Entropy 2026 Conference

Entropy 2026: Exploring Complexity and Information in Science

1–3 July 2026 | Barcelona, Spain

Conference Book

Conference Venue

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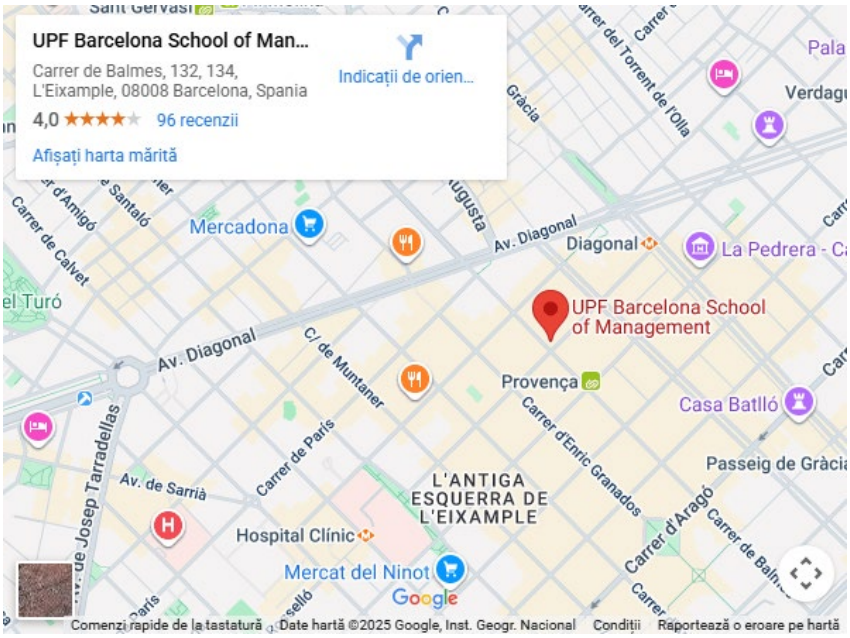

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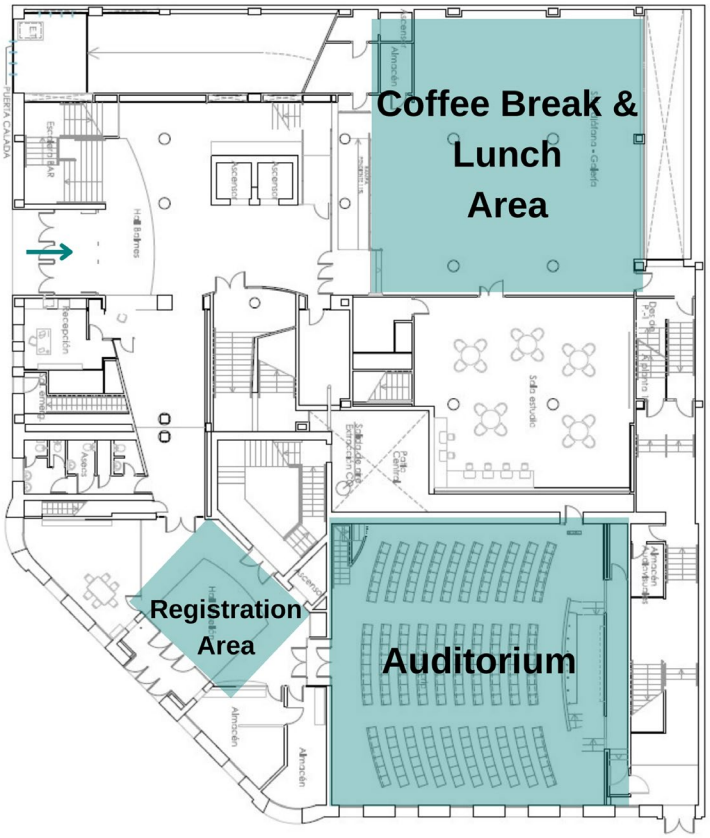
Venue Floor Plan



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- Manuscripts regarding research proposals and research ideas will be particularly welcome.
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Journal Website: https://www.mdpi.com/journal/entropy

Entropy 2026: Exploring Complexity and Information in Science

1–3 July 2026 | Barcelona, Spain

MDPI

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Welcome from the Chairs

We cordially invite you to partake in **Entropy 2026: Exploring Complexity and Information in Science (Entropy 2026)**, which will be held in Barcelona, Spain, from 1 to 3 July 2026.

Entropy is one of science's most frequently used terms, owing to its foundational relevance in two major disciplines: physics and information theory. Originally rooted in thermodynamics, the concept of entropy has, since Shannon's pioneering work, become central to the understanding of information processing and communication.

This conference is organized by MDPI's open-access journal Entropy (ISSN 1099-4300; IF: 2.1) and presents a unique opportunity to unite researchers from both fields, fostering collaboration and cross-disciplinary innovation.

The main topics and sessions of the conference include the following:

- Complex Systems and Network Science
- Information Theory, Data Science and Artificial Intelligence
- Quantum Information and Quantum Computing
- Thermodynamics and Energy Systems
- Non-Equilibrium Systems and Entropy Production
- Statistical Physics and Stochastic Processes
- Soft and Living Matter
- Applications of Entropy in Science and Engineering

We particularly welcome interdisciplinary contributions from both theoretical and applied perspectives. Submissions may also address conceptual and methodological advances, as well as innovative applications of entropy and information theory across a broad range of domains.

We very much look forward to your participation.

Prof. Dr. Miguel Rubi
Conference Chair
University of Barcelona

Prof. Dr. Kevin H. Knuth
Conference Chair
University at Albany

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Email: **entropy2026@mdpi.com**

Keynote Speakers

Prof. Dr. Ariel Caticha

Department of Physics, University at Albany

Prof. Dr. Bernardo Spagnolo

"Emilio Segrè" Department of Physics and Chemistry, Interdisciplinary Theoretical Physics Group, University of Palermo

Prof. Dr. David Reguera

Departament de Física de la Matèria Condensada, Universitat de Barcelona

Prof. Dr. Eli Barkai

Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University

Prof. Dr. Hong Qian

Center for Interdisciplinary Studies, Westlake University

Prof. Dr. José Fernando F. Mendes

Department of Physics & I3N, University of Aveiro

Prof. Dr. Jose M.G. Vilar

Biofisika Institute (CSIC, UPV/EHU), University of the Basque Country

Prof. Dr. Juan F. Pedraza

Institute of Theoretical Physics, UAM/CSIC

Prof. Dr. Karl Heinz Hoffmann

Institute of Physics, Technical University Chemnitz

Prof. Dr. Kevin H. Knuth

Department of Physics,
University at Albany

Prof. Dr. Marta Sales Pardo

Department of
Chemical Engineering,
University of Rovira i Virgili

Prof. Dr. M. Ángeles Serrano

ICREA and
University of Barcelona

Prof. Dr. Olivier Rioul

LTCI, Télécom Paris,
Institut Polytechnique de Paris

Dr. Péter Ván

Department of Theoretical
Physics, Institute for Particle and
Nuclear Physics, Wigner
Research Centre for Physics

Prof. Dr. Ralf Metzler

Institute for Physics &
Astronomy,
University of Potsdam

Prof. Dr. Stefano Mancini

School of Science
and Technology,
University of Camerino,
INFN Sezione di Perugia

Prof. Dr. Syed Ejaz Ahmed

Department of Mathematics and
Statistics, Brock University

Event Scientific Committee

Prof. Dr. Airton Deppman

Institute of Physics, The São Paulo University

Dr. Andrea Frazzica

Institute of Advanced Technologies for Energy, Italian National Council Research (CNR)

Prof. Dr. Antonio J. Ramirez-Pastor

Departamento de Física, Instituto de Física Aplicada, Universidad Nacional de San Luis-CONICET

Prof. Dr. Antonio Sellitto

Department of Industrial Engineering, University of Salerno

Prof. Dr. Chang-pu Sun

Graduate School of China Academy of Engineering Physics and Beijing Computational Science Research Center

Prof. Dr. Colin Johnson

School of Computer Science, University of Nottingham

Prof. Dr. Dick Bedeaux

PoreLab, Department of Chemistry, Norwegian University of Science and Technology

Prof. Dr. Edson D. Leonel

Departamento de Física, Universidade Estadual Paulista (UNESP)

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Department of Chemistry, Imperial College London

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Department of Condensed Matter Physics, Universitat de Barcelona

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Department of Mechanical Engineering, University of West Attica

Prof. Dr. Jan Sładkowski

Institute of Physics, University of Silesia

Dr. Jarosław Kwapień

Complex Systems Theory Department, Institute of Nuclear Physics, Polish Academy of Sciences

Prof. Dr. Jayanta Deb Mondol

Belfast School of Architecture and the Built Environment, Centre for Sustainable Technologies, Ulster University

Prof. Dr. Jiulin Du

School of Science, Tianjin University

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Department of Physics, Institute of Applied Physics, National University of San Luis

Prof. Dr. Laszlo Bela Kish

Department of Electrical and Computer Engineering, Texas A&M University

Prof. Dr. Mostafa Elsharqawy

School of Engineering, College of Engineering and Physical Sciences, University of Guelph

Prof. Dr. Peter McClintock

Department of Physics, Lancaster University

Prof. Dr. Petr Jizba

Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

Prof. Dr. Qi Ouyang

Institute for Advanced Study in Physics, School of Physics, Zhejiang University

Prof. Dr. Raúl Alcaraz Martínez

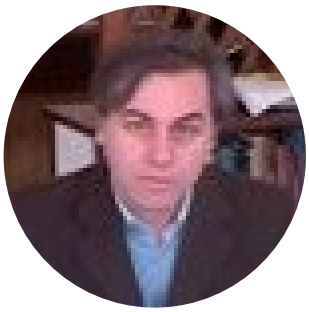
Research Group in Electronic, Biomedical and Telecommunication Engineering, Universidad de Castilla-La Mancha

Prof. Dr. Regino Criado Herrero

Director of the Research Center DCNC, University Rey Juan Carlos

Prof. Dr. Roberto de Lieto Vollaro

Department of Industrial, Electronic and Mechanical Engineering, Roma TRE University



Dr. Roberto Zivieri

Department of Engineering, University of Messina, Istituto Nazionale di Alta Matematica Francesco Severi

Prof. Dr. Santiago Aparicio

Department of Chemistry and ICCRAM, University of Burgos

Dr. Sauro Succi

Center for Life Nano Science@La Sapienza, Istituto Italiano di Tecnologia

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Macedonian Academy of Sciences and Arts, Department of Physics, Korea University

Prof. Dr. Ugur Tirnakli

Complex Systems Research and Application Center, Izmir University of Economics

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Dept. of Mathematics, FNSPE, Czech Technical University in Prague

Prof. Dr. Xinsheng Sean Ling

Department of Physics, Brown University

Program Overview

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*Poster Session A includes posters from Sessions 3,4,8,1,7
*Poster Session B includes posters from Sessions 5,6,2

Entropy 2026 Program

1st July 2026 (Wednesday)

Session 3. Quantum Information and Quantum Computing

Time in CEST	Speaker	Title
8:00–9:00	Registration	
9:00–9:15	Opening Ceremony Session 3 Introduction	
9:15–9:45	**Ariel Caticha** Keynote Speaker	Towards an Entropic Quantum Gravity
9:45–10:15	**Eli Barkai** Keynote Speaker	First-Passage and Hitting Times in Monitored Quantum Systems on NISQ Platforms
10:15–10:30	**Thomas Scheidsteger** Oral Presenter	The Quantum Turn of Entropy: A Bibliometric Journey Through Quantum Information and Quantum Computation
10:30–10:45	**Newshaw Bahreyni** Oral Presenter	A Study of Fluctuation Growths of Observables in Open Quantum Systems
10:45–11:20	Coffee Break Poster Session A (35 min)	
11:20–11:50	**Stefano Mancini** Keynote Speaker	The Capacity of a Single Quantum Neuron
11:50–12:05	**Luca Nigro** Oral Presenter	Quantum Reservoir Computing via Intrinsic and Engineerednon-Unital Dynamics
12:05–12:20	**Seyedali Mousavi** Oral Presenter	Multi-Objective Quantum Architecture Search under Noise via Expressibility-Guided Evolution
12:20–14:00	Lunch Break	

Session 4. Thermodynamics and Energy Systems

Time in CEST	Speaker	Title
14:00–14:05	Session 4 Introduction	
14:05–14:35	**Karl Heinz Hoffmann** Keynote Speaker	Finite-Time Thermodynamics of Endoreversible Systems
14:35–15:05	**Péter Ván** Keynote Speaker	Fundamental and Emergent: Testing the Second Law of Thermodynamics
15:05–15:20	**Adam Gadomski** Oral Presenter	Superlubric Effect of Vanishing Classical-Quantum-Measured Coefficient of Friction with Inclusion of Van der Waals Monolayer Contaminants Deposited on Graphene-Type Substrates
15:20–15:35	**Angel Cuadras** Oral Presenter	A Stochastic Entropy-Based Approach to Electrochemical Battery Modeling
15:35–15:50	**Özge Özkılınc** Oral Presenter	Data-Driven Screening of Choline Chloride–Monoterpenoid and –Fatty Acid Deep Eutectic Solvents for PFAS Extraction
15:50–16:25	Coffee Break Poster Session A (35 min)	

Session 8. Applications of Entropy in Science and Engineering

Time in CEST	Speaker	Title
16:25–16:30	Session 8 Introduction	
16:30–17:00	**Juan F. Pedraza** Keynote Speaker	Krylov Complexity as a Probe of Quantum Chaos in Many-Body Systems
17:00–17:30	**Syed Ejaz Ahmed** Keynote Speaker	Reliable Post-Estimation Inference in High-Dimensional Sparse Regression
17:30–17:45	**Amilcare Porporato** Oral Presenter	Environmental Thermodynamics: Bridging Science and Technology in a Changing Environment
17:45–18:00	**Vítor Costa** Oral Presenter	Looking at Economics Through the Eyes of Thermodynamics: Economic Entropy, and Economic Entropy Generation
18:00–18:15	**Serge Provost** Oral Presenter	Quantifying the Representational Power of Consecutive Moments: A Relative Entropy Perspective
18:15–18:30	**Ignácio Iturrioz** Oral Presenter	Linking Entropy Measures in Quasi-Brittle Material Specimens and Statistical Models to Global Acoustic Emission
18:30–18:45	**Kazuko Sugimoto** Oral Presenter	Internal Defect Detection Using Spatial Spectral Entropy in Noncontact Acoustic Inspection and COMSOL Analysis of Flexural Vibration
20:00–21:00	Dinner Banquet	

2nd July 2026 (Thursday)

Session 1. Complex Systems and Network Science

Time in CEST	Speaker	Title
8:30–9:00	Registration	
9:00–9:05	Session 1 Introduction	
9:05–9:35	**Ángeles Serrano** Keynote Speaker	Statistical Mechanics of Random Graphs within the Fermionic Maximum-Entropy Framework
9:35–10:05	**José Fernando F. Mendes** Keynote Speaker	When Does Diversity Matter in Binary-Choice Dynamics?
10:05–10:20	**Luciano Telesca** Oral Presenter	Quantifying complexity in synthetic earthquakes generated by the Olami–Feder–Christensen spring-block model
10:20–10:35	**Antoni Hernández-Fernández** Oral Presenter	Do Linguistic Laws Emerge from Physics? Statistical Regularities in Photonic Neurons
10:35–11:10	Coffee Break Poster Session B (35 min)	
11:10–11:40	**Marta Sales Pardo** Keynote Speaker	The Physics of Network Alignment
11:40–11:55	**Johan L.A. Dubbeldam** Oral Presenter	Understanding Extinction Events in Minimal Nonlinear Random Models for Population Using the Theory of Statistical Learning
11:55–12:10	**Jan Korbel** Oral Presenter	Homophily-Based Social Group Formation in a Spin Glass Self-Assembly Framework
12:10–12:25	**Ioannis Antoniadis** Oral Presenter	Network Generation by Vertex-based Wiring and Restricted Resources
12:25–14:00	Lunch Break	

Session 7. Soft and Living Matter

Time in CEST	Speaker	Title
14:00–14:05	Session 7 Introduction	
14:05–14:35	**Jose M.G. Vilar** Keynote Speaker	Entropy as an Active Remodeling Principle in Biomolecular Nanostructure Disassembly
14:35–15:05	**David Reguera** Keynote Speaker	Shaping Viruses with Entropy: Assembly Kinetics of Viral Capsid Formation
15:05–15:20	**Santiago Pelosso Rodríguez** Oral Presenter	Modeling Chaotropic and Kosmotropic Ion Effects on Entropy and Diffusion of Water
15:20–15:35	**Miriam Martinez** Oral Presenter	Quantifying Insect Dynamics in Euclidean and Non-Euclidean Spaces
15:35–16:10	Coffee Break Poster Session B (35 min)	

Session 5. Non-Equilibrium Systems and Entropy Production

Time in CEST	Speaker	Title
16:10–16:15		Session 5 Introduction
16:15–16:45	**Bernardo Spagnolo** Keynote Speaker	Noise-Assisted Metastability and Noise-Enhanced Perception
16:45–17:00	**Veaceslav Albu** Oral Presenter	Entropy's Other Half: How Information Melts Potential into Memory
17:00–17:15	**Rudolf Hanel** Oral Presenter	Irreversibility in the Ideal Gas Model and a Thermodynamic Time-Energy Uncertainty Principle
17:15–17:30	**Oded Farago** Oral Presenter	Entropy Production in Run-and-Tumble Particles Mapped to Brownian Motion in an Inhomogeneous Temperature
17:30–17:45	**David Papo** Oral Presenter	Time-Reversal Symmetry in Brain Pathology
17:45–18:00	**Jean-Marc Simon** Oral Presenter	Adsorption Kinetics Model of Hydrogen on Graphite
18:00–18:15	**Francisco J. Cao-García** Oral Presenter	Ligand Binding in Crowded Polymers
18:15–18:30	**Matteo Colangeli** Oral Presenter	Stochastic Chains Coupled to Thermal Reservoirs

3rd July 2026 (Friday)

Session 6. Statistical Physics and Stochastic Processes

Time in CEST	Speaker	Title
8:30–9:00	Registration	
9:00–9:05	Session 6 Introduction	
9:05–9:35	**Hong Qian** Keynote Speaker	Neo-Gibbsian Statistical Energetics with Applications to Nonequilibrium Cells
9:35–9:50	**Aleksei Chechkin** Oral Presenter	Genuine and Spurious (Non-)Ergodicity in Single Particle Tracking
9:50–10:05	**Ronen Zangi** Oral Presenter	Chemistry with Small Number of Molecules
10:05–10:20	**Jean-Luc Garden** Oral Presenter	Entropy Fluctuations in Stochastic Thermodynamics
10:20–10:35	**Guillermo Chacón-Acosta** Oral Presenter	Curvature-Induced Effects in Time-Subordinated Diffusion
10:35–11:00	Coffee Break (25 min)	
11:00–11:30	**Ralf Metzler** Keynote Speaker	Anomalous Diffusion, Non-Gaussianity and Long-Range Dependent Motion
11:30–11:45	**Jose Luis Calabrese** Oral Presenter	Why Do Spiral Galaxies Rotate So Fast? Same Gravity Theory, Different Dynamical-Regime Model
11:45–12:00	**Lamberto Rondoni** Oral Presenter	Power-Law Tails and Universality for Strong Anomalous Diffusion
12:00–12:15	**Ofir E. Alon** Oral Presenter	Solvable Model of Induced Interactions in Bose-Einstein Condensates
12:15–13:30	Lunch Break	

Session 2. Information Theory, Data Science and Artificial Intelligence

Time in CEST	Speaker	Title
13:30–13:35	Session 2. Introduction	
13:35–14:05	**Kevin H. Knuth** Keynote Speaker	The Statistical Mechanics of Motion
14:05–14:20	**Andres Aragoneses** Oral Presenter	The Linguistic Organization of Complex Systems
14:20–14:35	**Hiroshi Matsuzoe** Oral Presenter	Invariant and Dually Flat Structures in Information Geometry for Deformed Exponential Families
14:35–14:50	**Federico Fogolari** Oral Presenter	K-th Nearest Neighbour Entropy for Classification
14:50–15:05	**Veronica Sanz-Arqué** Oral Presenter	Stochastic Resetting with Limited Information
15:05–15:30	Coffee Break (25 min)	
15:30–16:00	**Olivier Rioul** Keynote Speaker	Dual Representations of Classical and Quantum Entropies: Theory and Perspectives
16:00–16:15	**Valeria Rossi** Oral Presenter	Mutual Information Based on Kolmogorov Complexity for Randomness Evaluation
16:15–16:30	**Francisco J. Valverde-Albacete** Oral Presenter	On Information Transmission in Multilabel Classifications Tasks
16:30–16:45	**Martin Schlather** Oral Presenter	70 Years of Bandwagon: Shannon's Viewpoint Revisited
16:45–16:55	**Interview** Speakers	
16:55–17:10	Award Ceremony & Chairs' Closing Remarks	

Poster List

Poster Session A (S3, S4, S8, S1, S7)		
1.	Mile Dželalija	*Entropy-Based Correlation Operator in the Hilbert Space Representation of Biomedical Complex Systems*
2.	Michel Aguilera	*Thermodynamic Behavior of the Dipolar Q-State Clock Model on Large Lattices: A Monte Carlo Study*
3.	Juan C. Pacheco-Páez	*Efficient Power in an Arrangement Series of Endoreversible Thermal Engines*
4.	Juan C. Pacheco-Páez	*Entropy Generation Trade-Offs in Finite-Time Irreversible Otto–Atkinson/Miller Engines under Efficient Power, Ecological, and Hybrid Ecological Regimes*
5.	Fernando Moreno	*From Data-Driven to Physics-Informed AI: Explainable Energy Optimization in Industrial Systems*
6.	Takuya Yamano	*Thermodynamic Meaning of Statistical Factor in Systems with Temperature-Dependent Energy Levels*
7.	Miloslav Pekař	*Gibbs Energy, Chemical Reactions–(In)Consistencies*
8.	Dani Rodríguez Castellanos	*Thermodynamic Framework for q-Affinity*
9.	Angel Cuadras	*A Holistic Approach to Residential Metabolism: The Entropic Cost of Demographic Fragmentation*
10.	Angel Cuadras	*Entropy Description of Projectile Motion in Dissipative Media*
11.	Rytis Petrauskas	*Transposing Econophysical Entropic Criteria to Scientific Time Series: A Framework for Volatility-Scaled Data Curation*
12.	José Juan Peña	*The Decay Equation: A Generalization from Nonextensive Statistics and k-Statistics Based on the q-Calculus*
13.	Milan Rybář	*Entropy Dynamics Differentiate Deliberate and Arbitrary Decisions in EEG*
14.	Ghaya Mehdi	*Dispersion Phase Entropy: An Enhanced Complexity Measure Incorporating Phase Dynamics in Nonlinear Time Series*
15.	Ghaya Mehdi	*Multi-Scale Circulant Determinant-based Permutation Entropy for HDsEMG Signal Processing*
16.	Sayuri Ishiyama	*Emergence of Life and Relational Entropy: Nonlinear Dynamics of the Fetus–Maternal System*
17.	Marta Lotka	*Multiscale Structural Organization of the Brain Breaks Down in Aging and Dementia: Insights from Multifractal Space-Filling Curve Analysis (MFSCA)*
18.	João de Sant'Ana	*Prejudice and Discrimination in a Society of Neural Networks*
19.	Rustu Demirer	*Spectral Criticality at the Interface of Analytic Number Theory and Neural Field Theory: Entropy Production, Zero Repulsion and Cortical Symmetry Breaking*
20.	Gordon Morison	*Generalized Permutation Entropy Measures on Graph Signals*
21.	Anna Monclús I Rojo	*Correlations in Active Nematic Defects*
22.	Javier Orradre Altabas	*A Many-State Conformational-Binding Model to Describe Polymer Force-Extension Curves*

Poster Session B (S5, S6, S2)		
1.	Vicent Moltó-Gallego	*Rolling Bearing Fault Classification Approach Combining Slope Entropy and Downsampling Schemes*
2.	Klaus Morawetz	*Correlational Entropy by Nonlocal Quantum Kinetic Theory*
3.	Huilong Ren	*Path-Dependent Energy Lagrangian for Irreversible Thermomechanical Systems*
4.	Andrés Vallejo	*Alternative Analisys of Single-Qubit Quantum Heat Engines*
5.	Amna Khraibut	*A Stochastic Analysis of a Hypersonic Planar Flow Using a Fokker–Planck Approximation*
6.	Eugenio Vogel	*Mutability as a Dynamic Function Bound by Entropic Functionals*
7.	Pasquale Vozza	*Bridging Exact Response Theory with the Karhunen-Loève expansion*
8.	Carlos Escudero	*Structural Conditions for a Driftless Langevin Representation of Heterogeneous Fickian Diffusion*
9.	Mateusz Wiśniewski	*Fast Directed Transport via Energy Recuperation in Non-Markovian Media*
10.	Karol Białas	*Absolute Negative Mobility in the Overdamped System Driven by Active Fluctuations*
11.	Giuliana Paradiso	*Statistical Scaling Analysis of Seismic Acceleration Signals*
12.	Antonio Pons	*Exploring Complex Systems as Language Generators*
13.	Federico Vello	*Benchmarking the kth-Nearest Neighbur Method for Classification*
14.	Pieter van Rooyen	*Entropy, Annealing, and the Continuity of Agency in Human–AI Systems*
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Session 1. Complex Systems and Network Science

sciforum-181611: Multiscale structural organization of the brain breaks down in aging and dementia: insights from Multifractal Space-filling Curve Analysis (MFSCA)

Marta Lotka [1], Jacek Grela [2], Zbigniew Drogosz [3], Jeremi K. Ochab [2], Paweł Oświęcimka [4]

[1] Doctoral School of Exact and Natural Sciences, Jagiellonian University, Kraków, Poland; Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, Kraków, Poland
[2] Institute of Theoretical Physics, Jagiellonian University, Kraków, Poland; Mark Kac Center for Complex Systems Research, Jagiellonian University, Kraków, Poland
[3] Institute of Theoretical Physics, Jagiellonian University, Kraków, Poland
[4] Complex Systems Theory Department, Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland; Mark Kac Center for Complex Systems Research, Jagiellonian University, Kraków, Poland

The brain is a complex system whose multiscale organization supports cognitive functioning. In neurodegenerative disease, alterations in brain structure are accompanied by a broad cognitive decline, motivating the question of whether changes in multiscale brain organization track these impairments. Multifractal measures provide a promising description of brain organization that captures its cross-scale heterogeneity. Whereas established methods for estimating fractal characteristics have largely been developed for one-dimensional series, neuroimaging – including MRI and fMRI – produces multidimensional data. This creates a need to extend these approaches to the multidimensional case.

