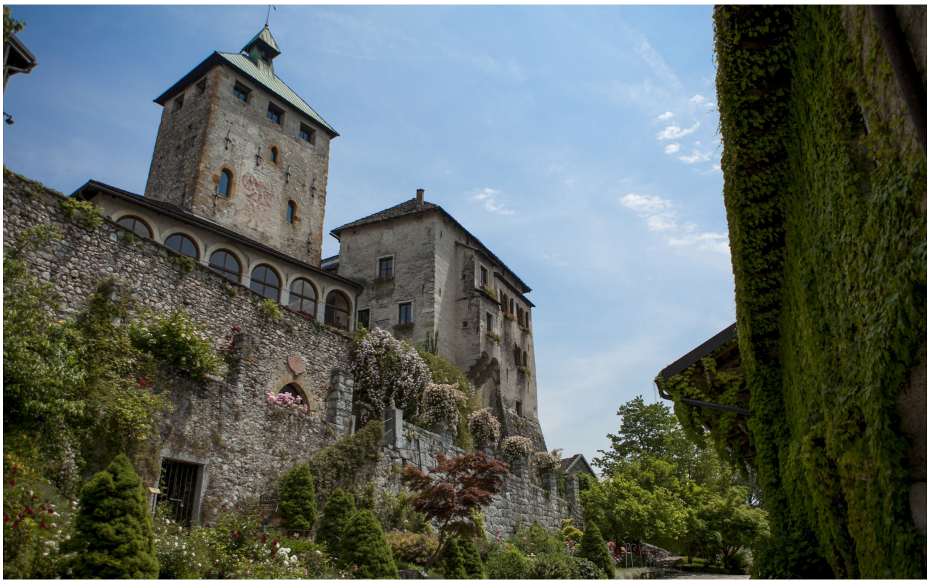
About

COMPENG is a series of international workshops founded in 2010 aimed at providing a forum for experts and professionals working on the latest developments in complexity science and its application in an engineering perspective. Previous editions of the workshop were held in Rome (Italy, 2010), Aachen (Germany, 2012), Barcelona (Spain, 2014), Catania (Italy, 2016), Florence (Italy, 2018, 2022, 2024).

The eighth Workshop on Complexity in Engineering **COMPENG 2026** takes place on **July 8–10, 2026**. The conference is hosted at the beautiful **Castel Ivano**, an imposing structure dating back to the 6th century, located in Trentino (Italy) on the promontory of Mount Lefre, within the Valsugana and Tesino area.



Covered themes span a wide range of research topics, from nonlinear dynamics and stochastic processes to complex phenomena in electronics and optics, from time-series analysis and network science to their applications in climate science, biophysics, biomedical engineering, and neuroscience, as well as data-driven systems and machine learning.

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Timetable

Wednesday, July 8

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10:15–11:00	**C. Clementi**	*Modelling Protein Dynamics with Machine Learning and Molecular Simulation*
11:00–11:20	**Coffee break**	
	Session: **Complex Networks** *(Chair: Alessio Perinelli)*	
11:20–11:45	**M. Frasca**	*Controlling synchronization in multi-agent systems via higher-order interactions*
11:45–12:10	**C. Mocenni**	*Escaping Stagnant Traps: Joint Agency and Metastable Dynamics in Anti-Coordination Networks*
12:10–12:35	**D. Febbe**	*Random Walk on Simplicial Complexes*
12:35–13:00	**R. Potestio**	*We can't see the forest for the trees: investigating complex systems through the hazy lens of low-resolution representations*
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	Session: **Machine Learning I** *(Chair: Lorenzo Buffoni)*	
14:15–14:40	**L. Chicchi**	*Spectral Decomposition of Feed-Forward Networks: Identifying Task-Essential Structure via Eigen-Projectors*
14:40–15:05	**L. Giambagli**	*Opening the black box: Interpreting Graph Neural Networks for Molecular Potentials*
15:05–15:30	**G. Peri**	*Spectral Higher-Order Neural Networks Have Finely Tunable Expressiveness*
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14:50–15:15	**L. Fu**	*Higher-Order Interactions in Complex Oscillatory Networks: From Single-Transistor Chaotic Oscillators to Brain Dynamics*
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Abstracts

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From the Lorenz system to non-hyperbolic chaotic systems

Guanrong Chen

City University of Hong Kong

We begin with the classical Lorenz system, outlining the fundamental principle of its chaotic dynamics before introducing the mathematical and physical characterization of chaos: the intricate entanglement of stable and unstable manifolds within phase space, governed by the system's local divergence and global boundedness. This defining feature arises from the hyperbolic eigenvalue structure of the Jacobian matrix at equilibrium. We then turn to a recent development in the study of non-hyperbolic chaotic systems. Like the Lorenz system, these are first-order, three-dimensional, quadratic polynomial systems with deceptively simple expressions. Yet they differ profoundly in their equilibrium behaviour, exhibiting no equilibrium points, only stable equilibria, or even infinitely many equilibria. In such cases, traditional analytical tools, such as the manifold entanglement framework, lose validity. Research into general non-hyperbolic chaotic systems is still in its early stages, leaving a wide landscape of compelling and unresolved problems for future exploration.

Biography

Prof. Chen received Master's degree in Computational Mathematics from Sun Yat-sen University in Guangzhou, China in 1981 and Ph.D. in Applied Mathematics from Texas A&M University, USA in 1987. He then worked at Rice University and University of Houston, Texas, USA. Since 2000, he has been a Chair Professor at City University of Hong Kong.

Professor Chen was elected IEEE Fellow in 1997 and is currently Life Fellow. He was awarded the Euler Gold Medal by Russia and conferred Honorary Doctorate by St. Petersburg State University, Russia in 2014. He was conferred Honorary Doctorate by the University of Normandy, France, and elected Member of the Academia Europaea and Fellow of The World Academy of Sciences in 2015.

Modelling Protein Dynamics with Machine Learning and Molecular Simulation

Cecilia Clementi

Freie Universität Berlin

The last years have seen an immense increase in high-throughput and high-resolution technologies for experimental observation as well as high-performance techniques to simulate molecular systems at a microscopic level, resulting in vast and ever-increasing amounts of high-dimensional data. However, experiments provide only a partial view of macromolecular processes and are limited in their temporal and spatial resolution. On the other hand, atomistic simulations are still not able to sample the conformation space of large complexes, thus leaving significant gaps in our ability to study molecular processes at a biologically relevant scale. We present our efforts to bridge these gaps, by exploiting the available data and using state-of-the-art machine-learning methods to design multiscale models for complex macromolecular systems. We show that it is possible to define simplified molecular models to reproduce the essential information contained both in microscopic simulation and experimental measurements.