We introduce *Multifractal Space-filling Curve Analysis* (MFSCA), a novel method for quantifying multifractal properties in multidimensional data. Its central insight is that multidimensional data can be projected onto a one-dimensional representation using a Hilbert space-filling curve while partially preserving their spatial correlations. Multifractal Detrended Fluctuation Analysis is then applied to the resulting sequence, quantifying e.g. the width and asymmetry of its multifractal spectrum. We validate the method on synthetic multifractal structures and apply MFSCA to MRI brain scans (T1w) from the OASIS-1 dataset, which includes early dementia patients and healthy controls.

MFSCA accurately recovers multifractal properties of two-dimensional deterministic cascades. In OASIS-1 data, the method reveals specific brain locations exhibiting systematic differences in multifractal profiles between patient cohorts differing in age and dementia severity, suggesting progressive loss of structural complexity in neurodegeneration and healthy aging. Nonlinear dimensionality reduction of multifractal measures reveals that patients are arranged along a continuum in latent space, in a manner consistent with aging and dementia progression.

Overall, MFSCA provides a framework for studying multifractal properties of multidimensional data. In MRI data, it identifies signatures of aging and dementia, supporting the view that neurodegeneration involves a breakdown of multiscale brain organization.

sciforum-175520: Spectral Criticality at the Interface of Analytic Number Theory and Neural Field Theory: Entropy Production, Zero Repulsion and Cortical Symmetry Breaking

Rustu Murat Demirer [1], Oya Demirer [2]

[1] Electrical and Electronics Engineering Department, Biomedical Engineering Programme, Işık University, Meşrutiyet Mahallesi, Üniversite Sokak No:2, 34980 Şile/İstanbul, Turkey
[2] Faculty of Engineering and Natural Sciences, Istanbul Arel University, Türkoba Mahallesi, Erguvan Sokak No:26, PK 34537, Tepekent-Büyükçekmece/İstanbul, Turkey

We establish a cross-disciplinary mathematical framework that integrates analytic number theory with neural field theory, focusing on the De Bruijn–Newman constant Λ and the Freeman–Vitiello dissipative quantum field theory of cortical dynamics. The De Bruijn–Newman family of entire functions, characterized by a real disorder variable t, modifies the Riemann Xi function at t = 0 and demonstrates a distinct spectral transition at t = Λ: below this threshold, the family contains pairs of complex conjugate zeros (symmetry-broken spectral sector), whereas at and above it, all zeros are real (spectral order). Given that Λ is non-negative and the Riemann Hypothesis is equivalent to Λ = 0, the transition at criticality possesses profound arithmetic implications. This spectral phase shift serves as the number-theoretic counterpart of spontaneous U(1) symmetry breaking in the Freeman–Vitiello model, wherein the cortex vacuum attains a non-zero dipole condensate, leading to the emergence of massless Nambu–Goldstone bosons as cortical carrier waves. The Nambu–Goldstone frequency spectrum that regulates long-range cortical coherence aligns precisely with the imaginary components of the Riemann zeros, positioning the initial ten within the alpha–beta EEG band (9–32 Hz) for physiologically plausible cortical correlation durations, constituting a falsifiable arithmetic prediction devoid of any free parameters. Zero-repulsion dynamics adhere to Calogero–Moser equations exhibiting Gaussian Unitary Ensemble spectral statistics, aligning with the Montgomery pair-correlation conjecture and eigenvalue repulsion in extensive cortical connection matrices. The von Neumann entropy of the cortical vacuum diverges logarithmically as t approaches Λ from above, designating the Riemann Hypothesis as a quantum critical point. Entropy creation in both frameworks adheres to the same de Bruijn–Fisher information identity, but the Selberg trace formula encapsulates re-entrant cortical circuits as prime closed geodesics. The correspondences imply that the Riemann Hypothesis, if valid, articulates a maximum-entropy criticality principle common to prime arithmetic and biological brain computing.

sciforum-175170: Do Linguistic Laws Emerge from Physics? Statistical Regularities in Photonic Neurons

Antoni Hernández-Fernández [1], Andrés Aragoneses [2], Antoni J. Pons [3]

[1] Institut de Ciències de l'Educació, Universitat Politècnica de Catalunya
[2] Physics Department, Whitman College, Walla Walla, WA, 99362, USA
[3] Departament de Fisica, Universitat Politecnica de Catalunya, St. Nebridi 22, 08222 Terrassa, Spain

In this work we present a unified framework for investigating the emergence of analogues of linguistic laws in non-biological physical systems, focusing primarily on photonic neurons operating with dual delayed feedback. Building on previous work on the physical origins of linguistic regularities in speech (Torre et al., 2019) and the multiscale dynamics of photonic neuromorphic devices (Aragoneses, 2025), we introduce the notion of "optical words" as discrete, symbolic-like units extracted from continuous optical intensity time series.

Through threshold-based segmentation we reconstruct symbolic sequences from photonic spike trains and assess whether statistical patterns analogous to classical linguistic laws—such as Zipf's law, Herdan–Heaps law, the Brevity law, and the Menzerath–Altmann law—emerge in these purely physical optical systems.

Our results suggest that the statistical patterns characteristic of human language may reflect some features of multiscale physical processes rather than exclusively biological or cognitive mechanisms. This work establishes a novel definition of 'optical units' in communication systems, and also a theoretical novel connection between photonic neuromorphic systems and quantitative linguistics, supporting the hypothesis that linguistic-law analogues may emerge from fundamental physical constraints of complex systems.

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sciforum-173797: Emergence of Life and Relational Entropy: Nonlinear Dynamics of the Fetus–Maternal System

Sayuri Ishiyama [1], Takashi Tahara [2], Hiroaki Iwanaga [2]

[1] Department of Maternal and Child Nursing, The Japanese Red Cross Kyushu International College of Nursing, Munakata, Fukuoka 811-4157, Japan
[2] Institute for Basic Medical and Welfare Research, Fukuoka 810-0051, Japan

Introduction

During pregnancy, the fetus and mother exist as two individuals but may form a single dynamic system through physiological coupling. No study has quantitatively described the fetus–maternal relationship as a unified dynamic field. This study conceptualized the fetus–maternal system as an interacting dynamic field and quantified its nonlinear dynamics using chaos and complex systems theory.

Methods

Four pregnant women and their fetuses participated. From 11 weeks of gestation to the postnatal period, heart sound waveforms were recorded using Doppler ultrasonography under five conditions (rest, maternal vocal stimulation, post-stimulation, unfamiliar vocal stimulation, and post-stimulation). Time-series data were embedded in multidimensional phase space, attractors were reconstructed via correlation dimension analysis, and the Lyapunov dimension and Kolmogorov–Sinai(KS) entropy were calculated to assess structural complexity and information generation.

Results

Both fetal and maternal heart sound series showed five-dimensional structures with positive maximum Lyapunov exponents, and surrogate analysis confirmed deterministic chaos. The fetal attractor evolved from a disordered state to a stable chaotic structure as pregnancy progressed; maternal vocal stimulation facilitated this transition. Fetal Lyapunov dimension and KS entropy increased with gestation and approached maternal values after birth. Maternal complexity remained high throughout pregnancy, with a temporary reduction in KS entropy during late gestation followed by recovery postpartum.

Conclusion

The fetus–mother system was quantitatively characterized as a nonlinearly interacting field. This developmental process was demonstrated as relational KS entropy in five-dimensional space. The fetus's increased complexity and degrees of freedom enhance information generation, while the mother maintains system stability and exhibits decreased entropy in late pregnancy. This may function as a dynamic constraint supporting fetal development. These dynamics could not be captured by reductionist analysis and became apparent through non-additive, scale-translatable emergence and recursive dynamics. This framework contributes to the theoretical foundation of developmental support and perinatal care.

sciforum-180699: Empirical Validation of the Polarization Transition in a Double-Random Field Model of Elections

Jan Korbel [1], Remah Dahdoul [1], Stefan Thurner [2,3,4]

[1] Complexity Science Hub Vienna, Metternichgasse 8, 1030 Vienna, Austria
[2] Section for Science of Complex Systems, CeMSIIS, Medical University of Vienna, Spitalgasse 23, A-1090 Vienna, Austria
[3] Complexity Science Hub Vienna, Josefstädter Strasse 39, A-1080 Vienna, Austria
[4] Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, United States of America

In this paper, we model bipartisan elections where voters are exposed to two forces: first, the local homophilic interaction between family, friends, and colleagues, and second, the external influence from two political campaigns. The model is mathematically equivalent to the random field Ising model with a bimodal field. We derive the full phase diagram and identify the critical curve as well as a tricritical point. When both parties exceed a critical campaign spending, the system undergoes a phase transition to a highly polarized state where homophilic influence becomes negligible, and election outcomes mirror the proportion of voters aligned with each campaign, independent of total spending. The model predicts a hysteresis region, where the election results are not determined by campaign spending but by incumbency. Calibrating the model with historical data from US House elections between 1980 and 2020, we find the critical campaign spending to be ∼1.8 million USD. Above the threshold, the campaigns polarize society, while the election result remains largely unchanged. Campaigns exceeding critical expenditures increased in 2018 and 2020, suggesting a boost in political polarization. We also briefly investigate further issues, such as the time-dependence of the model parameters and comparison to the support vector machine model. Journal reference: Phys. Rev. Lett. 136, 127402 DOI: https://doi.org/10.1103/9gjj-1df6.

sciforum-181584: Generalized Permutation Entropy Measures on Graph Signals

Gordon Morison, Ryan Meeten

[1] School of Computing, Engineering and Physical Sciences
[2] University of the West of Scotland
[3] Paisley

Since its introduction, the Bandt-Pompe ordinal pattern method has been demonstrated to be a powerful tool for nonlinear data analysis. It has been utilised extensively to quantify disorder in a time series or by considering local ordering of values on regularly sampled data. Recently this concept has been extended to the analysis of graph signals, which expands the technique beyond that of time series or regular grid-based data to measure the complexity of signals defined over irregular graph structures by considering values on neighbouring nodes. These methods have predominately utilised the classic Shannon Entropy to quantify the complexity of the discrete permutation patterns on these graph signals. This work further extends the approach to include a wider range of non-extensive and fractional calculus-based entropy methods which are characterised by an entropic index q. Through computational experiments the complexity of different chaotic systems and real-world examples it is demonstrated that these generalised methods can provide better discrimination for appropriate ranges of values of the entropic index. These methods help to distinguish between chaotic and structured data across complex networks and highlight the potential of the proposed graph permutation entropies as powerful tools for complexity analysis. This provides a robust framework for developing further understanding of dynamical systems.

sciforum-166930: Homophily-Based Social Group Formation in a Spin Glass Self-Assembly Framework

Jan Korbel [1], Simon Lindner [1,2], Tuan Minh Pham [3], Rudolf Hanel [1,2], Stefan Thurner [1,2,4]

[1] Complexity Science Hub Vienna, Metternichgasse 8, 1030 Vienna, Austria
[2] Section for Science of Complex Systems, CeDAS, Medical University of Vienna, Spitalgasse 23, A-1090 Vienna, Austria
[3] Institute of Physics, University of Amsterdam, Amsterdam, Netherlands
[4] Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, United States of America

Similarity in attitudes, traits, and attributes strongly shapes how people connect, a phenomenon commonly referred to as homophily. This mechanism is widely believed to play a central role in the emergence of organized social structures, yet its ability to account for quantitative properties of social groups, such as their characteristic sizes, has not been sufficiently understood. In the presented work, we investigate how far homophilic interactions alone can drive the formation and scaling of social groups. To this end, we introduce a theoretical framework inspired by disordered spin systems, in which individuals are described by multidimensional opinion variables that evolve through mutual interactions. Groups emerge endogenously as a result of self-organization: agents within the same group tend to align their opinions, while agents belonging to different groups are driven toward dissimilarity, giving rise to a tension between intra-group cohesion and inter-group separation.

The model admits a rich collective behavior that can be captured through a self-consistency relation for an order parameter representing the aggregate alignment of opinions. Solving this relation reveals a nontrivial phase structure. At high levels of social noise, the system remains disordered, with opinions fluctuating independently and no persistent groups forming. Below a critical threshold, however, two locally stable regimes coexist: an ordered state characterized by nonzero global alignment and the emergence of large, coherent clusters, and a disordered state lacking both alignment and stable group structure. The transition between these regimes is discontinuous, indicating a first-order phase change.

Beyond the phase behavior, we analytically derive the distribution of group sizes generated by the model. Remarkably, the resulting distributions closely reproduce empirical patterns observed in online social communities, suggesting that homophily-driven self-assembly can provide a parsimonious explanation for the observed heterogeneity in group sizes.

Journal reference: Phys. Rev. Lett. 130, 057401

sciforum-175741: Network Generation by Vertex-based Wiring and Restricted Resources

Ioannis P Antoniadis

Aristotle University of Thessaloniki, School of Physics, Thessaloniki, Greece

We introduce a general class of algorithms for generating networks by adding links to a fixed number of vertices: the **Restricted Vertex-Based Wiring (RVBW) algorithms.** They are vertex-based because the addition of new links proceeds by selecting a starting and an ending vertex in two distinct, independent steps rather than assigning a link to two vertices in one step. They are "restricted" because link assignment is also subject to global and local restrictions based on prescribed available "resources." The restrictions are implemented by assigning fixed limits on the network's final size as well as on the degree of each vertex. We present two examples of RVBW algorithms, the **Random Linking (RL)** and **Preferential Linking (PL)** algorithms, and apply them to generate random networks with prescribed target degree configurations (which we call vertex "capacities"). In the RL algorithm, ending nodes are picked randomly with uniform probability, whereas in the PL algorithm they are picked with probability proportional to their capacities. We find that the resulting RL-generated networks are more assortative and have more triangles than the corresponding PL networks. Also, in the RL algorithm a larger proportion of vertices and edges are left unassigned for heavy-tailed (BA-based) target capacities; Apparently, prescribed degree limits may greatly affect generated network structure.

Following a mean-field approach under a Poisson-process continuous time approximation, we treat the problem analytically for a general capacity distribution $x_o(k)$, where k is the maximum allowed degree (capacity) and $x_o(k)$ is the fraction of vertices that can have up to k connections. We thus derive a set of ODEs that describe the temporal evolution of network generation. We also derive exact conditions on how a general $x_o(k)$ affects the "*inaccuracy*" of the algorithm, and the assortativity of the generated network. We compare theoretical results with Monte Carlo simulations.

sciforum-181053: Prejudice and Discrimination in a society of Neural Networks

João Henrique de Sant'Ana, Nestor Caticha

Institute of Physics, University of São Paulo

Opinion dynamics in agent based models frequently use agents with typically no internal structure. We however, consider agents that use an adaptive neural network to generate yes/no opinions about public issues. Agents exchange opinions and update a measure of distrust/trust towards other agents.

The neural networks (ideological sector) and the trust/distrust attribution (affinity sector) use algorithms obtained by a Maximum Entropy approximation to Bayesian learning, optimal in the limit of large dimensional issues and small societies.

Learning occurs primarily in the presence of dissonance, when the receiver agent disagrees and trusts the emitter, or reversely, agrees yet distrusts. This algorithm, despite being optimal in a small society leads, with high probability to a very polarized society: is not optimal for group adaptation. Polarization becomes infrequent when the receivers use the optimal algorithm but change pos-synaptic fields in order to be more `tolerant' towards the emitters.

Next we consider societies which can be separated into two classes of agents. An agent is said to be prejudiced if they extend different tolerance fields toward ingroup and outgroup agents.

The phase diagram in the space of tolerance/prejudice field d vs. fraction of prejudiced agents f_D, is constructed from three types of pair correlations combining opinions, distrust, and class, among the several phases, show the emergence of collective discrimination. Two types, ideological and affective, of triplet frustration, measure the balance of social relations, which depend, not surprisingly on f_D and d but significantly, on the size of the agenda. The diagram reveals a rich structure of distinct group formation regimes.

Optimal learning in small groups, but not simpler algorithms, yields undesirable collective behavior.

Our aim is to suggest the measurements by social scientists of quantities that can be inferred from the macroscopic properties of societies.

sciforum-171998: Quantifying complexity in synthetic earthquakes generated by the Olami–Feder–Christensen spring-block model

Luciano Telesca

Institute of Methodologies for Environmental Analysis, National Research Council, Tito, 85100, Italy

Earthquake sequences display complex patterns in space, time, and magnitude, which standard time-series techniques often fail to capture. This complexity has prompted the adoption of statistical approaches to reveal properties and relationships that would otherwise remain hidden.

Following the pioneering work of Bandt and Pompe, permutation entropy and statistical complexity have become fundamental tools for constructing the so-called complexity–entropy causality plane (CECP). Permutation entropy quantifies the level of intrinsic randomness in a dataset, while statistical complexity reflects the degree to which some ordinal patterns are preferred over others. By analyzing both measures together, one can simultaneously evaluate the randomness of a time series and the degree of structural ordering within its fluctuations.

Although widely used for continuous series, the CECP has rarely been applied to point processes like seismic events. Here, we extend it to the Olami-Feder-Christensen (OFC) model, a 2D system of blocks connected by springs and linked to a slowly moving plate, simulating interacting tectonic plates. Despite being introduced decades ago, the OFC model serves as a powerful framework, reproducing key aspects of real seismicity, like Gutenberg-Richter law, Omori law, etc.

In this study, the permutation entropy and statistical complexity analysis of OFC-generated magnitude series has revealed nontrivial patterns that depend on the model parameters. In particular, the elastic constant, which affects the magnitude of the generated synthetic earthquakes, strongly shapes the distribution of points in the CECP. These results underscore the sensitivity of the CECP to the internal dynamics of the OFC model and its capacity to capture emergent complexity arising from underlying physical parameters.

Although preliminary, these findings highlight the potential of CECP analysis in seismicity research, offering novel and multifaceted approaches to characterize, interpret, and investigate earthquake dynamics.

sciforum-194776: Statistical Mechanics of Random Graphs within the Fermionic Maximum-Entropy Framework

M. Angeles Serrano

University of Barcelona

Many natural and human-made systems are shaped by intricate relations among their elements, which give rise to complex processes organized as multiscale networks of interactions. Such networks can be represented as graphs, composed of nodes connected by links, and, regardless of their domain, they share a set of fundamental structural properties. The family of network models in hyperbolic space represents one of the most advanced frameworks for describing their observed connectivity. These networks are typically sparse, small-world, heterogeneous, highly clustered, and scale-invariant under network renormalization. These geometric models also show intriguing behaviour, such as an anomalous, temperature-dependent transition between a geometric and a non-geometric regime. In this talk, I will describe these models and explain how it can be derived within a statistical mechanics framework by maximizing entropy subject to constraints imposed by observations, with links effectively behaving as fermionic particles. Within this formulation, latent distances encode the attributes that drive connectivity and yield a distance-dependent connection probability that combines short- and long-range interactions in a single mechanism. The resulting maximum-entropy ensemble provides a minimally biased baseline for predicting network properties and a principled framework for analyzing network structure, offering new perspectives and analytical tools for both theoretical work and empirical studies.

sciforum-181585: Understanding extinction events in minimal nonlinear random models for population using the theory of statistical learning.

Johan L.A. Dubbeldam [1], Frederik Thomsen [2], Rudolf Hanel [3]

[1] DIAM, Delft University of Technology, Delft, Netherlands
[2] Delft Institute of Applied Mathematics, Delft University of Technology, Mekelweg 4, Delft 2628DC, Netherlands
[3] Section for the Science of Complex Systems, Center for Medical Data Science, Medical University of Vienna, Spitalgasse 23, A-1090 Vienna, Austria

There have been much research on (cascading) extinction events in ecosystems as well as in Gene Regulatory Networks (GRN) and chemical reaction networks. We present results on a piecewise linear model that arises in the context of autocatalytic systems, as occur in GRNs. This model is described by a system of ordinary differential equations with interactions modeled by a random matrix. The nonlinearity arises due to the nonnegativity constraint.

The populations can be mapped to an N-dimensional sphere on which the evolution of the population takes a specific form in terms of an equation known as Oja's equation in neural networks. We use the fact that the equilibrium state corresponds to the principal eigenvector to explore our population model.

We study this model for different correlations strengths between the matrix elements and demonstrate that, independent of the correlation strength, solutions of the system are confined to subsets of the phase space that can be cast as time-varying Gardner volumes.

These Gardner volumer play an essential role in the theory of learning in neural networks. Using the theory of Gardner and asuming replica symmetry allows us to calculate the high dimensional phase space volumes, that arise in the statistical theory of learning and to relate them to the diversity of the populations. More precisely, we show that the final diversity, that is the number of species that survive, after a cascade of extinction and revival events is equal to 0.5, which means that the total number of species that survive when starting from a random community of size N is N/2. Wecorroborate our analytical results by extensive numerical simulations.

Session 2. Information Theory, Data Science and Artificial Intelligence

sciforum-175354: 'I am not my language': human cognition, misattributed intelligence, and the extractive risk of large language models

Dana Polatin

School of Physical and Chemical Sciences, Queen Mary University of London, London, E1 4NS, United Kingdom

Drawing on Clark and Chalmers' (1998) extended mind thesis, this paper proposes that human-LLM interactions constitute a coupled cognitive system in which prompting functions as an epistemic action. Within this framework, the LLM operates as a passive external feature — a crystallised linguistic artifact trained on historical data, analogous to Putnam (1975) and Burge's (1979) passive externalism — while the active intelligence driving the exchange remains the human's. Crucially, however, the fluency and responsiveness of LLM outputs creates the conditions for misattribution: the interaction qualifies as active externalism in Clark and Chalmers' sense, causing users to animate the system as a cognitive agent rather than a sophisticated retrieval mechanism.

This misattribution carries measurable risks. Drawing on Loock's (2025) extracted cognition hypothesis, as well as the work of Shannon (1948) and Friston (2010), we argue that repeated human-LLM interaction may systematically reduce the entropy of human thought — narrowing the possibility space of ideas users generate independently — rather than expanding it as genuine cognitive extension would. This reframes LLMs not as minds, but as entropy-modifying feedback channels whose effects on human cognition remain largely unstudied.

We apply this reframing to AI alignment. Rather than orienting alignment research around the speculative threat of autonomous machine intelligence, we propose that the more immediate concern is the measurable restructuring of human cognition by systems that, as Crawford (2021) documents, encode and obscure the ideological commitments of their architects. AI systems are not becoming aligned or misaligned with human interests in the abstract — they are actively reshaping what those interests are. Alignment research should therefore prioritise empirical study of cognitive effects over anticipatory governance of machine sentience.

sciforum-189682: The Statistical Mechanics of Motion

Kevin H Knuth

University at Albany (SUNY)

Given the prominence of the concept of motion, it is surprising that in the last two thousand years the concept of motion keeps changing. Physics, had seemingly escaped from the doctrine of Parmenides, which held that motion was an illusion, and the paradoxes of Zeno, through the quantification of motion by Galileo and the connection of motion to forces by Newton. Motion was seemingly straightforward until Einstein clarified the relationship between space and time, which, again, made motion mysterious by identifying the speed of light as the maximum speed, and that it is impossible for massive particles to attain it. Around 1930, Gregory Breit and Erwin Schrödinger showed that the eigenvalues of the velocity of a particle described by wavepacket solutions to the Dirac equation are the speed of light, c. This led Schrödinger to coin the term Zitterbewegung (German for ”trembling motion”), where all particles of matter (fermions) zig-zag back-and-forth at the speed of light. The result is that any finite speed less than c, including rest, only makes sense as a long-term average velocity. There appears to be a difficulty. Relativity suggests that massive particles cannot move at the speed of light, and relativistic quantum mechanics suggests that massive particles can only move at the speed of light. We consider the problem of Zitterbewegung for a particle and two observers, and show that while every instantaneous velocity is the speed of light, the speeds that the observers measure are consistent with the relativistic velocity addition rule, such that massive particles cannot be observed to go the speed of light. The result is a statistical mechanics of motion, in which the maximum entropy state is the state of rest, and the act of adding energy to the particle results in a decrease of entropy that is accompanied by motion.

sciforum-162241: 70 years of bandwagon: Shannon's viewpoint revisited

Martin Schlather

Institute of Mathematics, University of Mannheim

Claude Shannon warned repeatedly and vehemently about an ill-founded use of the information theory outside communication theory, where the Shannon entropy had been developed. In his famous work on “A Mathematical Theory of Communication”, Claude Shannon gave a guideline, how to choose an entropy adequately. Still seventy years after Claude Shannon’s scathing letter, a lot of publications refer to Shannon’s entropy, but only a few to Shannon’s idea of entropy. Resuming Shannon’s original approach, Schlather (2025) suggests an abstract, mathematical definition of an entropy by means of the properties it should have from a physical, information theoretical or statistical point of view. This novel approach has already lead to a first general characterization of an area outside telecommunication, where the Shannon entropy should be applied (Schlather and Ditscheid, 2024), and to the extract of a best theoretically founded approach among several approaches in target tracking (Schlather et al., 2025). It has further entailed a first well-founded approach to principle component analysis for extreme values (Reinbott and Janßen, 2026; Schlather and Reinbott, 2021), and even a revision of fundamental algebraic laws (Schlather and Schlather, 2025). In this presentation, I will support my point of view by examples from natural sciences and daily (scientific) life. The examples show, that closely related problems can result in rather different approaches for the choice of the entropy. Moreover, these entropies can be far beyond common generalizations of the Shannon entropy, like the R´enyi entropy or the Tsallis entropy. Further, I will highlight some of the consequences of my approach. For instance, the use of the Pearson correlation coefficient is justified only in situations where random variables are added. Questioning fundamental concepts also in statistics, the bandwagon problem might be considered as more serious than expected from a purely information theoretical point of view.

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sciforum-181236: A Fund Rating Approach Based on the Expected Utility-Entropy-Variance Model and Its Application

Jiping Yang [1], Jinna Zhao [1,2]

[1] School of Economics and Management, Beihang University, Beijing, China
[2] China Post Securities, Beijing, China

Fund ratings, as a measure of fund performance, play an increasingly important role in helping investors and financial institutions make capital allocation decisions. It is therefore crucial to develop a reliable fund ranking approach. Yang and Qiu previously proposed the expected utility-entropy (EU-E) decision model, which integrates expected utility and entropy to effectively capture both decision-makers' subjective preferences and objective uncertainty across different states of nature. This risk measure for risky actions was further axiomatized by Luce et al.

In this paper, we extend the EU-E model to a normalized expected utility-entropy-variance (EU-EV) decision model by incorporating normalized variance as an additional measure of uncertainty. We establish an alternative fund rating approach based on the EU-EV model accordingly. Furthermore, we compare the prediction ability of performance of the EU-EV model-based fund rating with that of the Lipper rating method. Using panel data regression, we employ the Sharpe ratio, Jensen's alpha, Treynor ratio, and information ratio as performance metrics. The sample consists of 360 funds over the period from January 2010 to December 2019.

The results show that the EU-EV model-based fund rating approach performs better in predicting high-star funds and is significantly superior to Lipper fund ratings in this respect. It also demonstrates stronger predictive ability for short-term and medium-term fund performance than for long-term performance.

sciforum-183289: A study of the use of decoding based methods for estimating mutual information in biomolecular systems

Giorgos Minas [1], Chao Gao [1], Meritxell Sáez Cornellana [2], Elena Camacho-Aguilar [3], David A. Rand [4]

[1] School of Mathematics and Statistics, University of St Andrews
[2] Department of Mathematics and Data Analytics, IQS, University Ramon Llull, Barcelona
[3] Department of Gene Regulation and Morphogenesis, Centro Andaluz de Biología del Desarrollo (CSIC-UPO-JA), 41013 Seville, Spain
[4] Mathematics Institute & Zeeman Institute for Systems Biology and Infectious Epidemiology Research, University of Warwick

The processing of information is a central concept in biology, particularly in cell biology. From DNA to proteins and cellular function, from environmental stresses to cell survival processes, and from signalling agents to embryonic development, biological mechanisms operate by transferring information between components of an organism. Despite this, our understanding of information flow—and, in particular, our ability to quantify it—remains very limited.

Mutual information and channel capacity play a prominent role in addressing this challenge. However, the high dimensionality of these systems makes the computation of information-theoretic quantities difficult. Recently, decoding-based methods—closely related to supervised learning approaches, primarily classification—have been proposed as practical and flexible tools for estimating mutual information from complex, high-dimensional data. The wide range of available supervised learning methods makes these approaches especially promising, but also highlights the need for a careful study of their properties and limitations.

In this presentation, I will outline the use of decoding-based methods in biological signalling systems, illustrating their application through two examples. The first examines information flow between the cytokine TNFα and the transcription factor NF-κB, which regulates thousands of target genes. The second presents recent results where we used decoding-based methods to quantify information flow in stem-cell development and specialisation using a dynamical landscape model which, unlike previous approaches, allows us to quantify information flow at the level of cell fate allocation over the whole embryo. Finally, I will present results from an analysis and a simulation-based study that characterises the limitations of decoding-based methods. This includes a novel breakdown of the information loss incurred by these methods, which is quantified and enables strategies for loss elimination.

sciforum-188370: Benchmarking the kth-Nearest Neighbur Method for Classification

Federico Vello, Sara Fortuna, Federico Fogolari

DMIF - University of Udine, Udine, Italy

kNN-based approaches to entropy estimation are useful for systems with many mutually correlated variables and are often combined with strategies such as the Maximum Information Spanning Tree (MIST) algorithm to account for pairwise mutual information.

Here, we explore extending these entropy-based methods to classification problems involving highly correlated multivariable spaces. The classification criterion is based on Kullback–Leibler divergence computed after assigning test samples to the reference class distributions, introducing a log(1/n) correction prior term for class imbalance. A median entropy value over five k values was used to reduce sensitivity to the specific choice of k. In particular, a kNN-based classification protocol is applied, both with and without MIST implementation, to suitable cancer gene expression datasets from the CuMiDa collection. Three representative subsets were reported, chosen to show different classification regimes: data sets with many samples and two classes, many samples and multiple classes, and data sets characterized by a low number of samples.

Different gene reduction methods were tested, but we opted for a simple filter–embedded approach, combining multiclass ANOVA pre-filtering with a ranking via Logistic Regression. The low complexity of this passage helps to ensure that the observed performance can be attributed mainly to the proposed classifier.

The results, compared with the benchmark accuracies reported for the CuMiDa datasets, show that the proposed entropy-based model is generally competitive with established classification approaches. The performance appears particularly promising in low-sample regimes, where the method can reach comparable or improved accuracy. Interestingly, the use of the MIST algorithm improves classification in some cases, whereas in others the sum of marginal entropies gives better results. This behavior is currently under investigation, but the overall results support the validity of kNN entropy estimation as a classification tool, especially in contexts where interpretability and analysis of variable correlations are relevant aspects.

sciforum-181574: Dual representations of classical and quantum entropies: Theory and Perspectives

Olivier Rioul

Telecom Paris, Institut Polytechnique de Paris

The MAXENT (maximum entropy) principle gives a natural correspondance between (classical and quantum) statistical mechanics and information theory. Its general formulation leverages on log-concavity (or Klein's inequality) and the celebrated information inequality, which is equivalent to Gibbs' inequality. The resulting convex optimization allows one to relate entropy to the log-canonical partition function by Legendre-Fenchel duality. This can be further generalized to dual variational characterization of relative entropy or Kullback-Leibler divergence, relating Gibbs variationnal principle to Donsker-Vardhan variational representations.

From an information theoretical point of view, the Gibbs principle and its associated evidence lower bound serves as the basis of modern machine learning algorithms, such as the expectation-maximization (EM) algorithm and its restriction to parameters output by a neural network. Interestingly, a large class of alternating optimization algorithms including EM and Blahut-Arimoto for computing channel capacity and source rate-distortion functions can be cast in a generic information geometric alternating projections on convex sets of measures. On the other hand, Donsker-Vardhan representations, when restricted to the output of a neural network, allows one to efficiently estimate information measures, and when applied to parametric estimators with quadratic risk, provide HCR-like and CRB-like statistical lower bounds. An alternative derivation on such lower bounds in the Bayesian setting makes use of the Weyl-Heisenberg uncertainty principle, which opens up new perspectives.

In this keynote, I will select and review several of the aforementioned topics, and discuss the interactions between classical and quantum interpretations.

sciforum-181622: EID — Exponential Informational Decay: A Dynamic Model for Measuring Information Preservation in Multi-Agent Systems Based on LLMs

Thiago Nobre Mascarenhas

Sistemas Complexos, EACH - USP, EACH-USP (Escola de Artes, Ciências e Humanidades) Rua Arlindo Béttio, nº 1000, Ermelino Matarazzo, São Paulo - SP, Brasil, CEP: 03828-000

Communication among autonomous agents based on Large Language Models (LLMs) constitutes a complex system that revives the classical challenge of information preservation in distributed AI (Bond & Gasser, 1988): information is transmitted, reformulated, and synthesized across processing chains — and inevitably degraded at each hop. Traditional NLP metrics (BLEU, ROUGE, BERTScore) evaluate text-pair similarity in a static, unidimensional fashion, failing to capture propagation dynamics or the multifaceted nature of information.

This work proposes EID (Exponential Informational Decay), an information preservation metric derived from a differential equation — dP/dt = V(1−P) − (1−S)(1−K)·P — coupling three complementary dimensions: vectorial semantic similarity (V, via Sentence-BERT), Shannon structural preservation (S), and Kolmogorov algorithmic similarity (K, via NCD). The equilibrium solution, EID = V × exp[−(1−S)(1−K)], is parameter-free, grounded in Parker and Walker's (2010) dynamic information-entropy field model, and establishes direct correspondence with physical dissipation phenomena (radioactive decay, fiber-optic attenuation), including a computable informational half-life.

EID was validated across 7,010 records, eight LLM models, and four communication topologies: direct, 5-hop linear chain, recursive with feedback, and DAG with fusion. Results demonstrate that: (1) the EID formula achieves perfect correlation (r = 1.000) across all experiments, with 44–77% greater sensitivity than linear combination; (2) purely semantic metrics overestimate preservation by up to 40 percentage points, masking real degradation; (3) information decays exponentially between agents ($\bar{\alpha} \approx 0.42$), consistent with Shannon's Data Processing Inequality; (4) three distinct propagation regimes emerge — monotonic dissipation, entropic compensation through feedback (+1.8 pp, p 10^{-6}), and recovery through redundant-path fusion (+156%); and (5) preservation capacity is an intrinsic model property, introducing "informational impedance" as a network design variable.

This work contributes the first dynamical-system-grounded metric for agentic communication, an empirical mapping of informational propagation dynamics, and a proof of concept for EID as a real-time control variable in agent communication protocols.

sciforum-175729: Entropy Dynamics as a Diagnostic of Information Accumulation in Graph Neural Networks

Shanzi Bao, Mar Gonzàlez I Català, Pietro Liò

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

Message-passing graph neural networks (GNNs) learn node representations through iterative aggregation, but their performance is highly sensitive to both architectural depth and graph structure. Two common failure modes are depth-induced oversmoothing, where repeated aggregation erodes class-discriminative information, and heterophily-induced structural mismatch, where graph topology conflicts with the model's inductive bias. Although both can reduce final-layer accuracy, standard evaluation metrics often fail to distinguish between them.

We study these failure modes through predictive entropy measured by layer-wise linear probes. After training a GNN, we freeze the encoder and fit an independent classifier on each layer to obtain entropy trajectories across depth. We also introduce two node-level diagnostics: entropy separability AUC and the Spearman correlation between predictive entropy and true-class confidence.

Experiments on GCN and GAT across citation networks (Cora, CiteSeer, and PubMed) and synthetic graphs with controlled homophily reveal distinct entropy signatures. On homophilic graphs, entropy typically decreases in early layers and rises again in deeper layers, consistent with oversmoothing. Under low homophily, entropy remains high even in shallow layers, indicating structural mismatch. At the node level, entropy separability and entropy–confidence alignment remain strong under depth-induced degradation but deteriorate markedly under heterophily, suggesting a practical way to decide whether performance loss is better addressed by adjusting depth or by changing the model's inductive bias. Compared with structural or spectral diagnostics such as Dirichlet energy or homophily ratio, entropy trajectories provide a prediction-level view that remains informative across both regimes.

sciforum-166132: Entropy, Annealing, and the Continuity of Agency in Human–AI Systems

Pieter van Rooyen

Department of Electrical and Electronic Engineering, University of Stellenbosch, Stellenbosch, 7600, South Africa

Rapid advances in artificial intelligence are steepening informational, economic, and cognitive gradients across society, forcing individuals and institutions to adapt under conditions of accelerating change. Classical models of adaptation—grounded in static optimization, stable identities, and long-term professional blueprints—are increasingly fragile in this regime. This work presents a unified theoretical framework connecting thermodynamic entropy, information-theoretic entropy, and a formally defined entropy of the self through a shared stochastic gradient-flow model.

Drawing on non-equilibrium statistical physics, simulated annealing, and Langevin dynamics, we show that complex systems without foresight—ranging from physical matter to learning agents and human identities—do not adapt by executing predefined plans, but through regulated exploration followed by gradual stabilization. Within this framework, adaptive viability is governed not only by the steepness of external gradients but by a finite, rate-limited integration capacity. We formalize agency as a capacity-constrained process and demonstrate that when the externally imposed rate of change exceeds this capacity, agency collapses as a structural consequence, independent of motivation or intent.

Artificial intelligence acts as a gradient multiplier by accelerating option generation, feedback loops, and required model updates. While this increases apparent choice, it also raises the effective information rate, pushing human–AI systems toward overload. We reinterpret ambition as temperature control—the capacity to sustain stochastic exploration in the absence of immediate pressure—and show how environments of safety and abundance can induce premature cooling, yielding locally stable but globally brittle configurations.

Using phase-portrait analysis and worked examples, we derive an annealing-based decision protocol emphasizing controlled reheating, reversibility, and rate regulation. We further argue that emotions function as phenomenological signals of gradient–capacity mismatch rather than as optimization targets. The central implication is that adaptive human–AI systems should optimize for continuity of agency by training exploratory capacity early and explicitly managing rates of change, rather than maximizing efficiency, certainty, or short-term satisfaction.

sciforum-175440: Euclidean Geometry in Influence Network of Events: An Observer-Based Geometry

Newshaw Bahreyni [1], Carlo Cafaro [2], Leonardo Rossetti [3]

[1] Physics and Astronomy Department, Pomona College, Claremont, CA 91711, USA
[2] Department of Nanoscale Science and Engineering, University at Albany-SUNY, Albany, NY 12222, USA
[3] School of Science and Technology, Physics Division, University of Camerino, I-62032 Camerino, Italy

In this research the universe is viewed as a set of partially-ordered set (poset) of events where causal relationships among events, called event influence, are used to order the poset. The poset of events is then quantified consistently using a subset of events that are totally ordered, called chain or observer chain. In previous work it has been shown how consistent quantification of the poset of events gives rise to the emergence of Minkowski metric as well as all aspects of Special Relativity including the Lorentz transformation in this picture. Some fundamental geometrical properties such as distances, directionality and dimensions were also revisited, and it was shown how they emerge in this influence network of events. The current work explores geometrical aspects further and reexamines some fundamental Euclidean concepts. It is demonstrated how a discrete version of geometric properties such as geometric shapes, the dot and the cross product emerge as a result of consistent quantification of the poset of events. Furthermore, it is shown how a discrete version of the parallel postulate is derived in this picture. Thus, fundamental concepts in Euclidean geometry are not treated to be purely independent, rather they are expressed as a consequence of observer-based consistent quantification of events.

sciforum-181449: Information-Theoretic Analysis of the ENSO–Precipitation Relationship in Buenos Aires

SERGIO ALEJANDRO JALFIN

Facultad de Tecnología Informática (Faculty of Information Technology), Universidad Abierta Interamericana (UAI), Buenos Aires, C1147AAU, Argentina

This work presents an information-theoretic analysis of the relationship between the phases of the El Niño–Southern Oscillation (ENSO) and precipitation in the city of Buenos Aires during the period 1961–2022. Unlike traditional approaches based solely on linear correlations, the Shannon information theory framework is applied to quantify statistical dependence without assuming a specific functional relationship between the variables.

ENSO phases (El Niño, Neutral, and La Niña) and annual precipitation classified into terciles (dry, normal, and wet) are modeled as discrete random variables. From the ENSO–precipitation contingency table, joint and conditional distributions are estimated, allowing the computation of entropy, conditional entropy, mutual information, and normalized informational coefficients. The information-theoretic approach is compared with the classical statistical model using Pearson's correlation coefficient and a correlation coefficient derived from mutual information.

The results show that, at the annual scale, the mutual information between ENSO and precipitation is low, indicating weak and predominantly nonlinear dependence. However, when the temporal scale is reduced to the October–November–December season, mutual information increases significantly, revealing a more defined seasonal signal. In particular, the La Niña phase exhibits a higher probability of dry conditions, whereas Neutral and El Niño phases are more frequently associated with normal or wet precipitation.

These findings indicate that the ENSO–precipitation teleconnection in Buenos Aires is weak at the annual scale but significant and seasonally dependent. The information-theoretic framework allows the detection of nonlinear dependencies that are not captured by classical correlation, providing a robust tool for the analysis of complex climate relationships.

sciforum-180254: Information-Theoretic Limits for a Single-Layer Additive Cipher with Linear-Code Plaintext Source

Yuri L. Borissov, Miroslav Markov

Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria

We study a one-layer additive cipher C = X ⊕ K over F2m , where X is uniformly drawn from a fixed linear [n, k] code L ⊆ Fn 2m and the same key K ∈ Fn 2m is reused across all blocks. In the classical model, key reuse combined with source redundancy is often discussed through the Shannon theory of secrecy systems and the unicity-distance heuristic due to Shannon and Hellman [1,2]. For a linear source with per-block redundancy Dblock = m(n − k) bits and a uniform key of entropy H(K) = nm bits, the heuristic predicts U ≈ H(K)/Dblock = n/(n − k), provided that successive observations impose independent constraints on the key. In our ciphertext-only setting this independence fails. Let H be a parity-check matrix of L [3]. Since C ⊕ K ∈ L, each ciphertext satisfies H(C ⊕ K)T = 0 and reveals the same key syndrome s = HKT. Hence multiple blocks do not accumulate new linear information about K; the mutual information I((C(1), . . . , C(t)); K) saturates after the first block. The key remains undetermined within its coset K ⊕ L, containing (2m)k candidates. Thus, the Shannon–Hellman unicity-distance picture is not attained within this single fixed linear layer. To recover information accumulation one needs additional structure beyond the fixed L layer—e.g., block-varying linear transforms whose combined rank grows with t, or a nonlinear layer—so that distinct observations impose independent constraints on K.

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sciforum-175802: Invariant and Dually Flat Structures in Information Geometry for Deformed Exponential Families

Hiroshi Matsuzoe

Nagoya Institute of Technology

Information geometry views the space of probability measures or statistical models as a differentiable manifold, studies the geometric structures defined on this manifold, and applies these structures to areas such as statistics, information theory, and machine learning. Typical geometric objects investigated in this framework include Riemannian metrics, affine connections, and divergence functions, which provide geometric interpretations of statistical concepts such as estimation, hypothesis testing, and learning.

These geometric structures are primarily constructed based on two fundamental criteria: invariance under transformations of the sample space and dual flatness of a pair of affine connections on the manifold. Invariance ensures that the geometric description does not depend on arbitrary choices of coordinates or representations of the sample space, and is therefore essential for a consistent theoretical foundation. Dual flatness, characterized by the existence of mutually dual affine connections, plays a crucial role in simplifying computations and enables the development of efficient inference and optimization algorithms.

For exponential families, these two desirable properties, namely, invariance and dual flatness, are simultaneously satisfied, which explains their central role in classical information geometry. In contrast, for non-exponential families, these criteria generally do not hold at the same time, making the construction of a satisfactory geometric framework more challenging.

In this talk, we address this issue by constructing invariant and dually flat geometric structures for certain non-exponential families, including the q-Gaussian distributions arising from the maximization of the Tsallis entropy. This approach extends the scope of information geometry beyond the classical exponential-family framework and provides new insights into generalized statistical models.

sciforum-175745: k-th nearest neighbour entropy for classification

Federico Vello, Sara Fortuna, Federico Fogolari

Department of Mathematics, Computer Science and Physics, University of Udine, Udine, Italy

The k-th nearest neighbor (knn) method proposed by Demchuk and coworkers [1] hasbeen recently reviewed and successfuly applied to entropy estimation of complexmolecular systems [2]. The method provides an unbiased, consistent, adaptive estimator of entropy.

knn methods developed to address biomolecular systems characterised by a large number of multicorrelated variables (torsion angles) typically include ways to account for mutual information, such as the use of Maximum Information Spanning Tree (MIST) or Mutual information Expansion (MIE).

Machine learning classification is largely based on minimization of the cross-entropy between test samples and the training set, or variants thereof.

With the goal of implementing a general classification method, we here propose that the same methods developed for biomolecular simulations could be generalised and applied to highly correlated multivariable spaces.We explore the usage of knn entropy estimation for classification and present preliminary results by testing the method on diverse feature datasets, like handwritten digits MNIST dataset and different cancer gene expression sets from CuMiDa dataset.

The results show that there are advantages in using knn entropy estimation to classify samples, in particular when the number of samples is small, compared to well-established methods like multi-layer perceptrons and support vector machines. In other cases the performance is anyway similar to that reported for the latter methods.While the reuse of entropy calculation methods for classification is not inherently novel, the protocol has advantage in all those cases with moderate number of samples and/or where explanation, rather than computing time is an issue.