Biography

Prof. Dr. Cecilia Clementi is the Einstein Professor of Physics at FU Berlin since 2020, after 19 years as a Professor of Chemistry at Rice University in Houston, Texas, USA. Clementi obtained her Ph.D. in Physics at SISSA, Italy, and was a postdoctoral fellow at the University of California, San Diego. Her research focuses on the development and application of methods for the modeling of complex biophysical processes, by means of molecular dynamics, statistical mechanics, coarse-grained models, experimental data, and machine learning. Clementi's research has been recognized by a US National Science Foundation (NSF) CAREER Award (2004), the Robert A. Welch Foundation Norman Hackerman Award in Chemical Research (2009), and the Hamill Innovation Award (2007 and 2014).

Controlling synchronization in multi-agent systems via higher-order interactions

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Complex systems are characterized not only by pairwise interactions, typically modeled by networks, but also by higher-order interactions involving more than two units. While synchronization and its control in complex networks have been widely investigated, their analysis in structures with higher-order interactions is more recent. In this work, we study how higher-order interactions can be exploited to control synchronization. Specifically, we investigate how they can be used to induce synchronization in structures that do not support it in their absence. We focus on two types of higher-order interactions: generic hyperedges and simplices. In the first case, controllers introduce interactions among arbitrary groups of units, without constraints on their connectivity in the original network. In the second case, the units involved in the control interactions form a simplex, thereby preserving the property of downward closure. This means that, for example, if controllers introduce three-body interactions, such interactions can occur only among triplets of nodes that are fully connected in the original structure. Building on the hypothesis of natural coupling, we develop an approach based on the Master Stability Function (MSF) that allows us to assess whether the introduction of a given set of group interactions leads to a stable synchronization manifold. The key parameters in the analysis are the second-smallest and the largest eigenvalues of a semidefinite matrix, which depends on both the original structure to be controlled and the introduced group interactions. Using these parameters, we define two general measures of synchronizability to assess the impact of controllers based on higher-order interactions. Through numerical analyses, we investigate these synchronizability measures across different structures, while varying both the coupling strength in the original network and the control gain. We find that, for both hyperedge and simplicial control, the synchronizability of networks with a type II MSF increases with the control gain. In contrast, the behavior for networks with a type III MSF is more complex. In this case, simplicial control is generally not effective in improving synchronizability. Instead, a suitable selection of the group interactions introduced by the controllers proves effective in enhancing synchronizability, demonstrating the ability of the controllers to induce synchronization in such structures.

Escaping Stagnant Traps: Joint Agency and Metastable Dynamics in Anti-Coordination Networks

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The resilience of complex systems hinges on the delicate balance between microscopic incentives and macroscopic welfare. This work explores such dynamics through anti-coordination games and the strategic max k-cut problem. We demonstrate that while globally optimal configurations correspond to Strong Nash Equilibria, sub-optimal systems often remain caught in Nash equilibria that act as stagnant traps. In these states, purely individual actions are insufficient to trigger systemic improvement, leaving agents confined to inefficient configurations. The central contribution of this study is the identification of spontaneous coalition formation as a vital catalyst for global efficiency. Drawing on evolutionary game theory and exploiting the capacity of agents to synchronize their intentions and, at the same time, to maximize their individual reward, we illustrate how this symbiotic mechanism may overcome selfish barriers, ensuring an ascent toward the optimum. This model of shared agency finds fundamental applications in multiple domains: from the stability of biodiversity in competitive networks to Artificial Intelligence systems, where the cooperative integration of diverse drives is essential for resolving local conflicts and achieving productive dynamics. Particularly in Multi-Agent Reinforcement Learning and decentralized AI, where algorithms routinely get trapped in local optima, endowing agents with mechanisms for joint agency offers a robust strategy to resolve topological frustrations and achieve productive metastability. Rather than converging toward a single static optimum, our model reveals a metastable dynamic where coalitions continuously form and dissolve, which potentially contributes to improving the global welfare. We conclude that network resilience is not a fixed target but a process of constant adaptive reconfiguration, where residual conflicts serve as necessary topological anchors for systemic flexibility and evolutionary potential.

Random Walk on Simplicial Complexes

D. Febbe[1,2,*], D. Fanelli[1], and T. Carletti[2]

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In recent years, higher-order networks have emerged as a framework that extends the formalism of complex networks, enabling the description of interactions among multiple agents beyond simple pairwise relations. Examples of such higher-order structures are naturally encoded in simplicial complexes (SC), which have been employed in a variety of contexts related to the modeling of complex systems. We introduced a novel operator to describe a natural random walk process on simplicial complexes that models transitions across multidimensional structures. Walkers are allowed to wander across simplices of various dimensions, bridging nodes to edges, edges to triangles, and so on, within a nested organization that hierarchically extends to higher-order structures of arbitrarily large, yet finite, dimension. The asymptotic distribution of the walkers provides a natural ranking, enabling the assessment of the relative importance of simplices of different orders and types. We further applied this framework to compute the explorability of a simplicial complex in the presence of a long-range stochastic teleportation term. The effect of noise appears highly beneficial for optimal search strategies when the walk occurs on higher-order structures, compared to what is observed on the corresponding binary graph. This illustrates an interesting example of the interplay between topological structures and the dynamical processes defined on them. Furthermore, the introduced operator naturally provides a notion of adjacency among the structures and it can been applied to generate SC with a generalized preferential attachment mechanism modulated by dimension-related parameters. The growing processes and the final degree distributions have been studied both analytically and numerically. Finally, the introduced random walk can be applied as a community discovery method for SC, where the inclusion of higher-order interactions can lead to new types of clustering organization.

We can't see the forest for the trees: investigating complex systems through the hazy lens of low-resolution representations

R. Potestio[1,2,*]

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The emergent behaviour in complex systems is the consequence of the interactions among a large number of elements, possibly very simple ones, endowed with key ingredients such as noise and frustration. A major challenge in the study of such systems is to trace back emergent, large-scale features to specific elements, whose critical role is often shadowed by their interplay with many others. A promising avenue to identify these elements is to investigate the system varying the level of detail with which it is observed: a decrease in resolution, in fact, does not necessarily mean (only) a loss of detail, but it can also enhance specific, relevant features—and of the structural elements that determine them. In this talk I will provide an overview of the theoretical instruments to carry out this program, and present specific applications in the context of simple neural networks.