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sciforum-175515: Mutual Information based on Kolmogorov Complexity for randomness evaluation

Valeria Rossi [1,2], Cesare Gerolimetto Fabrello [2], Massimo Caccia [1,2]

[1] Department of Science and High Technology, University of Insubria, Como, I-22100, Italy
[2] Random Power s.r.l., Milan, I-20129, Italy

The main goal of this investigation is the assessment of unpredictability, a feature of randomness, through a measurement of the mutual information between two sequences of supposed-to-be random bits. This quantity can be defined both in terms of the Shannon entropy on the underlying random variables or of the Kolmogorov information on the whole strings. The latter is famously uncomputable, but can be estimated from the compressibility of the sequence. Considering the Lempel-Ziv algorithm, such property can by evaluated through the Lempel-Ziv Complexity, obtained by dividing the number of new words found in the sequence by $N/\log_2 N$, the expected count for a string of N random bits. Although valid asymptotically, this normalization is known to be troublesome for finite strings due to its slow convergence.

Considering two sequences A and B, the Kolmogorov complexity mutual information is evaluated as the relative reduction in the count of new words found in B knowing those of A, thus avoiding normalization issues. This quantity and the Shannon entropy mutual information are evaluated on the sequences generated by a reference Silicon based Quantum Random Number Generator. The sensitivity of this approach is tested by introducing deliberate correlations at different frequencies in the bit-stream and evaluating the output values of the two indicators. For each source, 10^3 sequences of 10^6 bits are considered across 20 files, for a total of $2\text{x}10^{10}$ bits. The distribution of the Lempel-Ziv word count is then tested against Gaussianity via chi-square tests on histograms; the resulting p-values are compared with the expected uniform distribution.

It is found that the two mutual information are positively correlated across sources, however the one based on the Lempel-Ziv counter shows an increased sensibility to temporal correlations in the bitstream, opening up the possibility to build a model independent unpredictability test possibly complementing Maurer's test.

sciforum-175513: On Information Transmission in Multilabel Classifications Tasks

Claudia Montero-Ramírez [1], Carmen Peláez-Moreno [1], Francisco J Valverde-Albacete [2]

[1] Signal Theory and Communications Department, University Carlos III of Madrid, 28911 Madrid, Spain
[2] Department of Signal Theory and Communications, Telematic Systems and Computation, Universidad Rey Juan Carlos, 28942 Fuenlabrada, Madrid, Spain

Multilabel Classification (MLC) datasets have already been studied from the point of view of the information they carry, both from the point of view of how much information (quantitative, Information-theory measured), and also what type of information (qualitative, Lattice-Theory represented) is carried ([1] and references therein). In this paper we go on to describe how this information is transmitted in the MLC pipeline and how it is assessed at the endpoint, using the Classification as Information Transmission scheme.

To assess quantitative information transmission we use information-theoretical channel multivariate entropy channels, which graphically plot a ternary balance equation between transmitted mutual information, non-transmitted remanent information, and non-realised possible information in the multivariate dataset to be labelled [2].

To assess qualitative transmitted information quality we use lattice theory, in particular Formal Concept Analysis for the labelling data considered as a formal context. The comparison of source dataset and transmitted dataset lattices allows us to explore a number of post-hoc issues in a more structured way than confusion lattices including hierarchical nature of confusions, well and badly transmitted individual labels, converved labelsets, etc. We further describe how this gives rise to a notion of task-related qualitative information degradation and discuss how to measure its transmission too.

This suggest that quantitative---Information-theory based---, and qualitative---Lattice Theory-based---techniques may both contribute to understanding and improving solutions to the MLC task, and provides an experimental stepping-stone onto a more complete theory of how information is encoded in Machine Learning tasks.

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sciforum-175542: Shifting the Foundations of Information Theory: From Numerical Optimization to Ordering Axioms

Raphaël Trésor [1], Thijs van de Laar [2], Bert de Vries [1]

Department of Electrical Engineering, Eindhoven University of Technology, 5612 AE, Eindhoven, The Netherlands

This paper proposes a fundamental shift in the conceptual foundations of Information Theory by reframing inference not as the minimization of a numerical functional, but as a logical consequence of ordering theory. While traditional approaches to inference—such as the Maximum Entropy Principle—rely on specific functional forms like the Kullback-Leibler (KL) divergence, we demonstrate that these forms are not arbitrary choices but the unique mathematical representations of a small set of natural, logical requirements for processing information.

We introduce a unified axiomatic framework that derives classical divergence families—including Csiszár-Morimoto f-divergences, Rényi α-divergences, and the KL divergence—from primitive preference relation axioms over the probability measures. A significant contribution of this work is bridging the gap between finite discrete spaces and general measurable spaces. By employing a rigorous "Ordering Closure" construction, we ensure that the logical ranking remains consistent across all levels of discretization, solving technical inconsistencies that have historically limited axiomatic treatments in continuous spaces.

Our representation theorems prove that any rational inference procedure satisfying these axioms must coincide with the minimization of a classical divergence. Furthermore, we show that within this framework, f-divergence minimization is uniquely consistent with Bayesian conditioning. By mirroring the transition in probability theory from Kolmogorov's axioms to Cox's Theorem, this work provides a complete, logic-based foundation for information-theoretic inference, showing that the fundamental performance quantities of the field arise uniquely from the structural requirements of coherent multiscale information processing.

sciforum-175566: Stochastic resetting with limited information

Veronica Sanz-Arqué [1,2], Francisco J. Cao-García [2,3]

[1] Department of Statistics and Operational Research, Faculty of Mathematics, University Complutense of Madrid, Madrid, 28040, Spain
[2] Department of Structure of Matter, Thermal Physics, and Electronics, Faculty of Physics, University Complutense of Madrid, Madrid, 28040, Spain
[3] IMDEA Nanoscience Institute, Madrid, 28049, Spain

Stochastic resetting refers to the random reinitialization of the position of a random movement, and to the overall resulting cinematics. The typical case is a Brownian motion that is reinitialized to the starting position at Poisonnally distributed time intervals. Several variations such as partial resetting and random amplitude resetting have been studied. However, generally these studies assume that the position is precisely known.

Here, we address the case where position precision is finite, and therefore the position information is limited. We choose for our computations a discrete realization, i.e., a jump process over a lattice with a Poisonian stochastic resetting. But where the position information for resetting is only known at a coarse-grained level. The problem is addressed from a probability density and an agent-based perspective. The latter allows us to study the sequences of resetting actions and its correlations.

We have found the different scaling of several characteristic magnitudes with the spatial position precision. These magnitudes include the gathered information, the entropy reduction by information, the entropy change at resetting, the entropy of the sequence of resetting actions, and the conditional probabilities between resetting actions, all of them as a function of the resetting rate to jump rate ratio.

These results provide a relevant insight for real world applications of stochastic resetting, where the position precision is finite.

sciforum-172847: Temperature-Driven Escape Explains Critical Learning Rates in Adaptive Optimization

Xin-Ya Zhang, Chao Tang

Center for Interdisciplinary Studies and Department of Physics, Westlake University, Hangzhou, 310030, China

The learning rate is a central control parameter in neural network training, even for adaptive optimizers such as Adam, which reduce sensitivity to gradient magnitude differences across parameters. It can either trap models in sharp basins or guide convergence toward flatter regions, yet its selection has largely remained empirical. Here, we introduce a temperature-driven escape framework that provides a heuristic statistical-physics view of second-moment-based learning-rate dynamics. By decomposing Adam's second-moment-normalized mini-batch updates into deterministic drift and stochastic fluctuations, we define an effective temperature T_eff induced by mini-batch noise and apply Kramers' escape theory to derive a closed-form expression for the critical learning rate α_c. This critical value theoretically delineates the boundary between entrapment in sharp minima and successful escape toward flatter, more generalizable regions of the loss landscape. Experiments on vision tasks (MNIST, CIFAR-10 with MLP, CNN, ResNet) and language tasks (SST-2 with BERT, GPT-2, TinyLlama) show that the theoretically predicted α_c achieves better generalization, whereas far deviations from this critical value lead to degraded performance. Beyond initialization, re-estimating α_c also serves as a qualitative diagnostic tool for probing the nature of minima reached by well-trained models, providing insight into whether a given solution resides in a sharp or flat basin. Our results elevate the learning rate from an empirical hyperparameter to a theoretically principled quantity, providing both a predictive rule for initialization and a new perspective on optimizer dynamics that bridges statistical physics and deep learning practice.

sciforum-175107: The linguistic organization of complex systems

Andres Aragoneses [1], Antonio J. Pons [2]

[1] Physics Department, Whitman College, Walla Walla, WA, 99362, USA
[2] Department of Physics, Polytechnic University of Catalonia, Terrassa, Barcelona, 08222, Spain

In this work we interpret physical dynamical systems as language generators and analyse their behaviour using quantitative tools of linguistics. We show that language structure is not exclusive to living systems but could be viewed as a generic property of the time traces recorded from dynamical processes. We introduce a minimal mathematical framework that transforms continuous time traces into evolving sequences of symbols, thereby converting measured dynamics into messages. The construction is controlled by a single resolution parameter, δ, and admits multiple symbolic encodings, each producing a distinct "pseudo-language" associated with the same underlying system. Within this framework, dynamical systems acquire vocabularies and statistical structure that can be quantitatively characterized using the laws of linguistics, including classical scaling relations. We illustrate the generality of the approach by applying it to systems of different complexity and nature: (i) the logistic map as a paradigmatic discrete chaotic system; (ii) a diode laser subject to external optical feedback from two mirrors as an experimental nonlinear physical system; and, for comparison, (iii) the text of Don Quijote de la Mancha by Miguel de Cervantes as a reference example of human language. Despite their very different origins, all three can be analysed within the same symbolic and statistical framework. Crucially, the resolution parameter δ determines the symbolic granularity and enables the identification of characteristic dynamical scales and temporal correlations embedded in the signal. By establishing a direct mapping between physical dynamics and linguistic organization, our approach provides a unified methodology to interpret complex systems as information-generating processes across physical, biological, and technological domains.

Session 3. Quantum Information and Quantum Computing

sciforum-185560: First-Passage and Hitting Times in Monitored Quantum Systems on NISQ Platforms

Eli Barkai

Department of Physics, Bar Ilan University, Israel

We introduce a time-energy uncertainty relation within the context of monitored quantum dynamics [1] . Previous studies have established that the mean recurrence time, which represents the time taken to return to the initial state, is quantized as an integer multiple of the sampling time, displaying point-wise discontinuous transitions at resonances. Our findings demonstrate that the natural utilization of the restart mechanism in laboratory experiments [2], driven by finite data collection time spans, leads to a broadening effect on the transitions of the mean recurrence time. Our proposed uncertainty relation captures the underlying essence of these phenomena, by connecting the broadening of the mean hitting time near resonances, to the intrinsic energies of the quantum system and to the fluctuations of recurrence time. Our uncertainty relation has also been validated through remote experiments conducted on an International Business Machines Corporation (IBM) quantum computer. We then discuss fractional quantization of the recurrence time for interacting spin systems using sub-space measurements [3].

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sciforum-175444: A Study of Fluctuation Growths of Observables in Open Quantum Systems

Newshaw Bahreyni [1], Paul M Alsing [2], Carlo Cafaro [2], Walid Redjem [2], Christian Corda [3,4]

[1] Physics and Astronomy Department, Pomona College, Claremont, CA 91711, USA
[2] Department of Nanoscale Science and Engineering, University at Albany-SUNY, Albany, NY 12222, USA
[3] SUNY Polytechnic Institute, Utica, NY 13502, USA
[4] Department of Physics and Electronics, Christ University, Bengaluru, 560029, Karnataka, India

Understanding the dynamics of fluctuations (standard deviations) in quantum observables is central to characterizing nonequilibrium behavior and precision limits in quantum systems. In previous work upper limits for fluctuations in a closed system in which the quantum system is isolated were studied. The result demonstrated that the rate of fluctuation growth for an observable in a closed quantum system is upper bounded by the fluctuation of its corresponding velocity-like observable. Furthermore, the bound indicated a tradeoff between the time derivatives of the mean and the standard deviation. In this work open systems in which the quantum system can interact with its environment are considered and rigorous upper bounds on the rate at which the fluctuations of observables can grow in open quantum systems are studied. To find the bounds for fluctuations in open quantum systems the results found for closed systems are extended to open dynamics by treating two distinct cases. In the first case the evolution generator is explicitly constructed via the Taylor expansion and the Dyson series methods, and in the second case minimal structural information about the evolution is assumed. In both scenarios it is shown that the evolution of fluctuations constrained by environmental interactions yield the same bounds. The result also suggests that including finer details of the system and state dynamics may lead to less restrictive bounds.

sciforum-180599: Entropy-Based Correlation Operator in the Hilbert Space Representation of Biomedical Complex Systems

Mile Dželalija, Marina Kranjac, Mija Marinković

University of Split, Faculty of Science, Split, Croatia

Biomedical systems are high-dimensional, multifactorial, and strongly correlated complex systems in which linear, reductionist approaches are often insufficient to capture the underlying regulatory structure. We present a quantum-inspired model that embeds biomedical observables as state vectors in a Hilbert vector space, enabling application of the full spectral theory of Hermitian operators and identification of the system's natural degrees of freedom as the eigenmodes of the constructed operator. Pairwise dependencies between variables are encoded in a Hermitian correlation operator whose off-diagonal elements are generalised mutual information quantities estimated from joint, conditional, and marginal Shannon entropies, providing consistent, bias-controlled estimates for continuous variables without parametric assumptions. Diagonalisation of the resulting operator yields eigenvalues that quantify the magnitude of independent biomedical drivers and eigenvectors that identify the corresponding collective modes. Large eigenvalues correspond to dominant regulatory axes, while the full eigenvalue spectrum provides compact scalar measures of structural complexity, informational redundancy, and effective dimensionality. Unlike kernel PCA, which requires specification of a kernel function, and unlike linear PCA, which is restricted to second-order statistics, the proposed formalism captures nonlinear and non-Gaussian dependencies within a rigorous operator-algebraic structure whose eigenvalue spectrum is interpretable in terms of information content. We illustrate the model on multivariate biomedical datasets, including clinical and high-dimensional omics data, and discuss its practical advantages for data-driven discovery of regulatory structure in complex biomedical systems, unifying factor analysis, linear PCA, and information-theoretic correlation analysis within a single operator-algebraic structure.

sciforum-181389: Multi-Objective Quantum Architecture Search under Noise via Expressibility-Guided Evolution

Seyedali Mousavi [1], Seyedhamidreza Mousavi [1], Masoud Daneshtalab [1,2]

[1] Department of Computer Science and Engineering, Mälardalen University, Västerås, Sweden
[2] Department of Computer Systems, Tallinn University of Technology, Tallinn, Estonia

Abstract

Introduction: Designing effective parameterized quantum circuits (PQCs) in the Noisy Intermediate-Scale Quantum (NISQ) era is challenging due to the strong impact of hardware noise. Quantum architecture search(QAS) has emerged as a systematic approach to address this problem by exploring circuit design spaces. To reduce the high computational cost of training and noisy evaluation, recent approaches have proposed using expressibility as a training-free proxy for guiding the search. However, this approach becomes less reliable for deeper circuits. As circuit depth increases, architectures that are more expressive also tend to be more sensitive to noise. This introduces an inherent trade-off between representational capacity and noise robustness, which cannot be captured by a single expressibility-based objective. **Methods:** To address this limitation, we reformulate quantum architecture search as a multi-objective optimization problem. We propose an NSGA-II-based evolutionary framework that jointly optimizes two competing criteria: (i) noise-free expressibility, measured via a KL-divergence-based information-theoretic proxy, and (ii) a noise-aware evaluation criterion capturing the sensitivity of circuit architectures to realistic hardware noise. The search produces a Pareto front of candidate architectures that balance expressive power and robustness. **Results:** We evaluate the proposed method against two baselines: random search and single-objective expressibility-guided search. The results show that the multi-objective formulation consistently identifies architectures with higher accuracy under noisy execution, particularly in deeper search spaces where single-objective expressibility becomes insufficient. **Conclusion:** These findings indicate that expressibility alone is not sufficient for reliable architecture search in deeper quantum circuits. By explicitly modeling the trade-off between expressibility and noise, the proposed framework provides a more robust and principled approach for designing PQCs in the NISQ regime.

sciforum-181366: Quantum Reservoir Computing via Intrinsic and Engineered non-Unital Dynamics

Luca Nigro [1], Francesco Monzani [1], Emanuele Ricci [2], Enrico Prati [1]

[1] Università degli Studi di Milano, Department of Physics, Via Celoria 16, 20133 Milano, Italy
[2] ScaDS.AI – Center for Scalable Data Analytics and Artificial Intelligence, Technische Universität Dresden, Dresden, Germany

Quantum reservoir computing (QRC) has rapidly emerged as a highly promising machine learning paradigm specifically tailored for the efficient processing of complex temporal data on quantum hardware. However, a fundamental challenge in gate-based QRC is the strict requirement for stable non-unital evolution. This non-unitality is essential to actively maintain the fading memory property required for sequential data processing and to prevent the quantum system from irrevocably relaxing into a featureless, maximally mixed state. In this work, we extensively explore the utilization of non-unital dynamics not as a detriment, but as a powerful computational resource via two distinct yet complementary approaches. First, we evaluate the role of intrinsic amplitude damping naturally present in contemporary superconducting qubits. Our findings demonstrate that a specific, optimal dissipation rate exists, which seamlessly balances energy loss and information retention, thereby drastically enhancing the network's short-term memory capacity. Next, transitioning from near-term devices to future architectures, we propose a robust circuit-level algorithm specifically designed for fault-tolerant hardware. This algorithmic approach successfully engineers tunable and highly stable damping through precisely controlled individual qubit rotations. Crucially, this method induces a stable, circuit-level amplitude amplification of the zero state. This engineered damping actively prevents the critical information loss typically caused by the repeated mid-circuit measurements necessary for reservoir readout. Consequently, it enables the continuous processing of arbitrarily long input sequences, extending operational capabilities well beyond the natural coherence times of the individual constituent qubits. Furthermore, we demonstrate that incorporating structured non-Markovian dynamics, where beneficial information backflow occurs between the system and its environment, fundamentally enhances the short-term memory retention of the quantum reservoir, solidifying its potential for advanced temporal signal processing.

sciforum-179355: The capacity of a single quantum neuron

Stefano Mancini

University of Camerino

We investigate a general quantum perceptron architecture equipped with an oscillatory activation function whose tunable frequency spans the entire range from zero to infinity. By applying analytical techniques from statistical mechanics, we derive the optimal storage capacity of this model and demonstrate that the well-known classical perceptron result is exactly recovered in the limit of vanishing activation-function frequency. As the frequency increases, however, the quantum perceptron exhibits a marked enhancement in its storage capability, suggesting at first sight a genuine quantum advantage. A closer analysis reveals that this improvement originates solely from the specific oscillatory structure of the activation function and is therefore not inherently quantum; in principle, an analogous effect could be engineered within a purely classical architecture.

To further assess the practical implications of this behaviour, we examine the same model in a teacher–student setting, where a student quantum perceptron attempts to learn from correctly classified examples generated by a teacher perceptron of the same type. In this supervised-learning scenario, we find that increasing the activation-function frequency leads to a persistent generalization error that remains close to its maximal value, even as the size of the training set grows. This indicates that the apparent gain in storage capacity is largely illusory, as it is accompanied by severe overfitting that prevents meaningful generalization.

sciforum-175755: The Quantum Turn of Entropy: A Bibliometric Journey Through Quantum Information and Quantum Computation

Thomas Scheidsteger, Robin Haunschild

Max Planck Institute for Solid State Research, Stuttgart, Germany

Introduction:

Entropy stands at the intersection of thermodynamics, information theory, and quantum physics. The rise of quantum information science has redefined entropy's role—from a measure of thermodynamic disorder to a fundamental quantifier of quantum entanglement. Understanding entropy's historical development is crucial for identifying foundational ideas that continue to shape modern quantum technologies.

Methods:

We applied Reference Publication Year Spectroscopy (RPYS), an established bibliometric method based on retrospective citation analysis, to trace the intellectual evolution of the interplay between Quantum Information and Quantum Computing on one side with Entropy on the other. Using a carefully collected set of peer-reviewed publications retrieved from the Web of Science via a targeted search combining these three topics, we analyzed the temporal distribution of cited references. RPYS identifies peak publication years and the seminal works mainly responsible for them, enabling a detailed reconstruction of this intersectional field's conceptual foundations.

Results:

Our analysis reveals multiple clearly distinguished peak years, allowing precise identification of the most influential contributions to this interdisciplinary domain. Notably, the comparison with a prior RPYS study by the authors on the historical roots of quantum technology (DOI: 10.1007/s11569-022-00424-z) confirms the importance of already known seminal papers in quantum information and quantum computing while highlighting other seminal papers that now emerge due to the special focus on entropy.

Conclusions:

This study maps the intellectual lineage of a core domain within quantum information science by highlighting the central role of entropy as a fundamental concept and measure of uncertainty in both physics and information theory. The results underscore the value of historical bibliometric analysis in revealing the evolution of scientific paradigms—from thermodynamic constraints to quantum information resources—and in guiding future research at the interface of complexity, information, and quantum technology—directly aligning with the interdisciplinary mission of Entropy 2026.

sciforum-175558: Towards an Entropic Quantum Gravity

Ariel Caticha

Department of Physics, University at Albany, Albany, NY 12222, USA

The framework of Entropic Dynamics (ED) allows one to derive dynamical theories from well-established inference methods – probability, entropy, and information geometry. Quantum theory has been derived as Hamilton-Killing flows on the cotangent bundle of a statistical manifold. These flows are such that they preserve the symplectic and the information metric geometries of the statistical phase-space. They explain the linearity of quantum mechanics and the appearance of complex numbers.

Our goal here is to deploy ED and information geometry to describe the kinematics of an Entropic Quantum Gravity (EQG). Our system consists of scalar matter and location fields [a field degree of freedom $\chi(x)$ is labeled by x and is located somewhere else at $y(x)$]. However, a priori the system does not include a spatial metric.

The Hamilton-Killing flow is described by a linear Schrödinger functional equation for the wave functional $\psi[\chi,y]$ from which standard quantum theory and standard information geometry allow one to identify the emergent Riemannian metric of space. Thus, we have derived the quantum geometrodynamics of interacting scalar matter χ and location y fields while the geometry is a property of the evolving ψ.

Some additional highlights are as follows: We impose spatial diffeomorphism as befits a theory of gravity. As one might expect, the superposition of two ψ's leads to a new quantum state with its own new geometry but does not lead to an indefinite superposition of geometries with its attendant indefinite causal structures. The possibility of a minimal length is pointed out. Here we only address the kinematic aspects of EQG and not the full foliation invariant dynamics which will be treated elsewhere.

Session 4. Thermodynamics and Energy Systems

sciforum-174288: Data-Driven Screening of Choline Chloride–Monoterpenoid and –Fatty Acid Deep Eutectic Solvents for PFAS Extraction

Özge Özkılınc, Santiago Aparicio Martinez

Department of Chemistry, University of Burgos, 09001 Burgos, Spain

Natural deep eutectic solvents (NADES) are emerging as greener extractants for persistent per- and polyfluoroalkyl substances (PFAS) from water (1–2). However, the explored chemical design space remains comparatively narrow and seldom includes choline chloride (ChCl) paired with monoterpenoid hydrogen-bond donors (HBDs). Here, we present a systematic computational screening of **ChCl–monoterpenoid** and **ChCl–fatty acid** binary mixtures, focusing on widely available bio-derived HBDs, to assess their suitability as **type III deep eutectic solvents (DES)** and their potential as PFAS extractants. Thermodynamic behavior is evaluated using a hybrid workflow combining **COSMO-based calculations**, **machine-learning (ML) modesl**, and a simplified **statistical-mechanical** treatment. COSMO-derived descriptors (e.g., σ-profiles, polarity metrics, hydrogen-bonding signatures) are used as ML inputs to predict **eutectic composition** and key mixture properties. Liquid-phase non-ideality is quantified with a **single-parameter Bragg–Williams mean-field model**, building on our previous work (3), which provides a compact connection between **excess Gibbs energy**, **eutectic depth**, and **composition**. This framework enables (i) discrimination of genuinely "deep" eutectic behavior from near-ideal eutectics and simple melts, and (ii) identification of how eutectic depth and polarity correlate with monoterpenoid and fatty-acid structure (functional group identity, polyfunctionality, rigidity, and hydrophobic volume). By integrating thermodynamic screening with PFAS-relevant polarity descriptors, we map which **classes of ChCl–monoterpenoid** and **ChCl–fatty acid** mixtures are most promising for PFAS extraction from water, and where **ChCl is intrinsically limited as a hydrogen-bond acceptor** in forming deep eutectics with specific HBD families. The resulting **design guidelines** extend NADES-based PFAS extraction studies into a broader, ChCl-centered and monoterpenoid-rich chemical space, and demonstrate how **mean-field models coupled to COSMO-RS descriptors and ML** can accelerate rational DES discovery.