Spectral Decomposition of Feed-Forward Networks: Identifying Task-Essential Structure via Eigen-Projectors

L. Chicchi[1,2,*], L. Giambagli[3], G. Peri[1], F. Vezzi[1], L. Buffoni[1], and D. Fanelli[1,2]

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Feed-forward neural networks (FFNNs) are the core architecture of many modern AI models, from multilayer perceptrons to transformer blocks in Large Language Models. Despite their widespread use, they are often treated as "black boxes". From a network science perspective, an FFNN can be modeled as a directed acyclic graph whose functional properties emerge from weight self-organization during training. However, analyzing this structure is challenging, particularly because the non-square nature of feed-forward weight matrices prevents standard spectral analysis. In this work, we propose a novel framework to access the spectral properties of FFNNs. By introducing auxiliary feedback loops that preserve input-output information flow, we map the layered architecture into a global square matrix representation. This enables the extraction of eigenvalues and eigenvectors describing the network as a unified dynamical system rather than a sequence of independent layers. We analyze the projectors derived from these eigenvectors and find that those associated with dominant eigenvalues capture the backbone of the network's decision-making process. These projectors reflect global, distributed structures across the network depth rather than localized neuron activity. Experiments on multiple datasets show that the network can be approximated using only a small subset of dominant projectors with minimal performance loss. This work bridges deep learning and spectral graph theory, suggesting that the effective dimension of trained networks is governed by a sparse set of spectral modes, offering new insights into information processing in hierarchical architectures.

Opening the Black Box: Interpreting Graph Neural Networks for Molecular Potentials

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In recent years, Graph Neural Networks (GNNs) have been recognised as accurate tools for approximating potential energy surfaces of molecular systems, both at atomistic resolution and in coarse-grained representations. Their high flexibility is however offset by limited physical interpretability: unlike classical force fields, in which each term has a precise meaning, learned potentials take the form of complex, high-dimensional functions whose output is difficult to trace back to the underlying physical interactions. Existing interpretability techniques typically operate a posteriori on individual configurations, with a computational cost that grows rapidly with the size of the system and with the number of configurations one wishes to explain. In this contribution we present an alternative approach, in which interpretable parameters are integrated directly into the network architecture and regularized during training, so as to yield solutions in which only the genuinely relevant interactions survive. Post-training inspection of these parameters makes it possible to identify which chemical species interact, on which spatial scale, and whether many-body contributions are involved. The learned structure is finally remarkably distilled into an analytical potential, providing a transparent approximation of the original model. In this way, a typically opaque object such as a GNN can be turned into a physically inspectable one, opening a concrete window into the so-called black box.

Spectral Higher-Order Neural Networks Have Finely Tunable Expressiveness

G. Peri*, D. Febbe, and D. Fanelli

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Neural hypergraphs are a natural generalization of neural networks, the reference models in modern machine learning, yet their deployment has proven demanding: the number of weighted hyperedges required leads to an intractable parameter explosion. However, a novel parametrization that leverages on spectral attributes for neural hypergraphs has been developed, that enables to recycle parameters via a weight sharing scheme. This latter leads to a significant reduction of the associated computational cost. Recently, early experimentations on these novel, spectral, higher-order architectures already point to meaningful improvements in both performance and interpretability. Building on these results, we advance the benchmarking efforts by evaluating these new models on N-bit parity tasks, a well-established testbed known to be particularly challenging. As we will convincingly argue, spectrally parameterized higher-order neural networks (SHONNS) possess a versatile and highly tunable hypothesis space.

Physics-informed Neural Networks with dynamical boundary constraints

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Physics-informed neural networks (PINNs) are numerical solvers that embed all the physical information of a system into the loss function of a neural network. In this way, the learned solution accounts for data (if available), the governing differential equations, or any other constraint known of the physical problem. However, they face serious issues, notably their tendency to converge on trivial or misleading solutions. The latter occurs when, although the loss function reaches low values, the model makes incorrect predictions. These difficulties become especially significant in differential equations involving multiscale behavior, such as those containing rapidly varying terms, as well as in problems whose solutions exhibit strong oscillatory behavior. To address these challenges, we introduce the Dynamical Boundary Constraint (DBC) algorithm, which imposes restrictions on the loss function based on prior training of the PINN. To demonstrate its applicability, we tested this approach on examples of different areas of physics.

On the Design of a High-Dimensional Hyperchaotic Hyperjerk System with Multiple Positive Lyapunov Exponents: A Case Study

Jacques Kengne

University of Dschang

The study of hyperchaotic systems with multiple Lyapunov exponents is among the most frequently addressed topics in nonlinear physics. In this work, we describe a simple approach for the design of a hyperjerk-type hyperchaotic system with several positive Lyapunov exponents. As an illustration, we consider an eighth-order autonomous hyperjerk system with hyperbolic sinusoidal nonlinearity, which has the advantage of being implemented using a simple pair of semiconductor diodes connected in reverse parallel. The argument of the hyperbolic sine function is a linear combination of judiciously chosen system state variables. A detailed study is conducted, focusing on dissipation, equilibrium behavior, bifurcation diagrams with corresponding Lyapunov exponent graphs, and the coexistence of attractors. Complexes dynamics, such as the hyperchaos with four positive Lyapunov exponents, dependent on the choice of system parameters, are highlighted. An experimental study, using a suitable analog computer, is carried out to verify/validate the results of the theoretical analysis. This work not only presents a novel hyperjerk-type hyperchaotic system but also underscores the practical applicability of theoretical findings through experimental validation. The results pave the way for further exploration of hyperchaotic systems and their potential applications in secure communications and complex dynamics.