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sciforum-185864: Finite-Time Thermodynamics of Endoreversible Systems

Karl Heinz Hoffmann

Chemnitz University of Technology

Finite-Time Thermodynamics looks at thermodynamic processes which are performed within a finite time interval or which have non-vanishing exchange rates. For such processes the classical equilibrium results like the Carnot efficiency as the maximum achievable efficiency no longer apply. Instead a new approach adapted to the non-equilibrium exchanges is required. From an application point of view such an adapted approach is needed to optimize technically relevant thermodynamic processes (which all operate with finite rates). The optimization needs two ingredients: an optimization goal and a description which allows one to quantify the dissipation occurring in the process. While the optimization objective is a matter of choice and might be for instance “maximum power” or “maximum ecological function”, an appropriate modelling of the processes occurring in detail is mandatory for a quantitative treatment. Only when the dissipation (or entropy production) can be quantitatively determined, does a quantitative optimization become possible.

Endoreversible Thermodynamics provides such a framework. Here we will present this modelling approach and show, how the quantitative determination of the entropy production is performed. This approach is adapted to systems consisting of discrete units like reservoirs, engines or reactors, which exchange thermodynamic extensities like volume, mole number or charge in the form of fluxes. This approach can also handle momentum or angular momentum fluxes and can thus seamlessly incorporate mechanical exchange processes. In order to exemplify the potential of Endoreversible Thermodynamics we will present also applications of this approach to real world thermodynamic optimization problems.

sciforum-183460: From Data-Driven to Physics-Informed AI: Explainable Energy Optimization in Industrial Systems

Diego Tuccillo, Fernando Moreno, Paula Monje

Deduce Data Solutions S.L.

Energy-intensive industrial thermal systems, such as furnaces and high-temperature processing units, represent a major source of operational cost and environmental impact. Despite the availability of large volumes of process data, the adoption of machine learning for energy optimization remains limited due to the lack of robustness, interpretability, and consistency with physical laws in purely data-driven models.

Methods:

This work proposes a hybrid framework that integrates Physics-Informed Machine Learning with Explainable Artificial Intelligence (XAI) to model and optimize energy consumption in industrial thermal processes. Physical constraints, including heat transfer dynamics and operational limits, are embedded into the learning process through structured regularization, guiding the model toward physically consistent solutions.

The approach is designed to operate under real industrial conditions, where data may be scarce, noisy, or subject to distribution shifts.

Results:

The proposed methodology improves model robustness compared to purely data-driven approaches, particularly under changing operating conditions. The integration of physical priors reduces data dependency and prevents non-physical predictions. Furthermore, the explainability component allows operators to identify key drivers of energy consumption and evaluate the impact of control actions on system performance.

Conclusions:

The combination of physics-informed modeling and explainability offers a practical pathway for deploying reliable AI systems in energy-intensive industrial environments. This approach enhances both performance and trust, supporting more efficient and transparent energy management.

sciforum-180041: Thermodynamic behavior of the dipolar Q-state clock model on large lattices: A Monte Carlo study

Michel Aguilera, Francisco Peña

Departamento de Física, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso 2390123, Chile

The presence of anomalies in the specific heat of two-dimensional spin systems with Q-state clock interactions and long-range dipolar coupling has been previously reported through exact free-energy calculations on small clusters. Moving beyond finite-size effects, this study investigates the thermodynamic behavior of larger lattices with linear sizes L = 16, 32, 64, and 128 using Metropolis Monte Carlo simulations. We extend the exact finite-cluster analysis of the dipolar Q-state clock model [Entropy 28, 181 (2026)] to large-scale systems by systematically increasing lattice sizes and employing both full real-space summation and the Ewald summation method to accurately account for long-range dipolar interactions under periodic boundary conditions. Our analysis focuses on four key aspects. First, we examine the convergence of the Monte Carlo method at low temperatures, carefully assessing equilibration and ergodicity to confirm the absence of degeneracy-related bottlenecks. Second, we track the evolution of specific-heat peaks in the Ising limit (Q = 2) across increasing lattice sizes, extracting finite-size scaling behavior and comparing with exact critical exponents. Third, we characterize low-temperature spin textures for different Q values, identifying domain structures, vortex patterns, and the role of dipolar frustration. Fourth, we investigate signatures of Berezinskii–Kosterlitz–Thouless (BKT) physics, including the helicity modulus and the emergence of quasi-long-range order. Our results establish a direct connection between microscopic spectral reorganizations observed in finite clusters and macroscopic phase transitions in extended systems, providing experimentally relevant benchmarks for van der Waals magnets and artificial spin-ice arrays.

sciforum-175052: Thermodynamic meaning of statistical factor in systems with temperature-dependent energy levels

Takuya Yamano

Faculty of Science, Kanagawa University, Yokohama, 221-8686, Japan

In this presentation, I revisit the statistical mechanics formalism that takes into account the effect of temperature-dependent energy levels. The formalism itself was introduced in 1940 by Fowler and Rushbrook, and was later considered by Landsberg et al. The most striking feature of this theory is the appearance of a statistical average of the derivative of temperature-dependent-energy levels with respect to temperature that leads to the generalized second law. Although this approach has recently gained renewed interests from several authors, the relationship between the statistical factor and the other thermodynamics quantities has not been thoroughly explored.

In previous studies, the statistical factor was indirectly identified as a constant multiple of the Boltzmann constant. In this study, this factor is shown to be constant at any different temperature. We show that comparing change in free energy in equilibrium and invoking the fluctuation relation in non-equilibrium processes can provide us with new physical insights into the statistically averaged factor. The explicit inclusion of work occurring in internal processes makes the consideration clear and connects the statistical factor to the equilibrium free-energy difference. We may regard this statistical factor as an amount of work required to adjust the spacings of the prethermal energy level in the bulk system through the fluctuation equality of work. This finding justifies that the factor is identified with a constant multiple of the Boltzmann constant for some systems.

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sciforum-175178: A Stochastic Entropy-Based Approach to Electrochemical Battery Modeling

Angel Cuadras

Electronics Engineering Dept. (EEL) Escola Enginyeria Barcelona Est (EEBE) Universitat Politècnica de Catalunya - Barcelona Tech Campus Besòs Av. Eduard Maristany 16 A10.8 08019 Barcelona Spain

Batteries are at the heart of the energy transition, making a deep understanding of their operation essential. Currently, battery modeling is dominated by three main frameworks: i) electrochemical models based on the Fuller-Doyle-Newman framework, which are accurate but computationally intensive; ii) empirical Equivalent Electric Circuit (EEC) models, which are sensitive to operating conditions and often inaccurate; and iii) data-driven models, which remain impractical due to training complexity and the vast heterogeneity of available cells. Consequently, a model that is both simple and accurate remains elusive.

In this contribution, we propose a disruptive modeling strategy rooted in statistical physics. Inspired by experimental Li-ion battery noise measurements, our approach models ion and electron trajectories through random particle movement. Entropy plays a pivotal role in simplifying the problem by introducing randomization at the microscopic (particle) level rather than the system level. As the electric field breaks symmetry and reduces the degrees of freedom, entropy governs the distribution of particle trajectories.

Simulation results provide insights at both the electrochemical level (voltage, impedance, porosity, and diffusion) and the energetic level (heat dissipation, thermal entropy production, and electrochemical noise entropy). Compared to existing literature, this approach offers four key advantages:

- Universal applicability: It can be applied to individual batteries with limited input data, without requiring statistical comparisons.
- No training required: It eliminates the need for extensive data-driven training.
- Real-time capability: Electrical parameters can be extracted in real time.
- Drastic simplification: Computational complexity is drastically reduced. In our case, code volume has reduced almost to 1 % of the original available code.

sciforum-175707: Efficient power in an arrangement series of endoreversible thermal engines

Delfino Ladino-Luna [1], Ricardo T. Paez-hernández [1], Juan C. Chimal-Eguía [2], Juan C. Pacheco-Páez [1]

[1] Metropolitan Autonomous University, Azc. Campus, Basic Sciences Department, Azcapotzalco Borough, Postal Code 02128, Mexico City, Mexíco
[2] National Polytechnic Institute, Center for Computing Research, Gustavo A. Madero Borough, Postal Code 07738, Mexico City, Mexico

Ussualy thermal systems are often studied as if they were a single machine. However, they can actually be considered similar to an arrangement of heat engines, with a total working power that can be found as a combination of the contributions of each engine [1,2,3]. The simplest case, and one that can form the basis of a broader study viewed as a combination of heat engines, is that of an arrangement of two engines. Previously studied as a non-endoreversible system [4], it has been shown that it is possible to obtain both its power and its effective power, known as the ecological function. In this paper, taking into account the above, an arrangement of two heat engines can then be considered under the efficient power criterion, obtaining its respective efficiency, with the aim of comparing these results with others previously obtained under the power and ecological function criteria in the case of endorreversibility. Considering the efficient power criterion and comparing it with the maximum power and maximum ecological function criteria allows for comparing the COP obtained in each case, among other possible results. It is expected expressions obtained that allow this comparison to be made. and graphic of the results of the study.

sciforum-175592: Entropy Generation Trade-Offs in Finite-Time Irreversible Otto–Atkinson/Miller Engines under Efficient Power, Ecological, and Hybrid Ecological Regimes

Juan Carlos Pacheco Paez [1], Javier Contreras-Sánchez [2], Ricardo T Páez-Hernández [3], Juan Carlos Chimal-Eguía [4], Delfino Ladino-Luna [3]

[1] Department of Basic Sciences, Autonomous Metropolitan University, Azcapotzalco Campus, Ave. San Pablo No. 420 Col. Nueva el Rosario, ZIP Code 02128, Mexico City, Mexico
[2] Department of Biophysics, National School of Biological Sciences, National Polytechnic Institute, Ave. Luis Enrique Erro n.n., Adolfo López Mateos Professional Unit, Col. Zacatenco, ZIP code 07738, Mexico City, Mexico
[3] Physics of Irreversible Processes, Autonomous Metropolitan University, Azcapotzalco Campus, Ave. San Pablo No. 420 Col. Nueva el Rosario, ZIP Code 02128, Mexico City, Mexico
[4] Center for Computing Research, National Polytechnic Institute, Ave. San Pablo No. 420 Col. Nueva el Rosario, ZIP Code 02128, Mexico City, Mexico

The optimization of real heat engines under finite-time operation requires balancing useful output, thermal efficiency, and irreversibility losses. In this work, we develop a finite-time thermodynamics model for an irreversible Otto–Atkinson/Miller-type engine and adopt entropy generation as a unifying indicator of non-equilibrium performance. Finite-rate heat exchange with the thermal reservoirs is described through Newtonian heat transfer using NTU-like parameters, which capture the combined effects of heat-transfer conductance and finite contact time. Internal irreversibilities in the adiabatic compression and expansion processes are incorporated via isentropic efficiencies, yielding explicit expressions for the cycle state temperatures and enabling a consistent evaluation of heat input, heat rejection, net work, and efficiency.

Besides the standard maximum power (MP), efficient power (EP), and ecological function (EF) operating criteria, we introduce for the first time a Hybrid Ecological Function (HEF) designed to provide a tunable compromise between useful work production and irreversible dissipation. The optimal operating condition is obtained by maximizing each objective with respect to the effective compression ratio , while the Atkinson/Miller character is represented by an over-expansion factor. A comparative assessment is performed in terms of net work, thermal efficiency, and total entropy generation.

The results reveal clear trade-offs among regimes: MP yields the largest output at the expense of higher entropy production; EF reduces irreversibility with a moderate power penalty; EP provides an intermediate compromise; and the proposed HEF achieves a favorable balance over a broad range of operating conditions. These findings suggest that HEF is a promising entropy-aware objective for practical finite-time engine optimization and for application-oriented operating-point selection in high-efficiency powertrains.

sciforum-174050: Gibbs energy, chemical reactions – (in)consistencies

Miloslav Pekař

Institute of Physical and Applied Chemistry, Faculty of Chemistry, Brno University of Technology, Purkynova 118, 612 00 Brno, Czech Republic

Claims on energy released by or extractable from chemical reactions can be found in literature, at least referring to standard conditions. Concrete examples are texts on biochemical reactions like ATP hydrolysis which thus should fuel other reactions. Closer inspection reveals that they, in fact, report values of the standard reaction Gibbs energy. However, reaction Gibbs energy is not energy but a derivative of (Gibbs) energy of reacting mixture. This derivative is usually constructed after transforming Gibbs energy of mixture to function of extent of reaction. Derivative of a function is not equal to its increment, though they are related. Further, reaction Gibbs energy is not expressed, calculated as derivative but as certain sum of chemical potentials. Expression of dependence of chemical potential on composition is not unique and is determined by the type of reacting constituents (phase state). Not all such expressions are simply consistent with the formula used to calculate reaction Gibbs energy. Consequently, minimum of Gibbs energy of reacting mixture need not coincide with zero reaction Gibbs energy as expected. The shape of Gibbs energy evolution during reaction (its dependence on extent of reaction) depends on the specific values of standard chemical potentials used in calculations. Additional complications arise in flow-through systems (reactors). Example of simple reaction, for instance, ammonia synthesis, is used to show differences between various (Gibbs) energies and serves as an illustration giving basic idea of potential consequences in complex reaction systems (reaction networks).

sciforum-175008: Superlubric Effect of Vanishing Classical-Quantum-Measured Coefficient of Friction with Inclusion of Van der Waals Monolayer Contaminants Deposited on Graphene-Type Substrates

Adam Gadomski, Natalia Kruszewska, Karol Karpiński

Faculty of Chemical Technology and Engineering, Bydgoszcz University of Science and Technology, 85-796 Bydgoszcz, Poland

In a paper [1], we introduced a classical-quantum measure for the coefficient of friction (*COF*), pointing to superlubricity (SL; *COF~0*) conditions, pertinent to such systems as graphene, graphite, HBN, MoS_2, or Planckian (doped) metals [2]. In [1], the influence of contamintants had not been studied.

We offer a completion of the superlubric conditions, by introducing a Van der Waals-type (monolayer) approximation, having considered experimental conditions applied to the graphene-type systems [3,4].

The study is based on two “concurrent” definitions of the mean sliding speed. In both cases, serving to uncover the corresponding quasiparticles' involving mechanism(s), virtual kinematics are explored.

When defining the quasiparticles’ speed as a harmonic-mean property, one arrives at a local mechanism of exciting a pair of atoms[1-4].

If the definition of the quasiparticles’ speed obeys to the arithmetic-mean property, a global spread of the quasiparticles arises.

Both types of the sliding speeds (V_{ss}) conform to common formula

$V_{ss} = (a/h)\, E_{T,i}$

and (h – Planck constant) for the harmonic-mean case ($i=H$) the thermal-energy factor reads $E_{T,H}=kT$ (k, Boltzmann constant, T – temperature). This H-case points to a local atom-atom effect of generating quasiparticles; in addition it fulfills the principa of equipartition theorem [5]. As for the arithmetic-mean case ($i=A$) the thermal-energy factor embarks on $E_{T,A}=N^2kT$, with N the number of atoms within the crystal surface of lattice constant a. The A-case corresponds to a global ($\sim N^2$) atom-atom excitation effect on quasiparticles.

It can be concluded that the kinematic rationale helps disclose basic mechanisms associated with the SL state, expressed in systems of graphene-type.

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Session 5. Non-Equilibrium Systems and Entropy Production

sciforum-175002: Time-reversal symmetry in brain pathology

David Papo [1,2]

[1] Università di Ferrara
[2] Fondazione Istituto Italiano di Tecnologia

Non-equilibrium systems such as the brain are characterised by non-trivial fluctuations even in the absence of external fields, which constitute a signature of the system's modus operandi. Resting activity and its fluctuations give away key aspects of the physics of the brain. Accumulating evidence shows that neurological and psychiatric conditions are associated with alterations of several aspects of resting brain activity.

A hallmark of systems operating away from equilibrium is time-reversal symmetry breaking. Such systems use part of their free energy budget to perform work or store energy in alternative forms, dissipating the rest as heat in the environment. The second law of thermodynamics prescribes that this transformation should be associated with an irreversible increase in entropy of the environment. Furthermore, in inherently multiscale systems such as the brain, irreversibility may present complex scale-dependence, the breaking of time-reversal symmetry possibly manifesting in different ways at different spatial and temporal scales, thereby inducing a multiplicity of characteristic scales.

In this talk, we illustrate how brain pathology can be understood in terms of resting brain fluctuations' time-reversal symmetry and its break-down. We review ways in which the breakdown of such symmetries can be detected and quantified in EEG and MEG brain activity from patients suffering from schizophrenia, Parkinson's disease, epilepsy, and obsessive-compulsive disorder and their respective control group. The results show that resting brain activity is generically time-irreversible at sufficiently long time scales, brain pathology is in general associated with increased time-reversal symmetry. Moreover, time-reversal symmetry alterations affect different time-scales in different pathologies. We discuss the implications of these results and more generally dynamical symmetry breaking for the physics of brain activity.

sciforum-175014: Entropy production in run-and-tumble particles mapped to Brownian motion in an inhomogeneous temperature

Oded Farago

Department of Biomedical Engineering, Ben-Gurion University of the Negev, Be'er Sheva, Israel

Run-and-tumble particle (RTP) dynamics, a paradigmatic model of active motion, offers a minimal setting in which nonequilibrium effects arise from the interplay between self-propulsion, external forces, and thermal fluctuations. In this talk, we present recent work on a mapping of RTP steady states onto overdamped Brownian motion in a spatially inhomogeneous temperature field, allowing thermodynamic concepts to be formulated within a thermodynamic framework based on an effective temperature field.

At the level of global entropy production, this mapping proves particularly useful in certain explicit examples. For RTP dynamics in a piecewise linear potential , the steady state assumes a double-exponential form that can be interpreted as an effective splitting of the system into two components with temperatures and , both different from the bath temperature [1]. This picture provides a natural description of the steady-state entropy exchange between the thermal bath and the effectively split system.

The main focus of the talk, however, is the more challenging problem of spatially resolved entropy production. Recently, we introduced an inverse-Clausius thermodynamic framework in which the effective temperature field is inferred directly from the steady-state density, without requiring explicit knowledge of the full position–velocity distribution [2]. Within this approach, local entropy fluxes and local entropy production rates can be reconstructed from steady-state observables directly accessible in simulations. The resulting description yields a physically transparent picture in which entropy production and entropy flux need not coincide spatially: entropy is be generated and transported from hotter to colder regions through an emergent temperature landscape, while being continuously exchanged with the bath. Langevin dynamics simulations in a harmonic potential reveal that the approach is exact for the standard two-state RTP model and quantitatively accurate for multistate models.

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sciforum-168943: Path-Dependent Energy Lagrangian for Irreversible Thermomechanical Systems

Huilong Ren

Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

Classical Lagrangian mechanics provides a compact and geometric generator for conservative dynamics, yet irreversible thermomechanical effects are usually incorporated by add-ons: Rayleigh-type dissipation, linear Onsager closures, or more elaborate algebraic constructions such as GENERIC and metriplectic brackets. In rational thermodynamics, the first and second laws are posed as separate balance statements, connected by constitutive restrictions and an entropy inequality. These paradigms are effective, but they typically split the variational structure: the mechanical equations follow from an action principle, while entropy production and heat generation are enforced externally, often leading to complexity when coupling multiple dissipative mechanisms.

We propose a Path-Dependent Energy Lagrangian (PDEL) that restores a single-action viewpoint for irreversible thermomechanics. The PDEL functional consists of a reversible part given by the Helmholtz free energy and an irreversible part expressed as a history integral of channel powers. By adopting an upper-limit/tangential stationarity rule for the history term, one obtains, from a single stationarity principle, both (i) the momentum and internal-variable evolution equations and (ii) the entropy/heat equation. A key consequence is channel-wise power closure: the same instantaneous power that produces dissipative forces in the mechanical and internal-variable equations reappears as a positive source term in the heat equation. This avoids double counting, closes the first law transparently, and guarantees nonnegative entropy production under mild monotonicity assumptions on the dissipative channels.

The framework preserves the classical Lagrangian structure while subsuming standard dissipative models such as Kelvin–Voigt viscosity and diffusion, including their associated viscous heating, and it clarifies the reversible nature of thermo-mechanical cross terms. Because dissipation is encoded through channel power histories rather than bracket algebras or secondary minimization principles, the formulation remains minimal and immediately extensible to multiphysics settings (e.g., diffusion and chemistry) with limited algebraic overhead.

sciforum-185366: Adsorption Kinetics Model of Hydrogen on Graphite

Jean-Marc Simon

[1] Université Bourgogne Europe, Dijon France
[2] Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR-6303 CNRS - Université Bourgogne Europe

A new kinetic equation for the adsorption and desorption of H_2 on graphite is derived based on the adsorption and desorption equilibrium rates obtained from the molecular dynamics [1], Figure 1. These rates are proportional to the activity in the gas and the adsorbed phase and thus do not obey Langmuir kinetics although the isotherm is well model with a Langmuir type [2]. The new equation offers a new route for understanding experimental results. It is used to simulate the kinetics under different thermodynamic conditions, both isothermal and non-isothermal. The relation between the kinetics and the mass flow equation is discussed within the framework of the non-equilibrium thermodynamics of heterogeneous systems [3,4]. Finally, expressions for the transport coefficients are proposed for both the transfer of mass and the coupling between the mass and heat fluxes.

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sciforum-174896: Alternative analisys of single-qubit quantum heat engines

Andrés Vallejo, Catty Lissardy, Mauricio Mendizábal, Santiago Silva-Gallo, Alejandro Romanelli, Raúl Donangelo

Institute of Physics, Faculty of Engineering, Universidad de la República, Montevideo 11300, Uruguay

Introduction

Heat engines provide a natural framework to explore different formulations of thermodynamics in the quantum regime. One such approach is *entropy-based quantum thermodynamics*, in which the first law includes an additional contribution termed *environment-induced work*, or *coherence work*. This term accounts for the energetic role of coherence variations in open quantum systems and quantifies deviations of the system's state from its free unitary evolution generated by the local Hamiltonian, thereby extending the conventional energy balance.

Methods

We analyze single-qubit heat engines undergoing analogs of the Carnot, Otto, and Stirling cycles within this entropy-based framework. The thermodynamic stages are characterized through the trajectories they generate in the Bloch sphere, providing a geometric description of isentropic, isochoric, and isothermal processes. Based on this representation, we evaluate the efficiency associated with the conversion of heat into coherence work.

Results

Within this unified formulation, the quantum Carnot cycle attains the classical Carnot efficiency. The efficiency of the quantum Otto cycle remains bounded by the Carnot limit determined by the extremal temperatures of the cycle. For the Stirling configuration without regeneration, the efficiency is likewise constrained by the corresponding Carnot bound. The inclusion of an ideal regenerator suggests, at least theoretically, the possibility of exceeding this limit.

Conclusions

These results provide a coherent entropy-based characterization of different quantum heat-engine architectures and clarify the role of coherence as an energetic resource. A complete assessment of regenerative schemes requires a detailed evaluation of the thermodynamic costs associated with control and system manipulation.

sciforum-181415: Correlational entropy by nonlocal quantum kinetic theory

Klaus Morawetz [1,2]

[1] Department Applied Physics, Münster University of Applied Sciences, Stegerwaldstrasse 39, 48565 Steinfurt, Germany
[2] International Institute of Physics - UFRN, Campus Universitário Lagoa nova,59078-970 Natal, Brazil

The nonlocal kinetic equation unifies the achievements of the transport in dense quantum gases with the Landau theory of quasiclassical transport in Fermi systems. Large cancellations in the off-shell motion appear which are hidden usually in non-Markovian behaviors [1]. The remaining corrections are expressed in terms of shifts in space and time that characterize the non-locality of the scattering process [2]. In this way quantum transport is possible to recast into a quasi-classical picture [3]. The balance equations for the density, momentum, energy and entropy include besides quasiparticle also the correlated two-particle contributions beyond the Landau theory [4]. Different forms of correlational entropy found in literature appear as special limit of the presented one. Several noval applications are discussed. Among them it is found that the medium effects on binary collisions mediate the latent heat, i.e., an energy conversion between correlation and thermal energy. For Maxwellian particles a sign change of the latent heat is reported at a universal ratio of scattering length to the thermal De Broglie wavelength. This is interpreted as a change from correlational heating to cooling [5].