Biography

Prof. Kengne was born in Bamougoum (Bafoussam) Cameroon, in 1971. He graduated from ENSET (University of Douala) in 1995 as a technical high school teacher. He then served in numerous technical high schools in Cameroon for about fifteen years before being recruited as a lecturer in IUT-FV, University of Dschang in 2010. He obtained a Master Degree with Honor and a PhD in Physics-Electronics from the same University in 2007 and 2011 respectively. Currently he is full professor in the department of Electrical Engineering and member of “Laboratoire d'Automatique et d'Informatique Appliquée (UR-AIA)”. Prof. Kengne has published more than 150 journals papers in renowned international journals. He has supervised more than 10 doctoral theses, all in nonlinear physics at the University of Dschang. He is a member of the editorial board of two scientific journals, namely Chaos Theory and Applications and Nonlinear Science and Control Engineering (NSCE).

Analog Computing as a Powerful Tool in the 21st Century

Bernd Ulmann

anabrid GmbH

The notion of "analog computing" sounds pretty dated (and might better be called natural of physical computing) but holds great promise for high-speed and high-efficiency computing in the 21st century. This talk gives a short historic overview of the development of analog (and hybrid) computers before detailing on modern developments such as automatically reconfigurable analog computers, their implementation, their applications, and the software stack required to integrated them seamlessly as co-processors with modern digital computer systems. Applications shown range from research in the field of dynamical systems to aerospace applications, industrial control systems, medical implants, artificial intelligence, etc. It will be shown that classic digital computers are about to hit fundamental boundaries, thus requiring different computational paradigms of which one of the most promising is that of analog computing. Analog computers excel in problems involving complex networks of coupled nodes such as neural networks consisting of spiking and bursting neurons, metric networks in the live sciences, etc., since they exhibit a basically constant runtime complexity of $O(1)$.

Biography

Prof. Dr. Bernd Ulmann studied mathematics (with a minor in philosophy) at the Johannes Gutenberg-University Mainz and finished with a Diploma thesis in number theory and cryptography. His dissertation at Hamburg university was on analog computers, his main passion. He is a Professor at FOM University of Applied Sciences in Frankfurt/Main, Germany, and one of four founders of anabrid GmbH, where he helps developing analog and hybrid computers for the 21st century. In his spare time he collects and restores classic analog computers, and has a passion for classic electronic measurement equipment.

Optical dynamics in microresonator networks for machine learning and neuromorphic computing

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Photonic computing offers emerging alternatives and exclusive enhancements to traditional electronics, featuring high parallelism, minimal latency, and energy efficient data transportation and linear operations [1]. For technologies relying on continuous streams of optical data, such as fiber optic sensing networks, deploying neuromorphic hardware directly in the optical domain is highly strategic [2]. However, experimental demonstrations are scarce, since useful operations on sensed temporal data are often nonlinear and require memory of past inputs. Indeed, due to the inherent lack of direct photon-photon interactions, achieving these computational properties in photonic processors remains a significant hurdle [3]. Silicon microring resonators (MRRs) provide an elegant and naturally suited solution to these limitations. These simple, CMOS-compatible devices are extensively used in both communications and sensing due to their ability to tightly confine light and significantly enhance light-matter interactions. MRRs exhibit strong nonlinearities based on local temperature and free-carrier concentration, presenting two distinct relaxation timescales[4]. When driven by a continuous wave input near the resonance wavelength, this interplay of competing shifts and mismatched temporal dynamics forces the MRR into self-pulsing (SP) oscillations. By coupling multiple silicon MRRs into a network architecture, the system can generate a rich variety of dynamic SP responses, including chaotic regimes, simply by tuning the input laser power and wavelength [5]. This yields a highly nonlinear, memory-rich physical substrate that can provide a large number of various responses to time dependent inputs, which is exploitable for native photonic processing of optical signals [3]. Within this contribution, we present and discuss our latest advances on dynamical MRR networks: long-term optical memory demonstrations [6], high-throughput photonics-based machine learning (reservoir computing) [7,8] and application to optical fiber sensing (ongoing).

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Hierarchical Lead Critic based Multi-Agent Reinforcement Learning

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Many complex engineering systems can be modeled at multiple levels, from local component behavior to system-level coordination. In cooperative Multi-Agent Reinforcement Learning (MARL), however, most approaches optimize from a single perspective—either local or global—limiting their ability to jointly address individual task execution and group-level coordination. We introduce the Hierarchical Lead Critic (HLC) framework, a novel approach for learning coordinated behavior across local, group-level, and global perspectives in MARL. HLC structures the learning process hierarchically by combining agent-level and group-level critic signals. The proposed *Lead Critics* evaluate subsets of agents, forming a flexible hierarchy that generalizes both local and fully centralized critics. Central to our method is a sequential multi-level update scheme, where each agent adapts its policy across critics of increasing scope. This allows policy updates to incorporate progressively broader coordination objectives while aiming to preserve stable learning signals across hierarchy levels. To support this process, we introduce an actor architecture combining multiple processing pathways via a mixture-of-experts design with cross-attention, providing a policy network suited to integrating multiple hierarchy-informed learning signals. We evaluate HLC on cooperative, partially observable multi-agent environments, including drone-based swarm Escort and Surveillance tasks that require distributed coordination without communication. Results show improved performance, sample efficiency, and scalability compared to single-level baselines, highlighting the benefits of explicitly combining local and group-level learning signals. These findings suggest that hierarchical critic structures provide a practical framework for bridging local policy learning and system-level coordination in complex multi-agent systems.

Spectral Autoencoders

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In recent years a novel approach for neural network parametrization, known as "spectral method", has been proposed in the literature [1]. In contrast to the conventional approach where training takes place in the direct domain of the weights, the spectral method proposes to guide the training of the neural network starting from the study of the reciprocal space, defined by the eigenvalues and eigenvectors of the transfer operator between consecutive layers. Such formalism allows for the identification of redundancies and the development of systematic procedures for dimensional reduction and pruning, maintaining the predictive capabilities of a neural network unaltered. In this work, we extend the spectral method to design a novel architecture called "spectral autoencoder" (SPAE). The SPAE leverages the spectral parametrization to construct an autoencoder whose latent space is directly related to the spectral components of the underlying operator. This architecture enables the association of the latent space with a set of eigenvalues and eigenvectors, which mathematically quantify the relative importance of each node within the network. Consequently, the SPAE can be utilized to discover the minimal set of parameters required to fully describe a dataset. We evaluate the SPAE on two distinct benchmarks: the standard MNIST dataset and a synthetic dataset based on the student-teacher paradigm, where the underlying complexity is known a priori. Experimental results demonstrate that the SPAE effectively identifies the intrinsic dimensionality of the dataset, successfully compressing the data while maintaining a high reconstruction accuracy.

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Ginoux-Meucci-Chua model with Piecewise-Linear Function

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In a previous contribution [1], starting from the original Chua's cubic model [2] and while removing the state variable y in its second equation, we built a model enabling to describe a continuous transition from Chua's chaotic oscillations to Van der Pol's relaxation oscillations [3]. Then, we proved a perfect agreement between this new mathematical model we dubbed Ginoux-Meucci-Chua model and its corresponding electronic circuit we designed. The aim of this work is to replace the cubic function modelling the current-voltage characteristic of this new model by a piecewise-linear function. Then, we prove that it exhibits the same features as the Ginoux-Meucci-Chua model as well as those of the original Chua's piecewise-linear model of 1986. We also proved a perfect agreement between this piecewise-linear Ginoux-Meucci-Chua model and its corresponding electronic circuit we designed.

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Structural Origin of Chaos in a Stabilized Semiconductor Laser

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The introduction of feedback loops in semiconductor lasers has historically represented a cornerstone of laser physics [1], serving both to stabilize emission and, conversely, to induce complex nonlinear dynamics. Since the first demonstrations of feedback-induced chaos nearly four decades ago, it has been established that even simple optoelectronic circuits can destabilize a laser, leading to deterministic chaos. From a dynamical systems perspective, these setups are described by a set of coupled differential equations involving the laser intensity, the population inversion, and the feedback signal, where the interplay of different time scales governs the system's evolution [2]. A distinctive feature of these systems is their ability to exhibit diverse chaotic regimes, ranging from local bifurcations to global homoclinic-like dynamics. The latter is particularly significant as it manifests through large-amplitude spikes, nearly uniform in height but erratically distributed in time. While previous studies have often relied on laboratory-grade diodes where technical noise could overlap with intrinsic dynamics, this work investigates the phenomenon using a commercial laser module equipped with high-precision current. In this work, we demonstrate that chaotic spiking persists even when the feedback is injected through a dedicated modulation input, isolated from the DC bias. This confirms that the observed instabilities are an intrinsic property of the laser-feedback interaction rather than an artifact of technical fluctuations. Our results provide a robust experimental framework for utilizing commercial photonic devices in applications requiring controlled complex dynamics.

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Higher-Order Interactions in Complex Oscillatory Networks: From Single-Transistor Chaotic Oscillators to Brain Dynamics

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Background: Complex systems can be described as networks of interacting components, where higher-order interactions (HOIs) emerge from collective dynamics and cannot be reduced to individual or pairwise interactions. Widely used approaches to analyze HOIs, such as partial information decomposition and O-information, are typically formulated in the time domain for random variables and cannot capture the oscillatory structure of complex systems, which are more appropriately modeled as random processes. To overcome this limitation, linear modeling–based extensions have been introduced, leading to measures such as partial information rate decomposition (PIRD) and O-information rate (OIR) for the analysis of frequency-specific interactions. However, these approaches rely on linear assumptions that may be restrictive for strongly nonlinear or chaotic dynamics. *Objective*: To evaluate whether OIR and PIRD can capture the macroscopic behavior emerging from highly nonlinear dynamics in simulated chaotic systems and brain networks form EEG signals. Methods: OIR and PIRD were applied to three types of systems: i) simulated networks composed of three-node Rössler chaotic systems; ii) an experimental network of 59 Minati-Frasca chaotic electronic oscillators and, iii) reconstructed cortical activity from 30 brain regions during motor task execution. HOI within each triplet were estimated starting from the power spectral density matrix of the full process in the time and frequency domain. Results: OIR and PIRD successfully captured redundancy and synergy emerging from nonlinear dynamics, identifying them in expected configurations and showing their prevalence around the carrier frequencies of the system oscillations in both oscillator and brain networks. *Conclusions*: OIR and PIRD capture the macroscopic organization of HOIs even under strong nonlinearities, especially when a frequency-domain description is required. In this setting, spectral analysis reveals how redundancy and synergy are structured across the system's oscillatory components. The similarity between oscillator and brain networks further suggests their potential as scalable, low-power platforms for studying complex brain dynamics.

Inhomogeneity of connectivity along a chain of chaotic oscillators

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The inference of links in complex networks primarily relies on the assessment of correlations—by means of linear measures or information-theoretic tools—between time series recorded from a subset of the network nodes. This procedure, common to many research fields, is based on the assumption that the recorded time series contain sufficient shared information to accurately infer connectivity between nodes. However, it was recently proven on experimental data that the emergence of chaotic regimes can hinder this inference, despite determinism and strong coupling between nodes. In a linear network of chaotic oscillators, estimates of connectivity between edge nodes appear to be exponentially suppressed as their topological distance increases, so that strongly coupled nodes can misleadingly appear to be independent. To further investigate the origin of this phenomenon of "topological unpredictability", here we experimentally study how connectivity between nodes at a given topological distance varies along a network of nonlinear electronic oscillators. Specifically, we address the question of how the information shared between node dynamics is washed out throughout the network, and how the edge connectivity can possibly be recovered by exploiting the information provided by intermediate nodes. The present contribution provides valuable insights on the experimental strategies that can be adopted to improve the inference of links within complex systems, especially whenever the access to the dynamics of individual nodes is limited.

Self-Induced Collective Dynamics in Cellular Populations under Hydrodynamic Forcing in Microchannels

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Understanding how collective cell-to-cell dynamics emerge from mechanical interactions is a key challenge in biophysical systems, with direct implications for functional diagnostics [Kalukula et al. 2025]. In microfluidic environments, hydrodynamic forcing couples cells through the surrounding fluid, enabling self-organized nonlinear behaviors linked to cellular state, which can serve as physics-based biomarkers [Ienaga et al. 2026]. In this work, a comprehensive study is carried out to investigate self-induced collective dynamics in cellular populations confined within microchannels. Cells are subjected to transient oscillatory hydrodynamic forcing, which is subsequently removed to probe their intrinsic dynamics. These dynamics are quantified using an image-based approach based on Digital Particle Image Velocimetry (DPIV) [Torrisi et al. 2023, Cutuli et al. 2025] for homogeneous population-level analysis, while a deep learning-based segmentation pipeline enables high-resolution single-cell characterization in heterogeneous samples. A comparison between viable yeast cells ($\approx 5 - 6\ \mu$m), apoptotic cells, and inert beads of comparable size reveals that self-induced oscillations in the 6 – 10 Hz band, distinct from the external forcing (0.2 Hz), are present in viable cells, decrease under apoptotic conditions, and vanish in inert particles. These oscillations persist after removal of external forcing, confirming their intrinsic origin. Extension to larger tumor cell lines (HL60, HeLa, $\approx 15 - 20\ \mu$m) identifies an additional 11 – 16 Hz band, absent in yeast and decoupled from the forcing. Both spectral content and amplitude vary across cell lines and show strong sensitivity to biophysical state, including drug exposure time (24 h, 48 h). These findings demonstrate that self-induced collective dynamics provide robust biophysical fingerprints, enabling physics-based phenotyping of heterogeneous cell populations at single-cell resolution.