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sciforum-175668: Entropy's Other Half: How Information Melts Potential into Memory

VEACESLAV ALBU

Vladimir Andrunachievici Institute of Mathematics and Computer Science, Moldova State University, Chisinau, MD-2009, Republic of Moldova

The Second Law commands disorder to increase, yet the universe blossoms with order - life, complexity, memory. Schrödinger (1944) spoke of “negative entropy” but left its cosmic meaning a mystery.

We propose an informational ontology where information is tripartite. Information Dualism distinguishes *Embedded Information* (NOW) in matter from *Evolutionary Information* (PAST, Plirophoria) - permanent, gravitationally encoded memory of what has been. A foundational postulate, Strong Conservation of Information (SCI), holds that information is never lost, only transformed. Gravity Dualism follows: NOW gravity (Newton-Einstein) rules present matter; PAST gravity arises from accumulated memory. The Archive Constraint - rooted in topological protection and the integrity of evolutionary memory - ensures records cannot be erased. The Einstein-Landauer coupling *m=KB*T*1n2/*c***2 (Landauer, 1961; Albu, 2024) shows how each irreversible event writes a PAST record. This happens only in natural kinds (stars, life, the cosmos); artificial systems merely dissipate heat.

A quaternionic representation *q=q*0+*q*1*i+*q*2*j+*q*3*k* places the classical world in the real scalar and the PAST archive in the three imaginary axes - the only normed division algebra with three units, naturally mirroring the three particle generations. The quantum border is the interface between the real (NOW) and the imaginary (PAST) - the meeting of an entropic world and a negentropic one. From its field equations emerge fluid-like dynamics: *light pliroholons* (simple stellar memory) as dark energy, *complex pliroholons* (memory from life-like processes) as dark matter. Chaotic dynamics (Lorenz, 1963) amplify the depletion of potential.

Empirical signs converge: Gough (2025) ties dark energy to star formation; Vazza & Feletti (2020) see the cosmic web mirrored in neuronal networks; the framework echoes quaternionic fluid models (Sbitnev & Fedi, 2017; Chishtie, 2025). This is entropy’s other half: the universe does not run down - it remembers.

sciforum-175759: Fundamental and emergent: testing the Second Law of Thermodynamics

Peter Ván

Hun-Ren Wigner Research Centre for Physics, Budapest, Hungary

In nonequilibrium thermodynamics, the Second Law can be used to derive the evolution equations of thermodynamic state variables. This method can be applied to fields and substitute variational principles for dissipative processes. Furthermore, governing equations of non-dissipative, ideal theories can be obtained as a marginal case of dissipative evolution.

The best way to test the applicability and validity of the construction method is to derive well-known evolution equations of fundamental physical theories, such as gravity and quantum mechanics. If the key parts of the theories are incorporated into the thermodynamic framework, this indicates the methodology's applicability, but it does not say anything about its performance. It looks like a pure philosophical question. How could we distinguish between an ideal theory with added small dissipative elements and an almost ideal, but inherently dissipative theory?

In the presentation, I show our efforts in this respect, focusing on thermodynamic extensions of fundamental evolution equations that predict qualitative differences, as well as our experimental efforts to measure the predicted phenomena. The Second Law of Thermodynamics is emergent. How can it be fundamental at the same time?

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sciforum-175580: Irreversibility in the ideal gas model and a thermodynamic time-energy uncertainty principle

Rudolf Hanel [1], Petr Jizba [2]

[1] Institute for science of complex systems, Center for Medical Data-science, Medical University of Vienna
[2] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

The statistical physics of the ideal gas has become text book knowledge. Yet, it holds surprises. Thermodynamics strongly operates in quasi stationary equilibrium. To move a piston in an ideal gas model we have to apply a little more force than for holding position to push the piston inward and a little less force to let the piston be pushed outward. Moreover, the faster the piston moves the larger this force differential needs to be. Isothermally it becomes impossible to recover all energy invested during compression in the expansion phase of a cycle. Similarly for adiabatic processes. The gas after one cycle has become hotter.

A statistical analysis of ideal gas particles colliding with a moving piston results in path-dependent equations of states for adiabatic, isothermal and finite time Carnot processes. How exactly we move a piston from here to there in finite time becomes relevant. The intuition above translates into a precise time-energy uncertainty relation. The time for performing one cycle times the energy lost irreversibly in this cycle is larger than a system specific constant with the dimension of an action that depends on the characteristic system dimensions. For macroscopic cylinders, like bicycle pumps, this constant is also macroscopic. At the scale of the hydrogen atom it interestingly attains a value that is of the same order of magnitude as Planck's constant, which implies that at the scale of molecular bonds purely classical irreversible thermodynamics effects are of the same order of magnitude as quantum effects. Further, we discuss efficiency and power output of finite time Carnot cycles, the irreversible energy loss in learning and erasing one bit of information, and we make an argument for an irreversible thermodynamic origin of friction.

sciforum-192842: Thermodynamic Framework for -Affinity

Dani Rodríguez Castellanos, Petr Jizba

Czech Technical University In Prague

We develop a thermodynamic framework for non-equilibrium affinities based on generalized entropies. In particular, we extend the classical concept of De Donder by introducing q-affinities associated with Rényi and Tsallis entropies. This in turn allows us to generalize thermodynamic driving forces to systems with long-range interactions and/or strong correlations. For Rényi entropy, we build on a thermodynamic interpretation due to Baez, where the entropy is expressed through finite differences of the Helmholtz free energy at two temperatures. This leads to a generalized thermodynamic potential whose derivative with respect to a reaction coordinate defines the Rényi q-affinity. The resulting expression admits a representation in terms of exponential work averages, establishing a connection to Jarzynski-type fluctuation relations. For Tsallis entropy, we consider Markov jump processes using a master-equation-based approach. We derive a q-deformed entropy balance law and obtain an explicit expression for the Tsallis entropy production rate, proving its non-negativity and thus recovering a generalized second-law structure. This allows us to identify a local stochastic q-affinity with the generalized thermodynamic force entering the entropy production rate. The proposed framework unifies generalized thermodynamic forces across deterministic and stochastic descriptions, providing new tools for studying complex systems far from equilibrium, their fluctuation properties, and the role of information-theoretic measures in nonequilibrium thermodynamics.

Session 6. Statistical Physics and Stochastic Processes

sciforum-181439: Bridging Exact Response Theory with the Karhunen-Loève expansion

Pasquale Vozza [1], Lamberto Rondoni [2,3], Matteo Colangeli [1]

[1] Department of Information Engineering, Computer Science and Mathematics, University of L' Aquila, Via Vetoio, 67100 L'Aquila, Italy
[2] Department of Mathematical Sciences "Giuseppe Luigi Lagrange", Politecnico di Torino, 10129 Torino, Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

While linear and exact response theories have been extensively developed for deterministic Hamiltonian and dissipative systems, their application to stochastic diffusion processes remains an active area of research. In previous works, Exact Response Theory (ERT) has been extended to stochastic systems with additive noise governed by the Fokker-Planck equation. Building on those results, this study proposes a complementary analytical framework in the context of Langevin dynamics.

To render the non-autonomous stochastic dynamics autonomous, we embed the system within an augmented phase space. We model the stochastic white noise through a Karhunen-Loève (KL) expansion by coupling the physical observable to a deterministic harmonic auxiliary subsystem. The added auxiliary variables possess a symplectic structure and effectively replace the explicit time dependence of the noise. Through this geometric embedding, the infinite-dimensional frequency spectrum is generated via an algebraic mapping using Chebyshev polynomials of the first kind. The augmented system's evolution is governed by the Liouville equation, allowing us to derive the dissipation function for an overdamped Langevin system.

By evaluating the exact response integral over the augmented phase space, we compute the analytical time evolution of the ensemble average of the squared displacement. We prove that sampling the initial angular phase of the KL expansion from a uniform distribution,which physically represents coupling the system to an already equilibrated, stationary thermal reservoir, naturally recovers the exact theoretical target derived via our prior Fokker-Planck generator method.

This autonomous mapping of stochastic dynamics analytically validates the ERT formalism for Langevin systems, suggesting a direct connection with the previous results. The effectiveness of such methodology increases the credibility of a structure that can facilitate the future extension of response theory to non-Markovian perturbed systems.

sciforum-181531: A Stochastic Analysis of a Hypersonic Planar Flow Using a Fokker--Planck Approximation

Amna Khraibut [1], Sudhir Gai [2], Edgar Roldan [1]

[1] Quantitative Life Sciences (QLS), The Abdus Salam International Centre for Theoretical Physics (ICTP), Via Beirut 2–4, 34151 Trieste, Italy
[2] School of Engineering and Technology, UNSW Canberra at ADFA, University of New South Wales, Northcott Drive, Campbell, ACT 2612, Australia

Hypersonic flows are flows travelling at speeds greatly exceeding the speed of sound. These are characterised by rapid boundary layer growth and nonequilibrium effects impacting the design and performance of a hypersonic vehicle. Typically, a hypersonic flight trajectory covers the continuum and molecular regimes. Continuum flows are governed by the Navier–Stokes equations, while rarefied flows are described by the Boltzmann equation. Rarefaction is characterised by the Knudsen number Kn, defined as the ratio of mean-free path to a characteristic length.

Theoretical analysis of flow stability has been performed by Lees & Lin (1946), who obtained a stability criterion in terms of the kinematic viscosity, mean density, and vorticity using a continuum assumption. Lees (1947) later included both heat transfer and compressibility effects, noting that near the surface, the heat transfer changes the fluid's viscosity and density, thereby affecting stability. Lees also showed the combined effect of heat transfer and compressibility on stability can be defined by a generalized inflection point (GIP), which is a *necessary* condition for instability.

In this paper, we investigate the stability of a compressible Couette flow in the continuum and slip flow regimes using the Fokker–Planck approximation of the Boltzmann equation:

∂F/∂t + v_i ∂F/∂x_i + ∂(a_i F)/∂v_i = S_B

where F = f(x, v, t). This replaces the collision operator S_B with drift and diffusion terms, transforming the equation into a continuous stochastic process, and relaxing any time constraints. The quality of a Fokker–Planck solution depends on the modelling of the drift term. Here, we implement entropic drift, which ensures positive entropy production.

For flow instability, we consider flow profiles for a moving plate at ~1500 m/s. Preliminary results show that the profiles satisfy the Lees & Lin stability criterion. This work extends the stability framework to rarefied regimes using a stochastic formulation.

sciforum-181006: Anomalous diffusion, non-Gaussianity and long-range dependent motion

Ralf Metzler

Institute of Physics & Astronomy University of Potsdam 14476 Potsdam, Germany

Deviations from the standard laws of Brownian motion, the linear time dependence of the mean squared displacement and the Gaussian probability density function, are quite commonly observed in an adundance of systems [1]. The physical mechanisms for these anomalies are non-universal, prompting the need for different stochastic models along with their identification from measured time series of dynamic motion. The model classification and parameter regression of anomalous diffusion can be successfully achieved by machine-learning tools such as Bayesian Deep Learning [2], which will be introduced along with a brief summary of the two recent AnDi (Anomalous Diffusion) Challenges [3,4]. The talk will focus on long-range dependent stochastic motion, identified in a large range of systems. In particular, it will be discussed how to generalise such models to situations, in which the observed probability density is non-Gaussian, or when the processes display scaling exponents varying in time or space. Diffusion models with stochastically and deterministically varying diffusion coefficients and scaling exponents will be introduced. Applications to experimental data will be discussed.

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sciforum-175614: Curvature-Induced Effects in Time-Subordinated Diffusion

Guillermo Chacón-Acosta, Elías P. Candelas

Applied Mathematics and Systems Department, Universidad Autónoma Metropolitana-Cuajimalpa, Mexico City, 05348, Mexico

Anomalous diffusion in constrained environments is a paradigmatic problem in non-equilibrium statistical physics and is commonly described within the framework of continuous time random walks and temporal subordination. In such systems, deviations from standard diffusion arise from memory effects, heterogeneity, and constraints that strongly influence the short-time dynamics of the process. When transport takes place on curved manifolds, geometric constraints introduce additional corrections that modify the evolution of statistical moments, particularly in the early-time regime, where curvature effects cannot be neglected. In this contribution, we investigate how curvature-induced effects in time-subordinated anomalous diffusion can be transferred from curved surfaces to diffusion processes constrained to curves. We first summarize recent results on anomalous diffusion on curved surfaces, where a generalized short-time expansion based on fractional derivatives reveals an explicit coupling between curvature terms and the anomalous diffusion exponent. This coupling leads to measurable departures from flat-space behavior and provides a clear physical mechanism through which geometry modulates anomalous transport, effectively competing with anomalous scaling in the short-time regime. As an illustrative application, we consider a stochastic model of telomere shortening by treating the telomere as a curved one-dimensional manifold and describing the dynamics as diffusion along the curve. Within this effective description, curvature-induced corrections emerge naturally from the constrained geometry. More generally, our results emphasize the role of geometry as a fundamental ingredient in anomalous transport processes and highlight the relevance of curvature effects in the statistical description of non-equilibrium systems.

sciforum-175275: Exploring Complex Systems as Language Generators

Antonio Javier Pons [1], Antoni Hernández-Fernández [2], Andrés Aragoneses [3]

[1] Department of Physics, Polytechnic University of Catalonia, Terrassa, Barcelona, 08222, Spain
[2] Institute of Educational Sciences, Polytechnic University of Catalonia, Barcelona, 08034, Spain
[3] Physics Department, Whitman College, Walla Walla, WA, 99362, USA

We introduce a minimal symbolic framework that transforms time traces produced by dynamical systems into structured sequences of discrete symbols, enabling their analysis using tools from quantitative linguistics. The method is governed by a single resolution parameter, δ, which controls the granularity of the encoding and generates a family of possible symbolic representations, or pseudo-languages, from the same underlying dynamics.

Within this formalism, both physical signals and written texts acquire measurable linguistic attributes that can be directly compared within a unified statistical setting. We apply this framework to three fundamentally different systems: the logistic map as a paradigmatic discrete nonlinear model, a photonic neuron as an experimental neuromorphic physical system, and the literary text Don Quijote de la Mancha as a representative example of human language. By converting the dynamical outputs of the physical systems into symbolic sequences and analysing the texts within this framework, we examine similarities and differences in the statistical laws of their linguistic components.

This comparative approach reveals how structured linguistic properties emerge not only in human language but also in chaotic and experimental nonlinear systems. Differences in symbolic organization reflect the underlying generative mechanisms of each system, and common statistical features suggest that language-like structure may arise as a generic property of complex dynamics. The proposed framework therefore establishes a unified methodology for comparing dynamical systems across domains by formalizing their measurable symbolic organization, recognizing that all such systems are ultimately physical and mathematically describable, and that human language constitutes a particular instance within this broader class of structured dynamical processes.

sciforum-175645: Genuine and spurious (non-)ergodicity in single particle tracking

Aleksei Chechkin

Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle (Saale)

In single-particle tracking experiments measuring anomalous diffusion dynamics, understanding ergodicity is crucial, as it ensures that the time average of an observable matches the ensemble average—and can thus be fitted with known ensemble-averaged observables. A commonly used criterion for assessing the ergodicity of a stochastic process is based on the comparison of the meansquared displacement (MSD) with the time-averaged MSD (TAMSD). This approach has been widely applied and proves effective in cases of weak ergodicity breaking across various systems in both theoretical and experimental studies. However, there is relatively little discussion regarding the theoretical justification and limitations of this definition. Here, we demonstrate that this widely accepted criterion to some extent contradicts the classical definition of ergodicity as well as physical intuition, leading to spurious (non-)ergodicity results when applied to several well-known stochastic models. To address this limitation, we propose using the mean-squared increment (MSI) instead of the MSD for comparison of ensemble- and time-averaged observables. Several well-established examples demonstrate that our MSI-TAMSD criterion not only effectively reveals weak ergodicity breaking, equivalent to the MSD-TAMSD approach, but also provides a more accurate characterization of the genuine (non-)ergodicity of systems where the MSD-TAMSD method fails. Additionally, for systems exhibiting "ultraweak" ergodicity breaking, the MSI can reveal the asymptotic stationarity and ergodic nature of the process' increments. Our findings emphasize the important role of the MSI observable for SPT experiments and anomalous diffusion studies. The MSI is, in fact, equivalent to Kolmogorov's structure function—a measure that is capable of unveiling aging and stationary properties, as originally introduced to describe locally homogeneous and isotropic turbulence.

sciforum-180931: Stochastic chains coupled to thermal reservoirs

Matteo Colangeli [1], Emilio N. M. Cirillo [2], Claudio Giberti [3,4], Lamberto Rondoni [5,6]

[1] Department of Information Engineering, Computer Science and Mathematics, University of L'Aquila, via Vetoio, 67100 L'Aquila, Italy
[2] Dipartimento di Scienze di Base e Applicate per L'Ingegneria, Sapienza Università di Roma, Via A. Scarpa 16, 00161 Rome, Italy
[3] Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, via G. Amendola 2, 42122 Reggio Emilia, Italy
[4] Interdepartmental Centers En &Tech and InterMech, University of Modena and Reggio Emilia Reggio Emilia, Italy
[5] Dipartimento di Scienze Matematiche, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[6] INFN, Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy

Deterministic chains of coupled oscillators provide paradigmatic models for investigating the microscopic mechanisms of heat conduction [1, 2]. A notable example is the Fermi-Pasta-Ulam-Tsingou model [3], originally introduced to study thermalization in nonlinear lattices and later found to exhibit long time correlations and anomalously slow relaxation. These features have motivated extensive research at the interface of ergodic theory, nonlinear dynamics, and statistical mechanics. Inspired by this literature, we introduce a stochastic one-dimensional model of interacting particles. The system consists of N particles performing continuous time random walks on the integer lattice $\mathbb{Z}$, confined by interaction forces to two immobile boundary particles at positions x_0 and x_{N+1}. The particles interact with thermal baths characterized by inverse temperatures β_L, β_B, and β_R, acting on different spatial regions. Particles are indexed and interact with nearest neighbors in index space through either a quadratic potential or an FPUT type coupling. While the interaction is local in index space, it can induce long range interactions on the spatial lattice, depending on the instantaneous configuration. Particle jump rates follow either the Metropolis rule or a modified dynamics that breaks detailed balance at the interfaces between regions coupled to different baths. In both cases, the dynamics drive the system toward the minimization of a suitable energy functional, even under nonuniform temperature profiles [4].

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sciforum-185339: When Does Diversity Matter in Binary-Choice Dynamics?

José Fernando F. Mendes [1], Arkadiusz Jedrzejewski [2]

[1] Department of Physics & I3N, University of Aveiro, Aveiro, Portugal
[2] Department of Computational Social Science, Wrocław University of Science and Technology, Wrocław, Poland

Understanding when individual-level diversity influences collective behavior remains a central question in social and complex systems. We introduce a unified and analytically tractable framework for binary-choice dynamics in well-mixed populations, where agents update their states via one of two competing mechanisms. The mechanism is selected according to individual preferences drawn from an arbitrary distribution, enabling a general treatment of heterogeneity.

We compare two regimes: annealed dynamics, where preferences evolve over time, and quenched dynamics, where they remain fixed. By embedding both within a common formalism, the framework unifies several models across social dynamics, statistical physics, and epidemiology. This allows us to derive a general criterion identifying when heterogeneity significantly affects macroscopic behavior and when it can be neglected.

A key result is a balancing condition on the transition rates. When satisfied, (i) heterogeneous systems can be mapped onto equivalent homogeneous ones, (ii) annealed and quenched dynamics become equivalent, and (iii) the system reduces to an effective one-dimensional dynamics, excluding oscillatory behavior.

We analytically characterize the stationary states and directly compare annealed and quenched outcomes. The framework is illustrated with examples from multiple domains, demonstrating its generality. We conclude by discussing its limitations and possible extensions to more complex interaction structures and higher-dimensional state spaces.

sciforum-174773: Absolute negative mobility in the overdamped system driven by active fluctuations

Karol Białas, Jakub Spiechowicz

Institute of Physics, University of Silesia, 41-500 Chorzów, Poland

Absolute negative mobility (ANM) is one of the most counterintuitive transport phenomena in which average transport occurs in a direction opposite to the applied force. Previously, the minimal system in which this effect could be observed was an inertial Brownian particle in a one-dimensional nonlinear symmetric periodic potential subjected to a constant bias and an external periodic driving force making the state nonstationary and nonequilibrium. We employ precise numerical simulations on graphical processing units (GPUs) to investigate a simpler system composed of an overdamped particle dwelling in a one-dimensional piecewise-linear symmetric periodic potential, which is in an equilibrium state. The constant bias is replaced by nonequilibrium active fluctuations in the form of white Poisson shot noise with equivalent mean. We show that ANM can occur in such a remarkably simplified system and derive a phenomenological toy model that explains the transport mechanism both qualitatively and quantitatively in the studied parameter regime. Our result may help explain exotic transport behavior emerging in inherently nonequilibrium biological cells, where dynamics is typically overdamped and subjected to active fluctuations arising from various metabolic activities or collisions with active agents. The presented transport mechanism can also be exploited to develop effective separation strategies in a microscopic world, thereby transforming fluctuations from a nuisance into a functional resource.

sciforum-171773: Chemistry with Small Number of Molecules

Ronen Zangi

[1] Department of Organic Chemistry, Faculty of Chemistry, University of the Basque Country, Donostia-San Sebastian, 20018, Spain
[2] Donostia International Physics Center (DIPC), Donostia-San Sebastian, 20018, Spain

Most of the physical laws formulated in chemistry are based on behavior of systems with large number of molecules. In this talk, I argue that fundamental chemical relations can breakdown when the system consist of small numbers of particles. This phenomenon arises from the treatment of two-body interactions and is exemplified for binding reactions, for which it is demonstrated that system's properties are not homogeneous functions. In other words, averages of intensive parameters, such as the concentration of the bound-state, observed for small systems are different than those observed for large systems under the same conditions. The discrepancy increases with decreasing temperature, volume, and numbers of particles. Utilizing statistical-mechanics formulations, we show that the equilibrium and reaction-rate constants for association processes should include correlations in reactants' concentrations, which are significant for small numbers, but negligible for large numbers, of particles. That means, the expressions of these constants ought to include the average of the product, and not the product of the average, of reactants' concentrations. The proposed derivation is extended for dimerizations, multimerizations, and Langmuir adsorption isotherms. I further apply this concept to fluorescence quenching spectroscopy, where non-linear Stern-Volmer plots are argued to emerge due to local equilibrium (steady-state) between a single fluorophore and a finite number of surrounding quencher molecules.

sciforum-169505: Entropy fluctuations in stochastic thermodynamics

Jean-Luc Garden

University of Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Entropy is a fundamental state function in thermodynamics, involved in the second law. In small systems that remain sufficiently large to admit a thermodynamic description in terms of a limited number of state variables, fluctuations of these variables (and in particular of entropy) can no longer be neglected. Here we investigate entropy fluctuations in small systems. The approach is not limited to fluctuations of state variables around equilibrium; rather, the evolution of entropy fluctuations allows us to describe, at the microscopic scale, systems driven out of equilibrium, either close to or far from equilibrium, by work and heat exchanges with their surroundings. This leads, first, to two expressions of the second law at the microscopic scale, one involving work and the other involving heat, and, second, to an extension of the canonical Gibbs distribution to nonequilibrium systems whose properties depend on time, even at constant temperature and fixed external parameters. Within this framework, for a system described in terms of discrete energy levels, the fluctuation theorem for entropy production is used to derive the Jarzynski equality, as well as a new equivalent relation for the random heat exchanged with the thermal bath during the work protocol in stochastic thermodynamics. We finally show that fluctuations of work and heat in stochastic processes directly follow from the fluctuation theorem for entropy production.

sciforum-174917: Fast directed transport via energy recuperation in non-Markovian media

Mateusz Wiśniewski, Jakub Spiechowicz

Institute of Physics, University of Silesia, Chorzów, 41-500, Poland

Recent experimental studies show that driven overdamped Brownian particles can recover energy stored in non-Markovian environments [1]. Using the Generalized Langevin Equation formalism, we demonstrate that energy recuperation is, in fact, an inherent feature of systems exhibiting memory and occurs even in the simplest models, such as an overdamped particle driven by thermal noise in a harmonic potential. Moreover, we show that inertial particles can recover energy from their environments even when thermal noise vanishes and without any external forcing. Next, we investigate the influence of energy recuperation on the directed transport of Brownian particles in the presence of energetic barriers. In particular, we demonstrate that the delayed response of the non-Markovian medium to the particle's motion results in the emergence of running solutions, which are absent in analogous Markovian media. The running solutions are qualitatively different from those encountered in viscous fluids in that the particle repetitively reverses the direction of its motion to recover energy from the non-Markovian medium, which enables it to overcome potential barriers. Notably, in our system, the transport in a non-Markovian medium can almost reach the free-particle limit, in contrast to the locked behaviour of particles in a Markovian case. Our findings shed new light on the role of energy exchange between Brownian particles and their environments in transport at the micro-scale, with direct applications to the dynamics of colloids in viscoelastic fluids and intracellular transport.