Phase-Controlled Complex Dynamics in a Silicon Microresonator

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Nonlinear photonic systems offer a platform for investigating complex dynamical behaviors, including multistability and self-oscillations, arising from the interplay between feedback, coupling, and material nonlinearities. In this work, we study a silicon microresonator featuring dynamically reconfigurable interactions between counter-propagating modes, enabled by two integrated side-lobes, each incorporating a Mach-Zehnder interferometer and a thermo-optic phase shifter. This architecture, referred to as the DRUM (Dynamically Reconfigurable Unified Microresonator [1]), provides direct control over the phase governing internal feedback and intermodal energy exchange. By tuning the feedback phase at constant input power, we experimentally access different nonlinear regimes driven by thermo-optic and free-carrier effects, including steady-state and self-sustained pulsatory (self-pulsing) dynamics. A key observation is the strong path dependence of the system response: forward and backward phase sweeps between 0 and 2π yield different dynamical outcomes, despite identical control parameters. This hysteretic behavior reveals emergent long-term memory effects. Theoretical analysis indicates that these features are associated with a global bifurcation scenario involving saddle-node annihilation and a distant limit cycle [2]. Beyond continuous-wave excitation, we extended our study to pulsed input conditions, where the microresonator exhibits spiking-like responses [3] whose qualitative behavior depends on both the feedback phase and the properties of the input pulses. These results establish the DRUM as a versatile and reconfigurable platform for the study and control of complex nonlinear dynamics in integrated photonics, with potential applications in optical information processing and neuromorphic computing.

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Physics-Constrained Machine Learning for Complex Swelling Dynamics in Biological Porous Media

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The hydration of active biological tissues and glassy biopolymers involves highly complex, nonlinear chemomechanical couplings between fluid transport and matrix swelling. Mathematically, this dynamic can be formalized as a moving-boundary Stefan problem. However, distinguishing the exact rheological regime (whether solvent penetration is throttled by slow macromolecular relaxation or pure hydraulic resistance) remains a challenge. Traditional models rely on a priori phenomenological closures for matrix permeability and porosity, limiting their predictive capability in complex biological and engineered systems.
In this contribution, we introduce a hybrid Machine Learning framework to resolve this physical ambiguity through data-driven discovery. We present a Universal Differential Equation (UDE) architecture that merges rigorous macroscopic continuum mechanics with Neural Ordinary Differential Equations. The neural network is embedded directly within the governing physical laws, strictly enforcing "hard" macroscopic constraints such as mass conservation, moving interface kinematics, and thermodynamic consistency. This allows the algorithm to discover the latent, complex microscopic porosity dynamics directly from macroscopic experimental observables, bypassing classical constitutive biases.
Applying this framework to the rapid swelling of myxospermous seeds (Brassica napus), the physics-constrained network autonomously identifies a globally sub-diffusive kinetic scaling. The discovered dynamics statistically confirm a hydraulic-limited transport regime, effectively overriding classical viscoelastic memory assumptions. By successfully bridging data-driven techniques with nonlinear mechanics, this framework provides a robust new tool for modeling complex active matter, with broad applications in bio-inspired engineering and smart materials.

Thin film technology meets distributed sensing: architectural considerations for networks of analog sensors based on chaotic oscillators

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Across the many applications of the internet-of-things, there is an insatiable drive towards ever smaller and cheaper sensors, to address use cases unreachable by traditional microprocessor-based node designs. Recently, sensing through coupling a transducer to an elementary chaotic analog electronic circuit, and coupling multiple such circuits with each other into a network at the physical rather than numerical level, has been gaining ground. Simulations and bench-top experiments have shown that arrangements from a few tens to hundreds of nodes can successfully integrate information, such as performing network-level distributed estimation of the average and variation of sensor readings. While those results are promising, the real-world potential of these ideas depends on the ability to closely integrate the transducer within the oscillator circuit, and to realize the entire device using materials and technologies that are more flexible and sustainable than traditional printed-circuit boards bearing assembled components. With this goal in mind, the integration of analog distributed sensing with thin film manufacturing technology becomes a natural target. On the one hand, transducers could be realized through suitable resistive or capacitive materials on the circuit board itself. At the same time, thanks to the existence of elementary circuit designs, the transistor and other supporting components could also be realized fully through deposition. This would allow creating networked sensors on nearly any physical substrate, including biological materials. In this paper, we present some conceptual and architectural considerations pertaining to these ideas, including possible future designs and functionalization strategies that would allow building large-scale complex networks of these entities. Aspects of signal acquisition and analysis are also briefly considered.

Chaos Regulation: From Geometric Regulation to Distribution Regulation

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Chaos regulation is a core research direction in nonlinear and chaotic system engineering, which lays a critical foundation for the practical application of chaotic systems in secure communication, signal processing, and nonlinear control systems. Chaos regulation represents a concise and efficient control paradigm relying on a single parameter or initial condition. This report reviews our over two decades of research on chaos regulation, covering chaotic amplitude control and offset boosting. It further introduces distribution regulation based on initial-value-induced hidden offset boosting, including the symmetrization of chaotic oscillations, the construction of conditionally symmetric chaotic oscillators, the generation of self-reproducing chaotic attractors, and dynamics editing. The report also extends to emerging implementation techniques for chaos regulation, such as memristive chaos regulation and neuron dynamics regulation via memristor modeling.

Extending Link-Prediction-Based Backbone Extraction to Temporal Networks

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Backbone extraction identifies the most informative edges of a network while preserving its main structural properties. In previous work, similarity-based link prediction was used to extract complementary backbones in static networks. This extended abstract proposes a temporal extension of this framework through a time-dependent edge-weighting layer, allowing backbone extraction to account for interaction recency and repeated activity.

Network backbone extraction reduces a network to a smaller set of informative edges while preserving relevant structural information. Classical approaches include statistical filters and structural methods. A complementary approach relies on link prediction, in which similarity scores quantify the structural support for edges. Similarity-based heuristics, such as preferential attachment and the local path index, can reveal latent organization in networks. In previous work, we used this principle to define a static backbone extraction framework. It produces two complementary representations: a high-similarity backbone that captures edges with strong structural support, and a low-similarity backbone that highlights weakly supported and less predictable connections. Temporal networks introduce an additional difficulty. Edge relevance depends not only on topology but also on time. Interactions may appear, disappear, intensify, or become inactive. Static aggregation removes information about interaction recency, repeated activity, and edge evolution. As a result, two edges with the same aggregated weight may correspond to different temporal behaviors. We propose a temporal extension of similarity-based backbone extraction. The main idea is to introduce a time-dependent weighting layer before computing similarity scores. Each edge occurrence is assigned a temporal relevance score according to its age. Weighted occurrences are then aggregated into a temporally weighted graph that captures both recency and repeated presence. Similarity scores are computed on this graph and used to extract high- and low-similarity temporal backbones. This design separates temporal modeling from backbone selection: the weighting layer captures edge aging, whereas the similarity measure defines the criterion for structural extraction. In this work, we instantiate the temporal weighting layer with the Adjusted Sigmoid Function (ASF). ASF models the life cycle of an interaction through three phases: an active phase, a decay phase, and a stable phase. Given the age x of an edge occurrence, its ASF score is defined as $ASF(x) = \frac{1}{1+\exp(x/p-a)} + \frac{q}{q+1}$, where p controls the active period, a determines the transition point between active and decaying behavior, and q sets the residual influence of old interactions. Thus, recent interactions receive higher importance, while older interactions retain a non-zero baseline contribution. Although ASF is used here as an interpretable instance, the temporal weighting layer can be instantiated with other age-dependent functions. We evaluate the proposed extension on real-world temporal networks across several domains, including social contact, communication, and urban mobility. Experiments use preferential attachment as the similarity measure, with node strengths computed on the temporally weighted graph. We first analyze how the active-period parameter p affects backbone composition within a snapshot. We then fix the parameters and track temporal backbones across successive snapshots. We compare backbones using edge overlap, temporal turnover, and retained-edge persistence. The results show that temporal weighting modifies the extracted backbone and reveals interactions that static aggregation may hide. Recent and persistent edges are better represented, while outdated interactions are progressively down-weighted. Different parameter settings provide complementary views of network dynamics. Overall, the proposed approach temporalizes the extraction of link-prediction-based backbones while preserving the logic of the original static framework.

From Symbolic Sequences to Fractal Growth. DLA-Based Complexity Signatures for Human, Machine, Code, and Synthetic Texts

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Symbolic sequences generated by human authors, large language models, source code, and controlled stochastic mechanisms can be regarded as traces of heterogeneous complex systems. Local token statistics are informative, but they may miss long-range organization, recurrence, burstiness, and multi-scale regularities induced by the underlying dynamics. This contribution investigates Diffusion-Limited Aggregation (DLA) as a geometric transform for structural analysis of token sequences. Each sequence drives a stochastic growth process whose morphology is summarized through box-counting dimension and multifractal indices. Tokens are mapped to walker emission directions through embedding-based angular coordinates, while token frequency and novelty modulate growth. Sequential organization is converted into a spatial morphology whose branching, density, and scale-dependent mass distribution provide compact signatures of the original stream. To assess structure beyond token marginals, two standardized DLA indices are introduced, one against permutation baselines preserving the token multiset and one against independent unigram baselines. Bootstrap confidence intervals quantify uncertainty. The geometric view is complemented with Epiplexity, a bounded-learnability index measuring structure extracted by a constrained predictor. A focused case study considers human prose, an LLM-generated essay, a C source-code file, and four synthetic generators inducing topic switching, burstiness, grammar recursion, and hybrid regimes. Results indicate that scaling descriptors vary across sources, while synthetic sequences validate the indices. The proposed framework combines stochastic growth, fractal scaling, robustness baselines, and learnability-based measures, providing low-dimensional descriptors for symbolic streams generated by natural, artificial, and algorithmic processes.

Wavelet-Based Parameter Selection for Topological Data Analysis of Financial Bubbles

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Topological Data Analysis (TDA) has emerged as an effective tool for detecting structural changes and critical transitions in financial markets. In this work, we extend an existing TDA methodology for identifying early warning signals of financial bubbles from time series by introducing a systematic procedure for selecting key parameters in the pipeline: the sliding-window size and the embedding time-delay. Our approach is based on time-frequency analysis using the synchrosqueezed wavelet transform (SST), which provides sharp localization of dominant frequencies in nonstationary signals. We first calibrate the procedure on the Log-Periodic Power Law Singularity (LPPLS) model of financial bubbles, where prices exhibit super-exponential growth with oscillations of increasing frequency as the system approaches a critical transition. The SST is used to extract dominant frequencies, which are converted into characteristic periods. These periods determine suitable ranges for the sliding-window size, while the embedding delay is chosen using theoretical results relating optimal delays to characteristic periods in sliding-window embeddings.

The resulting parameters are then used in the TDA pipeline. The time series is embedded into a higher-dimensional space using Takens' delay-coordinate reconstruction, sliding windows generate point clouds, persistent homology is computed, and persistence diagrams are transformed into persistence landscapes. The norms of these landscapes form a new time series whose spikes indicate significant topological changes associated with bubble dynamics.

We validate the method on synthetic LPPLS signals, noisy LPPLS simulations, and real financial data. In particular, we apply it to the SP 500 index before the 2008 financial crisis and Bitcoin before the 2018 cryptocurrency crash. In both cases, the proposed SST-based parameter-selection framework produces clear topological signals before the crash, supporting its usefulness for early detection of financial bubbles.