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sciforum-175248: Ligand binding in crowded polymers

Francisco J. Cao-García [1], Juan Pedro G Villaluenga [2]

[1] Department of Structure of Matter, Thermal Physics, and Electronics, Faculty of Physics, University Complutense of Madrid, Madrid, 28040, Spain
[2] IMDEA Nanoscience Institute, Madrid, 28049, Spain

Ligands change or modulate the physical and chemical properties of the bounded polymers. Ligand biding depends on the availability of the required binding sites. This feature greatly conditions the binding kinetics and the final coverage.

The binding possibilities were computed generalizing the Mc Ghee – von Hippel counting methods. This procedure was shown to provide a result equivalent to the Tonks gas model.

The results show that ligand binding to multiple sites do not usually fully cover the polymer. Because the random binding leaves gapes that are too short for a new ligand binding. The ligands can bind non-cooperatively, where binding of the individual ligands is independent; or can bind cooperatively, where binding of a ligand to the neighboring is energetically favorable, leading to a more ordered ligand binding. Additionally, competitive ligand binding has illustrated the interactions between ligands of different sizes. It has revealed that small ligands have a strong impact in the inhibition of large ligand binding. Ligand binding size is revealed to a have a leading order compared to affinity.

Ligand binding competition provides a key insight in a leading mechanisms that inhibits or enhances the presence of a ligand bound to a polymer. Determining the ligand modulation of the physical and chemical properties of the polymer.

sciforum-180085: Mutability as a dynamic function bound by entropic functionals

Eugenio E. Vogel [1,2], Gonzalo Saravia [1], Juan Martín Rodriguez [3], Antonio José Ramirez-Pastor [3]

[1] Department of Physics, Universidad de La Frontera, Temuco, Chile
[2] CEDENNA, FINARQ, Universidad Central de Chile, Santiago, Chile
[3] Department of Physics, INFAP, CONICET, Universidad Nacional de San Luis, San Luis, Argentina

Introduction. Let r be the number of equivalent measurements of a variable (independently of their values); the number of different values among previous set (independently of their frequency) is r*. Diversity is defined as d=r*/r. Recently, it was shown that diversity can be expressed as a an entropic functional $d=\exp(h_D-h_M)$, where h_M is the Shannon entropy of the equivalent measurements and h_D is the Shannon entropy of the different measurements [1]. This property can be extended to sorted mutability which turns out to be proportional to diversity. In the present work we show that regular mutability, although not an entropic functional is bound by two entropic functionals.

Methods. Mutability z is given by the ratio w*/w, where w is the weight in bytes of the r original measurements, while w* is the weight in bytes of the r* different values along with their position indexes in the original file [2]. The advantage of regular mutability is that bears dynamic information which is absent in the other entropic functions.

Results. The application of regular mutability to the well-known problem of k-mer deposition on a discrete substrate, presenting a nematic transition for k≥7, allows us to distinguish three different dynamic conditions depending on k and the coverage.

Conclusions. The critical k-mer concentration for the two nematic transitions is found for different k values using Shannon entropy, diversity, sorted mutability and regular mutability. Comparison among these four functions is done and discussed.

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sciforum-181029: Neo-Gibbsian Statistical Energetics with Applications to Nonequilibrium Cells

Hong Qian [1], Bing Miao [2], Yong-Shi Wu [3]

[1] Center for Interdisciplinary Studies, Westlake University, Hangzhou, Zhejiang, China
[2] Center of Materials Science and Optoelectronics Engineering, College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing
[3] Department of Physics & Astronomy, University of Utah, Salt Lake City, Utah

Generalization through novel interpretations of the inner logic of the century-old Gibbs' statistical thermodynamics is presented: **1)** identifying k B → 0 as classical energetics without fluctuations, one directly derives a pair of thermodynamic variational formulae F(T) = min_E{E – TS(E)} and S(E) = min_T {E/T-F(T)/T} ; that dictate all the more familiar 1/T = dS(E)/dE, E = d{F(T)/T}/d(1/T), and S(E) = – dF(T)/dT in equilibrium, which is maintained by a duality symmetry with one-to-one relation between $T^{eq}(E)$ = arg min T {E/T – F(T)/T} and $E^{eq}(T)$ = arg min E {E – TS(E)}. **2)** In contradistinction, taking the derivative of Gibbs' statistical free energy with respect to T, a mesoscopic energetics with fluctuations emerges: This yields two information entropy functions that historically appeared 50 years postdate Gibbs' theory. **3)** Combining the above pair of inequalities yields an irreversible thermodynamic potential ψ(T, E) ≡ {E – F(T)}/T – S(E) ≥ 0 for nonequilibrium states. The second law of thermodynamics as a universal principle reflects ψ ≥ 0 due to a disagreement between E and T as a dual pair. Our theory provides a new energetics of living cells that are nonequilibrium, complex entities under constant T, pressure p, and chemical potentials μ_1 , μ_2 , etc., with sustained $\mu_1 - \mu_2$ / =0. ψ provides a ''distance'' between statistical data from a large ensemble of cells and a set of intrinsic energetic parameters that encode the information within.

sciforum-181424: Noise-Assisted Metastability and Noise-Enhanced Perception

Bernardo Spagnolo

[1] Department of Physics and Chemistry E. Segrè, Group of Interdisciplinary Theoretical Physics, University of Palermo, Italy
[2] Stochastic Multistable Systems Laboratory, Lobachevsky University, Nizhniy Novgorod, Russia

Abstract – Keynote Lecture

Many-body and complex systems, both classical and quantum, often exhibit slow and nonlinear relaxation toward stationary states due to the presence of metastable configurations and environmental fluctuations. In a wide range of natural systems—from condensed matter and biological systems to cosmology and high-energy physics—nonlinear relaxation frequently proceeds through metastable states. In such contexts, noise-induced phenomena play a crucial role in shaping the dynamics of systems operating far from equilibrium.

In this keynote lecture, I present a unifying perspective centered on noise-assisted stabilization and on the statistical properties of metastable dynamics. As an example of noise-enhanced perception in biological systems, I also discuss the phenomenon of double stochastic resonance in stink bug sexual communication.

We first analyze escape processes driven by Lévy flights in smooth metastable potentials, highlighting the emergence of nonmonotonic residence-time behavior. These ideas are then connected to stochastic resistive switching in memristive devices, where noise-induced effects can enhance stability and reproducibility.

The analysis is further extended to driven dissipative quantum and mesoscopic systems, where the interplay between external driving and system–environment coupling reshapes escape pathways and metastable lifetimes. In particular, switching-time statistics in current-biased Josephson junctions are shown to provide a potentially accessible strategy for axion detection through an axion-induced resonant-activation signature.

Finally, I present recent experimental results on double behavioral stochastic resonance in stink bug sexual communication, illustrating how noise-enhanced perception can emerge across biological sensory systems.

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sciforum-175502: Power-law tails and universality for strong anomalous diffusion

Lamberto Rondoni

Department of Mathematical Sciences, Politecnico di Torino, Torino, 10129, Italy

Strong anomalous diffusion is commonly identified by a piecewise-linear scaling spectrum for the moments of displacement. This spectrum typically shows one slope for low-order moments and a different slope for high-order moments, with a crossover at a critical moment. The exponents ξ and ζ reflect distinct features of the displacement distribution: the first governs the asymptotic scaling of the bulk, while the second captures the scaling associated with rare, large-displacement events in the distribution's tails. In this work, we develop an asymptotic matching theory that links these regimes through their intermediate-scale behavior. The resulting constraint clarifies why algebraic (power-law) tails naturally generate strong anomalous diffusion and provides an explicit connection between the crossover order and the corresponding tail exponent. Beyond establishing these relationships, the theory produces new quantitative links among the key exponents ξ, ζ, and α, and derives leading-order corrections to the asymptotic power-law scaling of displacement moments. These corrections identify the time scales required before the dominant scaling becomes clearly distinguishable from subleading contributions, helping to diagnose systematic biases in numerical exponent estimation. Building on this, we propose a robust estimation procedure that extracts these parameters jointly, avoiding the instability of fitting separate exponents for each moment. We validate the theory and the estimation approach through combined analytical and numerical evidence across five different model systems that exhibit strong anomalous diffusion. In the case of transport dominated by close to ballistic flights, our approach is consistent with the theory of long jump.

sciforum-180751: Solvable model of induced interactions in Bose-Einstein condensates

Ofir E. Alon [1], Lorenz S Cederbaum [2]

[1] Department of Physics & Haifa Research Center for Theoretical Physics and Astrophysics, University of Haifa, Haifa 3498838, Israel
[2] Theoretical Chemistry, Physical Chemistry Institute, Heidelberg University, D-69120 Heidelberg, Germany

We consider a multiple-species mixture of Bose-Einstein condensates (BECs) in a harmonic trap. When all interactions are harmonic, this is the generic multiple-species harmonic-interaction model which is exactly solvable. Solving the many-particle Hamiltonian, we first concisely discuss the ground-state wavefunction and energy in explicit forms as functions of all parameters, the masses, numbers of bosons, and the intraspecies and interspecies interaction strengths [1]. We then compute explicitly the densities and some reduced density matrices of the BECs, thus generalizing the treatments in [2,3,4,5]. As an application, we investigate two BECs with no interspecies interaction between them but interacting with a third BEC which serves as a bath. The bath thus induces interaction between the two BECs. Some exact results on the induced interactions and correlations between the two BECs and the entanglement entropy with the bath are presented and discussed. Applications for BECs in a cavity [6] and driven BECs [7] are briefly mentioned.

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sciforum-180843: Statistical scaling analysis of seismic acceleration signals

Giuliana Paradiso [1], Lamberto Rondoni [1], Matteo Colangeli [2], Federica Di Michele [3]

[1] Department of Mathematical Sciences "Giuseppe Luigi Lagrange", Politecnico di Torino, 10129 Turin, Italy
[2] Department of Information Engineering, Computer Science and Mathematics, University of L'Aquila, 67100 L'Aquila, Italy
[3] Istituto Nazionale di Geofisica e Vulcanologia, 20133 Milan, Italy

Seismic ground motion recorded by accelerometric networks provides time series whose statistical structure is far from Gaussian. Motivated by the theoretical framework of Vollmer et al. (2021, 2024) for strong anomalous diffusion, we investigate whether signatures of anomalous transport are detectable in earthquake signals, analyzing acceleration, velocity, and displacement processes.

We analyze 66 three-component accelerometric recordings of a single earthquake, captured by 22 stations along the Italy-France border, for a total of approximately 2.6 million acceleration samples.

First, acceleration distributions are characterized through AIC-based model selection among Gaussian, Laplace, Student-t, and Lévy-stable fits. Lévy-stable distributions are preferred in 83% of cases, indicating heavy-tailed behavior.

Then, we compute q-th order moments of displacement increments to estimate the scaling spectrum and assess whether it exhibits signatures of strong anomalous diffusion. The analysis is performed on both the full signal and the isolated event window. All analyses are carried out on individual station recordings and on an aggregated dataset pooling all samples across stations, with results compared across three distance groups.

Results reveal superdiffusion in seismic displacement, with scaling exponents significantly exceeding normal diffusion predictions and a clear two-regime structure consistent with Vollmer's framework. Notably, anomalous scaling emerges only in displacement (not acceleration or velocity) and only when isolating the seismic event from pre-event noise, highlighting the critical role of non-stationarity in applying anomalous transport frameworks to real seismic data. The observed breakpoint separating bulk and tail scaling regimes provides evidence of distinct transport mechanisms governing typical and extreme ground motion fluctuations.

sciforum-172178: Structural conditions for a driftless Langevin representation of heterogeneous Fickian diffusion

Carlos Escudero

Department of Fundamental Mathematics, National University of Distance Education, Madrid, 28040, Spain

Fickian diffusion is often interpreted as the macroscopic description of an underlying stochastic dynamics governed by a Langevin equation. When the diffusion coefficient depends on position, however, constructing a consistent stochastic differential equation becomes nontrivial due to the ambiguity in the interpretation of multiplicative noise, commonly referred to as the Itô–Stratonovich dilemma. Different stochastic conventions—such as the Itô, Stratonovich, and Hänggi–Klimontovich interpretations—generally lead to different drift terms in the corresponding Langevin equations. It is well known that, under suitable regularity assumptions on the diffusion coefficient, one may pass from one interpretation to another by introducing an additional drift contribution. Motivated by this framework, we consider heterogeneous diffusion processes with position-dependent diffusion tensor and investigate under which conditions a Fick-type diffusion equation admits a Langevin representation without additional drift corrections. Starting from the Fokker–Planck description of diffusion, we analyze the structural compatibility requirements that the diffusion tensor must satisfy in order for a drift-free kinetic interpretation to reproduce the Fickian evolution of the probability density. Our analysis shows that this correspondence is not generic: only diffusion tensors with specific structural properties allow a Langevin formulation that preserves the purely diffusive Fick form without the appearance of drift terms. When these conditions fail, additional drift contributions must necessarily be included. These results clarify the precise relationship between macroscopic diffusion equations and their stochastic representations in heterogeneous media and provide a rigorous framework for determining when a Fickian diffusion process can genuinely be interpreted as arising from an underlying driftless Langevin dynamics.

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sciforum-173167: Why Do Spiral Galaxies Rotate So Fast?Same Gravity Theory, Different Dynamical-Regime Model

Jose Luis Calabrese

Independent Researcher, Belgium

Abstract

The persistent discrepancy between the observed rotation curves of spiral galaxies and the Newtonian predictions derived from the classical two-body (2B) approximation is commonly interpreted as evidence for non-baryonic dark matter or for modifications of gravitational dynamics. In this work, we propose an alternative interpretation that preserves the gravitational law while reconsidering the dynamical regime used to model disk galaxies.

We introduce the concept of a 2.5-body (2.5B) effective regime, defined as an intermediate configuration between the integrable two-body regime (2B) and the fully non-integrable three-body regime (3B). Systems in the 2.5B regime are globally stable and rotationally supported, yet formally non-integrable at the microscopic level. The defining feature of this regime is the coexistence of structural stability with a systematic amplification of observed acceleration relative to baryonic Newtonian expectations, governed by a single scaling exponent.

Using a quality-controlled subsample of galaxies from the SPARC database, we test whether disk galaxies exhibit the structural signatures required for classification within the 2.5B regime. Log–log regression analysis reveals a stable scaling relation between observed and baryonic accelerations, with an exponent statistically consistent across subpopulations. Although the amplitude of the discrepancy differs between gas-dominated and stellar-dominated systems, the exponent remains invariant and residual dispersion is bounded and approximately homogeneous.

These results support the interpretation of spiral galaxies as belonging to a unified effective dynamical regime within classical gravity. The observed amplification can thus be understood as a structural property emerging from the collective dynamics of non-integrable yet globally stable gravitational systems, rather than as evidence for new fundamental interactions.

Session 7. Soft and Living Matter

sciforum-181319: MODELING CHAOTROPIC AND KOSMOTROPIC ION EFFECTS ON ENTROPY AND DIFFUSION OF WATER.

Santiago Pelosso Rodríguez, Giancarlo Franzese -

Department of Condensed Matter Physics, Faculty of Physics, University of Barcelona, Barcelona 08028, Spain

Chaotropic and kosmotropic ions disrupt and strengthen the hydrogen-bond network of water, respectively, affecting biological systems such as protein denaturation, enzyme activity changes, or cellular stress. These effects arise from alterations in water's structure, thermodynamics (enthalpy and entropy), and dynamics (viscosity and diffusivity), with the latter often described by the empirical Jones–Dole relation. However, understanding their physical basis remains difficult, and replicating these effects in atomistic simulations is challenging. In this work, we extend a coarse-grained water model—already shown to qualitatively reproduce water anomalies–to include ionic effects in a mean-field manner. We examine how ions influence both the interaction of water's hydrogen bonds and its local density. Although this approach has many limitations, it maintains computational efficiency and qualitatively reproduces the Jones–Dole relation for viscosity and diffusivity across a wide concentration range at ambient pressure, including deviations at higher concentrations that match experimental data. Additionally, it allows us to estimate, in a mean-field way, the changes in water entropy caused by chaotropic and kosmotropic ions and to predict their effects at higher pressures. Surprisingly, we find that water's structure-making (kosmotropic) behavior remains stable under various thermodynamic conditions, while structure-breaking (chaotropic) behavior depends on pressure and shows a crossover at high pressure, where experimental data are lacking. Overall, this model offers a simple, efficient tool for interpreting and exploring how ions influence transport and thermodynamic properties in aqueous solutions.

sciforum-172383: A many-state conformational-binding model to describe polymer force-extension curves

Javier Orradre Altabas [1], Pablo Miguel Blanco Andres [2], Sergio Madurga Diez [1], Marina Inés Giannotti [1,3], Josep Lluis Garcés González [2], Francesc Mas Pujadas [1]

[1] Department of Material Sciences and Physical Chemistry, Faculty of Chemistry, University of Barcelona, Barcelona (08028), Spain
[2] Departament of Chemistry, Physics and Environmental and Soil Sciences, Univerity of Lleida, Lleida (25198), Spain
[3] Bioengineering Institute of Catalonia (IBEC), Barcelona (08028), Spain.

Polymers are macromolecules which can undergo binding of external ligands and change their conformational structure depending on the surrounding conditions. Some of the most commonly analysed agents are the pH, ionic strength, and lately, mechanical stretching. The effect of stretching is vital in many fields like medicine and biology, becoming key, for instance, in the transition of B to S-DNA or regulating the binding of Rec A and chromatin to DNA.

Our group has developed an exact two-state elastic freely jointed chain (EFJC) model, which allows single molecule force spectroscopy (AFM-SMFS) experiments to be described in great detail and therefore extract crucial information for the design of new applications. As an example, for poly(ethylene-glycol) (PEG) we have obtained values consistent with its helical and planar conformations, as well as with the transition energy between both states. For hyaluronic acid, we have found results in perfect agreement with other disaccharide-type macromolecules reported in the literature.

In the course of this work, we have observed that the key aspect in the development of models of this kind is that the conformational energy contribution can be treated effectively (REF 1st Article), allowing the model to be solved as a one-dimensional Potts model (REF Borkovec) by means of the transfer-matrix methodology introduced by Flory (REF FLORY). Thus, one of the main objectives of our research is to determine the limit in the description of the conformational contribution that still allows these models to be solved exactly without the use of simulations, thereby saving computational time while retaining parameters that are fully interpretable from both theoretical and experimental perspectives.

sciforum-174770: Correlations in Active Nematic Defects

Anna Monclús I Rojo [1], Alberto Fernández-Nieves [1,2,3], Jyothishraj Nambisan [1]

[1] Department of Condensed Matter Physics, Universitat de Barcelona, 08028 Barcelona, Spain
[2] Institute of Complex Systems, UBICS, Universitat de Barcelona, 08028 Barcelona, Spain
[3] ICREA-Institucio Catalana de Recerca i Estudis Avançats, Barcelona, Spain

In equilibrium statistical physics, the fluctuation-compressibility theorem states that the variance of the number of particles, in a region of space with size R, scales as $\sigma_N \sim R^d$, with d the spatial dimension. Active systems, however, often exhibit giant number fluctuations (GNF), where $\sigma_N \sim R^d$, with $\beta > d$. In contrast, when βd, the system is classified as hyperuniform (HU). In reciprocal space, hyperuniformity implies that the structure factor scales as $S(q) \sim |q|^\alpha$, with $\alpha = d - \beta$ and q the scattering wavevector, so that $S(q) \to 0$ as $q \to 0$.

We study an active nematic liquid crystal of microtubules at an oil/water interface, driven out of equilibrium by ATP-fueled kinesin–streptavidin complexes. In the active turbulent regime, the system continuously creates and annihilates ±1/2 topological defects. Previous results in our group showed that $\beta 2$ for the system of active defects, for values of R as large as the system size. The system of active defects is thus HU. Using both hydrodynamics and particle-based simulations, we unravel how defect-defect correlation and their creation/annihilation processes all conspire to result in this behavior (*Hidden order in active nematic defects*, PNAS, 2025).

Recent experiments, however, using larger active nematic cells allow accessing smaller q. In this regime, we observe that $S(q)$ does not vanish at the lowest accessible q, but that instead it decays and saturates to a finite non-zero value. This suggests a crossover from hyperuniform to uniform behavior beyond a characteristic length scale. Uniformity suggests that at sufficiently large length scales random noise, akin to thermal effects, dominates over activity-induced fluctuations. To assess this, we compare our results with those of electric charges in equilibrium, finding that the relation between partial structure factors in this system holds for active nematic defects, thus confirming the transition from HU to uniform behavior.

sciforum-185453: Entropy as an Active Remodeling Principle in Biomolecular Nanostructure Disassembly

Jose Vilar [1,2]

[1] Biofisika Institute (CSIC, UPV/EHU), University of the Basque Country, 48080 Bilbao, Spain
[2] IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain

Entropy is often treated as a tendency toward disorder and dispersion, yet in soft and living matter it can generate structured, force-producing mechanisms. In this context, entropic forces can act as active remodeling agents in the disassembly of biomolecular nanostructures, where molecular constraints, fluctuations, and excluded-volume interactions are coupled to nonequilibrium biochemical cycles. Analytical theory and Brownian dynamics simulations show that tether-mediated interactions between nanofilaments obey simple scaling laws controlled by the ratio between excluded-volume radius and tether length. This physical parameter determines whether filaments are driven apart or, paradoxically, stabilized in attractive metastable states. The resulting nanofilament framework provides a physical basis for chaperone-driven amyloid disassembly, in which ATP-regulated binding and release create the molecular constraints that allow entropic forces to separate amyloid filament bundles. Experiments on α-synuclein fibrils further show chaperone-triggered destabilization, protofilament unzipping, and all-or-none clearance of toxic species. Together, these results suggest that entropy is not merely a passive statistical tendency but a design principle for active remodeling in biological matter [1–3]. More broadly, this perspective provides a physics-based route to understanding how living systems exploit fluctuations, constraints, and excluded volume to reorganize nanoscale structures.