Power Law Characterization of Age Related Cortical Information Decay

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The brain is a complex system of interconnected neural populations that relay information through dense neural connections. This network property has been extensively studied using mathematical models and neuroimaging techniques, including EEG. Despite these advances, how healthy aging alters macro-scale cortical information exchange is still not fully understood. This study investigates how the spatial extent of information transfer changes with age and examines whether this change carries a frequency-specific signature. We analyzed resting-state EEG data from the MPI-Leipzig LEMON dataset, comparing young (20–35 y, $N = 136$) and older adults (60–75 y, $N = 59$) in eyes-closed (EC) and eyes-open (EO) conditions. Pairwise mutual information (MI) between every channel pair was estimated using the Gaussian Copula method. For each subject and frequency band (delta, theta, alpha, beta), the relationship between MI and inter-electrode distance was examined on log-log scales, revealing a clear power-law decay. The scaling exponent quantifies how rapidly statistical dependency decreases across the scalp, with smaller values indicating spatially extended coupling and larger values indicating more locally confined coupling. Older adults showed significantly steeper scaling exponents in the theta and alpha bands during both EC and EO resting states. All four effects survived Bonferroni correction across the eight comparisons performed (theta EC: Cohen's $d = -0.43$, $p = 0.005$; theta EO: $d = -0.49$, $p = 0.003$; alpha EC: $d = -0.49$, $p = 0.004$; alpha EO: $d = -0.66$, $p < 10^{-4}$). The largest age-related difference was observed in the alpha band during EO rest. In contrast, delta activity showed no significant age effect, while beta-band effects were weaker and less consistent. Channel-wise analyses revealed that the strongest age effects were concentrated over fronto-central and sensorimotor regions, where several electrodes exhibited very large effect sizes, reaching Cohen's $d = -1.05$ at FC4 in the alpha EO condition. Additional robustness analyses indicated that these findings could not be explained by spectral power differences. In particular, the alpha EO effect remained significant after distribution-matched power resampling and after controlling for band power using robust regression. This study presents a power-law framework to characterize age-related changes in large-scale cortical information transfer using resting-state EEG. Healthy aging was associated with a steeper spatial decay of information sharing, primarily in the theta and alpha bands and predominantly over sensorimotor and fronto-central regions. These findings suggest that aging alters the spatial organization of cortical communication in a frequency-specific manner. The proposed scaling exponent provides a compact and power-independent measure of large-scale brain network organization, complementing conventional spectral EEG metrics. The results demonstrate that statistical scaling analysis can capture macroscale changes in cortical communication and may provide a useful biomarker for healthy brain aging.

Adaptive Digital Predistortion with Batch-Identified Volterra-Laguerre Models and Mixture-of-Experts Supervision

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Modern RF transmitters are affected by nonlinear and memory effects in power amplifiers, particularly near high-efficiency operating regions, where spectral regrowth and distortion become significant [1]. This work presents an adaptive digital predistortion approach based on batch-identified Volterra-Laguerre models under a Mixture-of-Experts supervision scheme [2–5]. The proposed structure combines the nonlinear representation capability of Volterra series with the compact dynamic description provided by Laguerre basis functions, aiming to obtain a reduced-complexity model that is nonetheless capable of capturing the most relevant memory effects [2,3]. The predistorter is identified from input-output data through batch estimation; this description is used both for initial calibration and for model updating during changes in operating conditions. To improve robustness against varying signal conditions and different plant behaviors, multiple specialized models are employed under the supervision of a Mixture-of-Experts, which selects or combines the most suitable predistortion action according to the current operating regime [4,5]. This allows the system to handle heterogeneous nonlinear conditions that would be difficult to represent with a single static model. The implementation was developed in MATLAB, with explicit traceability between the mathematical formulation and the code structure. Particular attention is paid to consistency between model equations, identification routines, and control logic, as well as modularity, with a view to preparing the functional chain for future implementation on an FPGA or DSP. The result is an adaptive predistortion framework designed to compensate for nonlinearities in advanced communication transmitters.

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Effects of Pipelining Delay and Discretization on an FPGA Emulation of a Single-Transistor Chaotic Oscillator

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Digital implementations of continuous-time chaotic systems on FPGAs offer significant advantages for high-speed physical computing, including real-time signal generation and high architectural flexibility. However, achieving high clock frequencies in feedback-based chaotic systems typically requires pipelined architectures, which inherently introduce effective delays into the feedback loop. In addition, the numerical realization introduces further constraints. The choice of integration method plays a key role. Beyond differences in resource consumption, higher-order Runge-Kutta methods require multiple intermediate calculations, which impose more complex temporal structures on state updates and thereby modify the effective feedback timing. In contrast, the explicit Euler method provides a more direct update structure and requires significantly fewer hardware resources, but is inherently less accurate and introduces time-step dependent discretization effects. Furthermore, finite precision leads to quantization of state variables, which also depends on the scaling strategy used to map floating-point models to fixed-point representations. In this work, we investigate an FPGA-based Minati-Frasca chaotic oscillator. Rather than treating delay, discretization, and precision independently, we analyze their joint influence on the system dynamics. Preliminary numerical and experimental results suggest that the interaction among these non-idealities can induce qualitative changes in the observed dynamical regimes, including transitions between dynamical states and implementation-dependent behaviors not present in ideal continuous-time models. These findings indicate that digitally implemented chaotic nodes should be analyzed as effective dynamical systems shaped by algorithmic choices and hardware constraints. This perspective provides insights for the design of reliable hardware-based computing frameworks, including physical reservoir computing.

Sound Synthesis on a Reconfigurable Analog Computer: Real-Time Physical Modeling

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Physical modeling sound synthesis generates audio by solving the differential equations that describe a vibrating object, in contrast to signal-based methods that approximate the radiated waveform. The approach captures the response of the generator itself and supports the design of new virtual instruments, but the underlying partial differential equations are expensive to evaluate in real time on digital hardware once the model becomes stiff or includes coupled resonances. We demonstrate that a one-dimensional fixed-end wave equation can be solved in real time on the REDAC (REconfigurable Discrete Analog Computer), an industrial platform developed at anabrid, by combining its analog integrators for continuous-time evolution with a finite-difference discretization in space. The implementation reproduces the expected modal spectrum and time-domain response once coefficient ranges, line assignment, and time scaling are matched to the hardware. The main intrinsic drawback of the spatial discretization is an unavoidable frequency dispersion of the propagating modes, which we mitigate by refining the grid and by widening the finite-difference stencil to further neighbors. We further characterize accumulated electronic noise and slow-growing instabilities at high node counts, and outline mitigations that guide ongoing work on stiff and damped strings and on instrument bodies treated as modal banks.

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