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sciforum-175585: Information Geometry–Mellin Representation Correspondence in Linear Viscoelasticity

Dimiter Prodanov

Laboratory of Neurotechnology, PAML-LN, IICT, Bulgarian Academy of Sciences, Sofia, Bulgaria

Relaxation spectra describe linear viscoelasticity by distributing stiffness across Maxwell elements with distinct relaxation time constants. Because these constants span many decades, spectral comparison becomes most meaningful on a logarithmic relaxation-time scale - a coordinate naturally suited to Mellin analysis, which organizes scale-invariant structure across decades. Recent work by Uneyama (2025) showed that the log-normal spectrum maximizes entropy under minimal assumptions, establishing log-time as the natural information-geometric coordinate. Independently, a Mellin-space framework classified viscoelastic models by their modal complexity into a finite Prony class (finite exponential relaxation series) and a transcendental class (requiring infinite series of exponential relaxations), distinguished by pole-structure criteria. This work unifies these perspectives by establishing an exact duality: the curvature of a spectrum's log-Mellin transform equals the Fisher information of its log-time probability density when that density is exponentially tilted by the Mellin variable. The Mellin transform thus directly encodes how broadly the spectrum spreads in log-time and reveals whether that spread admits a finite or infinite modal representation. The duality provides an information-theoretic interpretation of modal complexity: spectra that are "most probable" under entropy maximization - such as the log-normal - are precisely those requiring infinite Prony series, while finite Prony series correspond to more constrained informational states. This bridges complex analysis and information geometry, offering a unified language for classifying linear relaxation systems. This perspective is relevant to neurotechnology and neuroimaging, where brain and neural tissues are routinely modeled as linear viscoelastic media (e.g., in MR elastography) using Prony-series fits across broad frequency bands, making the finite-versus-transcendental distinction practically important for model selection and identifiability.

sciforum-175761: Quantifying insect dynamics in Euclidean and non-Euclidean spaces

Miriam MARTINEZ MARTINEZ [1], Alberto Ferandez-Nieves [1,2,3]

[1] Department of Condensed Matter Physics, Universitat de Barcelona, Spain
[2] ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
[3] Institute for Complex Systems, University of Barcelona, Spain

Grapholita molesta (the oriental fruit moth) is one of the most important pests of stone and pome fruit trees, and is established worldwide. Previous studies have shown that some volatile compounds emitted by host plants act synergistically with sex pheromones, increasing male attraction. Others, however, when presented as continuous stimuli, reduce male response, leading to the hypothesis that supranatural emissions of plant volatiles may interfere with sexual communication and, consequently, disrupt mating. In this context, we have designed an experimental system consisting of a cubical cell, with the moths typically walking on its flats walls, together with a synchronized camera and lighting system capable of recording the entire space to study patterns of attraction, encounter dynamics, and mating-related behaviour in the presence of well-defined chemical stimuli under controlled conditions. We also developed an image-analysis methodology to extract positions, orientations, and trajectories from the images, integrating binarization processes, algorithms for separating individuals in contact, and multi-view identity association. Beyond this, we are beginning to apply this approach to curved arenas produced by 3D printing, including spherical and toroidal surfaces, where the methodology is generalized to address the influence of curvature on single-insect dynamics and thir collective behaviour with a focus on ants.

sciforum-181446: Shaping Viruses with Entropy: Assembly kinetics of viral capsid formation

David Reguera

Universitat de Barcelona

Entropy and nonequilibrium processes play a central role in the organization, transport, and function of biological matter. An outstanding example are viruses, that due to their relative simplicity, rely on the use of entropy in the different steps of their replication cycle. One of these key steps is the assembly of their protective shell, also named capsid, from multiple copies of the capsid proteins. For most viruses this process is spontaneous and ends up forming a spherical or tubular shell with well-defined size and structure. Although the architectural principles and the equilibrium aspects of viral assembly are starting to be unveiled, the kinetics of this process is not yet fully understood, and it is crucial to understand how viruses can replicate so efficiently.

In this talk, I will present a unified mesoscopic thermodynamic framework that shows how entropy is the key to describe the kinetics of viral assembly. Combining classical nucleation theory and simulations, we will explore how the interplay between the different energetic contributions and the kinetics dictates the shape and size of the resulting viral shell. I will analyze the possibility to alter kinetically the size of the resulting capsid and explore the possibility to induce misassembly as a potential route to hinder viral infections.

Session 8. Applications of Entropy in Science and Engineering

sciforum-180785: Quantifying the Representational Power of Consecutive Moments: A Relative Entropy Perspective

Serge B. Provost

Department of Statistical and Actuarial Sciences, The University of Western Ontario, London, N6A5B7, Canada

A methodology is introduced for assessing the degree to which consecutive moments capture the features of a probability distribution. The proposed approach relies on the key fact that a sample of n observations is uniquely determined by its first n moments, a result that motivates the use of moment sequences as compact summaries of distributional features. Building on this result, a finite sequence of moments, up to a prescribed order, is mapped to a set of representative points belonging to the support of the underlying distribution. These points are selected with a view to minimize the Kolmogorov–Smirnov discrepancy, a supremum-norm distance between distribution functions that ensures the resulting approximation remains close to the empirical or population distribution in a uniform sense. The selected points are then connected via monotone cubic Fritsch–Carlson interpolants to produce a smooth cumulative distribution function, which is subsequently differentiated to obtain an associated density estimate.

The fidelity of this moment-based approximation is evaluated by comparing it with the target density function via the Kullback–Leibler divergence, a standard measure of relative entropy. This quantity provides a natural quantitative metric for determining the extent of structural detail being retained as additional moments are incorporated. Examples sourced from both simulated and empirical data are presented and graphically illustrated. In each case, the the extent to which a given number of moments captures the characteristics of the distribution at hand aligns closely with expectations, demonstrating the practical utility of the constructed framework for elucidating the representational power of moment sequences.

sciforum-180525: A Holistic Approach to Residential Metabolism: The Entropic Cost of Demographic Fragmentation

Angel Cuadras

Dept. Electronics Engineering, Escola Enginyeria Barcelona Est, Universitat Politècnica de Catalunya - BarcelonaTech, Barcelona, Spain

The transition toward sustainability requires integrating social behaviour with objective physical metrics. Current energy models frequently underestimate how demographic dynamics—particularly aging and the reduction in household size—impact global demand. This paper proposes a novel theoretical framework that causally connects demographic evolution with irreversible environmental degradation through a Regional Entropic Index, using Catalonia as a proof-of-concept. To achieve this, we model residential metabolism by integrating three dimensions of entropy alongside a temporal variable. First, we introduce Social Entropy (H_{soc}), based on Shannon's information theory, to quantify the statistical dispersion of the population. Second, building on the Constructal Law and Graph Theory, we demonstrate how this social fragmentation forces the physical inventory to evolve into a highly capillary network of residential nodes. Third, we evaluate the impact of this changing morphology by integrating the operational thermodynamic entropy and the embodied entropy of the materials required to construct these new nodes, unifying them under the Entropic Footprint metric (S_f, measured in J/K). We establish that an increase in H_{soc} irreversibly multiplies the active nodes, each demanding an irreducible base entropy generation (S_{base}). Finally, introducing the temporal variable reveals a socio-demographic rebound effect: the rise in morphological fragmentation offsets the technological gains derived from energy efficiency over time ($\Delta S_{base}(t)$). This holistic approach concludes that minimizing global thermodynamic degradation depends not only on technological efficiency but also on preventing morphological dispersion through optimal socio-demographic aggregation.

sciforum-175738: Dispersion Phase Entropy: An Enhanced Complexity Measure Incorporating Phase Dynamics in Nonlinear Time Series

Ghaya Mehdi, Meryem Jabloun, Philippe RAVIER, Olivier Buttelli

Laboratoire PRISME, University of Orleans, Orléans, 45000, France

Context—Understanding the temporal complexity of time series is essential in many scientific and engineering applications, particularly in biomedical signal processing for characterizing neuromuscular dynamics and functional connectivity. Conventional entropy measures typically focus on amplitude variations or temporal ordering but often fail to adequately capture phaserelated structures. Phase Permutation Entropy (PPE), introduced in [Kang et al., Statistical Mechanics and its Applications, 2021], improves the detection of dynamic changes in phase information of nonlinear time series. However, PPE remains highly sensitive to noise and inherits limitations of classical permutation entropy, as it relies on ordinal relationships within the phase signal and does not consider amplitude magnitudes or differences between values.

Method—In this work, we propose a novel irregularity measure termed Dispersion Phase Entropy (DPE). The proposed approach addresses the limitations of PPE by combining phasebased analysis with dispersion-based symbolic representation [Rostaghi et al., IEEE Signal Processing Letters, 2016]. DPE jointly characterizes the temporal evolution of phase increments and the variability across discretized classes, yielding a robust complexity metric that is sensitive to subtle structural changes in nonlinear signals.

Results—The performance of DPE was evaluated under varying noise levels and signal bandwidths using synthetic time series (including random Fourier series, Hermite–Rodriguez wavelet trains, and Logistic map) as well as real biomedical signals (sEMG). The results show that DPE more effectively captures increases in phase-related complexity and demonstrates improved robustness to noise compared to PPE-based measures. These findings suggest that DPE is a reliable tool for analyzing multiscale phase dynamics in physiological signals, with potential applications in neuromuscular assessment, diagnostics, and motor control research.

sciforum-174968: Entropy Description of Projectile Motion in Dissipative Media

Angel Cuadras

Electronics Engineering Dept. (EEL) Escola Enginyeria Barcelona Est (EEBE) Universitat Politècnica de Catalunya - Barcelona Tech Campus Besòs Av. Eduard Maristany 16 A10.8 08019 Barcelona Spain

Ideal projectile motion is a cornerstone of undergraduate physics, typically solved analytically using Newtonian, Lagrangian, or Hamiltonian mechanics. However, realistic scenarios involving air resistance introduce significant complexity. In these cases, drag is modelled as a force proportional to either the velocity or the square of the velocity, depending on the projectile's geometry and the Reynolds number. While the solution remains analytical for linear drag, quadratic drag generally requires numerical methods. This work aims to help students integrate entropy into mechanical systems, providing a practical example of the transition from ideal to dissipative Systems, a transition often overlooked in undergraduate curricula.

In this study, we describe the system's evolution toward a stationary state as the projectile approaches terminal velocity. We demonstrate that, given the initial speed and launch angle, the problem can be framed in terms of thermodynamic entropy. By expressing the equations of motion in terms of velocity and angle, we find that analytical solutions for entropy exist for both linear and quadratic drag regimes. Consequently, thermodynamic entropy emerges as a robust quantity for describing the system's trajectory. Furthermore, we investigate geometric entropies related to trajectory curvature and establish their correlation with thermodynamic entropy. Finally, we examine non-stationary cases, such as ground impact (y=0). While these cases can be described through entropy, the system does not reach a stationary state, and thus the solution does not maximize entropy.

sciforum-172961: Entropy dynamics differentiate deliberate and arbitrary decisions in EEG

Milan Rybář, Tom Froese

Embodied Cognitive Science Unit, Okinawa Institute of Science and Technology, Okinawa, Japan

Decision-making involves both spontaneous and deliberate components, yet the neural dynamics that differentiate meaningful, goal-directed choices from arbitrary ones remain unclear. Classic electroencephalography (EEG) studies showed readiness potentials preceding arbitrary but not deliberate choices, suggesting distinct underlying mechanisms. Here, we re-analyzed EEG data from a donation-choice task in which participants made deliberate (meaningful, consequential) or arbitrary (consequence-free) decisions between non-profit organizations. To capture temporal complexity in neural activity, we computed multiple entropy and complexity measures. Entropy-based metrics provide a quantitative framework for assessing the unpredictability and richness of neural dynamics. They capture how patterns evolve over time and how much information a system generates, offering insight into the organization of neural variability. These measures have been widely applied as an indicator of the depth of anesthesia, disorders of consciousness, sleep, psychedelic state, and mental disorders, among others. Higher entropy is typically associated with more flexible and adaptive brain states. Our results showed systematic differences in post-stimulus entropy dynamics between decision types. Deliberate choices exhibited higher entropy and complexity than arbitrary choices. Our findings reframe neural "noise" as a functional component of cognition rather than as a nuisance variable. Entropy does not simply quantify uncertainty in brain signals; it reveals how unpredictability is differentially recruited when decisions are meaningful versus arbitrary. Entropy-based measures thus provide promising biomarkers of agential involvement, highlighting the constructive role of neural variability in adaptive behavior and decision-making.

sciforum-175527: Environmental Thermodynamics: Bridging Science and Technology in a Changing Environment

Amilcare Porporato

Department of Civil and Environmental Engineering and High Meadows Environmental Institute, Princeton University, Princeton, 08540, USA

Environmental thermodynamics offers a unifying framework for understanding energy transformations, irreversibility, entropy production, and efficiency across systems spanning an extraordinary range of scales, from molecular interactions to ecosystems and the climate system. As both a research paradigm and an educational lens, it brings engineering, geophysics, ecology, and Earth system science into a common physical language. In this perspective, thermodynamics does more than describe environmental behavior: it establishes bounds and constraints, reveals limiting factors, and suggests optimality principles that help explain the organization, persistence, and emergent dynamics of complex systems. It also extends naturally to nonequilibrium settings, where dissipation, entropy production, and fluctuations are central to understanding change, stability, and resilience. A particularly important insight is the second law asymmetry between dissipative loss and restorative recovery: irreversible environmental change destroys available free energy and generates entropy, whereas restoration requires renewed free energy input and need not retrace the pathway of degradation, making recovery path dependent and often hysteretic. By providing a coherent framework for interpreting processes and fluctuations in both built and natural environments, environmental thermodynamics links canonical principles to climate change, the energy transition, and environmental mitigation, while offering a rigorous, integrative, and modern basis for both research and teaching.

sciforum-175462: Internal defect detection using spatial spectral entropy in noncontact acoustic inspection and COMSOL analysis of flexural vibration

Kazuko Sugimoto, Tsuneyoshi Sugimoto

Graduate School of Engineering, Toin University of Yokohama, JAPAN

Noncontact acoustic inspection is a non-destructive testing technique that detects and visualizes internal defects in composite materials, especially concrete, without contact or destruction. Airborne acoustic waves are emitted to vibrate the target surface to be inspected, and the two-dimensional vibration velocity distribution is measured using a laser Doppler vibrometer. Frequency analysis is performed on the acquired data using the fast Fourier transform technique, and an acoustic image of the internal defects is constructed using the vibrational energy. In conventional imaging, the images were constructed with the frequency range of the excitation sound waves, which could result in unclear images due to the influence of various noises. Therefore, we introduced Spatial Spectral Entropy (SSE) analysis to detect the resonance frequency band of internal defects and visualize them with that frequency range, thereby obtaining clear acoustic images of internal defects. SSE treats the frequency spectra of the vibration velocity distribution as a probability density and extends the spectral entropy to a frequency-real space distribution, making it possible to detect and identify the resonance frequency of both the internal defects and the laser Doppler vibrometer. The graph of the SSE analysis results detects the resonance frequency of flexural vibration, but in some cases the resonance frequencies of multiple other vibration modes may also be detected. In order to distinguish between the flexural vibration of defects, which is the main vibration mode, we evaluated the spatial vibration state at the detected resonance frequency and investigated a method for detecting flexural vibration. In addition, we performed a vibration structural analysis using COMSOL to simulate experiments, calculated the resonance frequencies of multiple vibration modes, and verified the SSE analysis results.

sciforum-184174: Krylov complexity as a probe of quantum chaos in many-body systems

Juan F. Pedraza

Instituto de Física Teórica UAM/CSIC

In this talk, I examine Krylov state complexity (or spread complexity) as a robust diagnostic of quantum chaos and information spreading in many-body systems. Constructed via the Lanczos algorithm and grounded in the optimal basis theorem, Krylov complexity provides a natural and broadly applicable spectroscopic probe of quantum dynamics that captures how quantum information propagates across Hilbert space. In particular, I discuss how the growth and saturation of Krylov complexity encode universal features of nonequilibrium dynamics and distinguish chaotic from integrable behavior in interacting quantum systems. A central observation is the emergence of a characteristic overshoot in chaotic systems: a pronounced complexity peak in which chaotic dynamics drive quantum information deeper into the Krylov chain than in their integrable counterparts, before eventually relaxing to equilibrium. This phenomenon offers a simple, physically transparent signature of many-body chaos and complements more traditional diagnostics, such as spectral statistics and out-of-time-order correlators. I will also outline recent applications of these ideas in the context of black holes and gravitational holography, where Krylov complexity provides a useful framework for characterizing quantum chaos, horizon dynamics, and information scrambling in strongly coupled systems, and may help bridge concepts from quantum information theory with modern approaches to quantum gravity.

sciforum-181081: Linking Entropy Measures in Quasi-Brittle Material Specimens and Statistical Models to Global Acoustic Emission

Leandro Friedrich [1], Danilo D'Angela [2], Gennaro Magliulo [2], giuseppe lacidogna [3], Ignácio Iturrioz [4]

[1] PPEng, Federal University of Pampa, Campus Alegrete, Alegrete, RS, Brazil
[2] University of Naples Federico II Polytechnic and Basic Sciences School Dept. of Structures for Engineering and Architecture, DIST Via Claudio 21, 80125 Napoli, Italy
[3] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy
[4] Department of Mechanical Engineering; School of Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

ABSTRACT: Acoustic Emission (AE) is a well-established technique for monitoring damage in various engineering systems. The spatiotemporal distribution of AE events is known to characterize the damage process experienced by a structure. In this context, different measures of system entropy can be derived using AE signal amplitude as the primary data. We consider Shannon Entropy [1], KL Entropy [2], two entropy measures based on the Natural Time approach originally introduced by Varotsos [3] and used in a similar context by our research group in Friedrich et al. [4], and a novel methodology for determining the and parameters that govern the non-additive entropy proposed by Tsallis [5]. It is known that a change in system behavior occurs close to the point where the system enters another regime, where the statistical characterization may follow a power law. These changes can be identified using the global parameters mentioned above. Three applications are presented: first, three different typical series with known statistical distributions—uniform, exponential, and power law, are considered as input, and the global parameters based on measured entropy are computed. In the other two applications, acoustic emission tests on concrete specimens subjected to compression and on reinforced concrete structures are analysed. In these applications, it is observed how variations in these parameters provide insight into the damage process in the studied systems.

KEYWORDS: Acoustic Emission; Shannon Entropy; Natural Time; Tsallis Entropy

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sciforum-170413: Looking at Economics through the eyes of Thermodynamics: Economic entropy, and economic entropy generation

Vítor Costa

TEMA – Center for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro
3810-193 Aveiro, Portugal

Looking at Economics through the eyes of Thermodynamics, the financial value of merchandise and monetary units appears as the economic entropy, and the economic temperature as the inverse of their unit prices [1-3].

Looking trading operations as merchandise units transfers through finite economic temperature differences, the profit emerges as the economic entropy (financial value) generation.

If an Economics four laws structure is developed, starting from the economic Clausius and Kelvin-Planck statements of the Second Law, a differential equation emerges defining the merchandise economic entropy, and the economic entropy balance equation can be set [2].

The economic Carnot engine analysis highlights its reversible operation, without economic entropy generation, and releasing merchandise wealth [1,2].

Mechanical work can be seen as heat at an infinite temperature, and similarly merchandise wealth can be seen as traded merchandise at an infinite economic temperature (at a null unit price), reason why they are absent respectively from the entropy and the economic entropy balance equations [1,2].

Friction is seen as a source of irreversibility, and services with no reproductive effects can be seen as *economic friction*.

This poses challenging questions: (*i*) Individuals are *naturally* trained to conduct economic Second Law balance equation calculations (financial value calculations), but not (thermodynamic) Second Law balance equation calculations; and (*ii*) Thermodynamic systems are firstly First Law analyzed, and only secondly are they Second Law analyzed by experts; contrarily, economic systems are firstly Second Law analyzed by everyone, and only after that are they First Law analyzed.

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sciforum-175715: Multi-scale Circulant determinant-based Permutation Entropy for HDsEMG signal processing

Ghaya Mehdi [1], Meryem Jabloun [1], Ales Holobar [2], Nina Murks [2], Philippe RAVIER [1], Olivier Buttelli [1]

[1] PRISME Laboratory, University of Orleans, Orléans, 45000, France
[2] Faculty of Electrical Engineering and Computer Science, University of Maribor, 2000 Maribor, Slovenia

Context—Quantifying the complexity of physiological time series such as surface electromyography (sEMG) provides valuable insight into neuromuscular organization and control mechanisms. Entropy-based measures, particularly permutation entropy (PE) and its extensions, have been widely used for this purpose.

Method—In [Jabloun et al., EUSIPCO 2025], we introduced Circulant Determinantbased PE (CDPE), an enhanced formulation that incorporates amplitude information by exploiting the spectral properties of circulant determinants of the embedding matrix. CDPE accurately estimates the theoretical PE of sinusoidal signals within the normalized frequency range [0.01, 0.2], outperforming existing amplitude-dependent PE (ADPE) methods. Importantly, this interval matches the dominant spectral content of sEMG signals (5–500 Hz) sampled at 2048 Hz. Building on this framework, the present study proposes a **multiscale** extension of CDPE to capture the multiple temporal scales in physiological signals.

The sensitivity of the multiscale CDPE to controlled excitation variations under constant fatigue conditions is evaluated and compared with established multiscale ADPE approaches. To this end, synthetic high-density sEMG (HDsEMG) signals were generated to emulate spatially distributed sEMG acquisition using dense electrode arrays.

Synthetic HDsEMG signals were constructed from experimentally recorded HDsEMG acquired during slow, fatiguing contractions of the Abductor Pollicis Brevis muscle in healthy subjects. The motor units and their corresponding action potentials (MUAPs) were identified from these recordings using the algorithm described in [Holbar et al., IEEE TSP, 2007]. To enable controlled fatigue modeling, each MUAP was mapped to a discrete fatigue level. The MUAPs were then incorporated into a motor unit recruitment and firing-rate modulation model [Fuglevand et al., J. Neurophysiol., 1993] to generate synthetic HDsEMG signals arranged on a 12×5 electrode grid.

Results—The proposed multiscale CDPE exhibits improved sensitivity to excitation variations and superior discriminative performance compared to multiscale ADPE approaches, demonstrating enhanced robustness for excitation variations in HD-sEMG under controlled fatigue conditions.

sciforum-175540: Reliable Post-Estimation Inference in High-Dimensional Sparse Regression

S. Ejaz Ahmed

Department of mathematics and statistics, Brock university, St. Catharines, Canada

In this talk, I address estimation and prediction problems in regression models where regression coefficients may be constrained to lie in a candidate subspace, considering both low- and high-dimensional settings. Such structural information naturally arises in many modern applications, particularly under sparsity or approximate sparsity assumptions. We develop a unified class of penalized, pretest, and shrinkage estimators that incorporate subspace restrictions while maintaining flexibility when these restrictions are uncertain.

The large-sample properties of the proposed procedures are rigorously established through analysis of their asymptotic distributional quadratic bias and risk. These theoretical results provide clear insights into efficiency gains and robustness properties across different regions of the parameter space. Extensive Monte Carlo simulations are conducted to support the asymptotic findings and to evaluate finite-sample performance under varying signal strengths and degrees of model misspecification.

Real data applications further illustrate the practical relevance of the methodology. Comparisons with standard penalized estimators and selected machine learning–based approaches demonstrate that the proposed strategies consistently achieve superior or comparable predictive performance. Importantly, they remain stable even when the commonly adopted sparsity assumption is substantially violated, offering strong evidence of robustness and practical reliability in complex modeling environments. This is a key note talk, I will be given.

sciforum-173400: Rolling Bearing Fault Classification Approach Combining Slope Entropy and Downsampling Schemes

Vicent Moltó-Gallego, David Cuesta-Frau

Department of System Informatics and Computers, Universitat Politècnica de València, Campus d'Alcoi, 03801 Alcoy, Spain

Measuring entropy enables the extraction of meaningful information regarding the complexity and evolving dynamics of temporal datasets, and it is often employed as a single feature in classification tasks. Rolling bearing fault detection is crucial for preventive maintenance in industrial environments. In this work, we propose the combination of downsampling and entropy-based features for bearing fault classification. Specifically, we use Slope Entropy (SlpEn), a slope-based entropy measure, and Permutation Entropy (PE), a classical entropy approach. Two downsampling strategies are evaluated: uniform downsampling (UDS) and non-uniform downsampling through Trace Segmentation (TS), which discards low-variability regions. Downsampling is applied prior to entropy computation to reduce computational cost. Experiments are conducted on the publicly available IMS bearing dataset provided by the University of Cincinnati and distributed through NASA, which includes outer race, inner race, and rolling element defects. Classification performance is assessed using ROC-based accuracy metrics. Results show that downsampling up to 60–70% of the original samples yields an approximate ×1.35 computational speedup, representing an effective trade-off between efficiency and accuracy. Compared to baseline approaches without downsampling (i.e., PE and SlpEn computed on full signals), inner race detection improves by up to 9% for PE (reaching 85% accuracy) and 3% for SlpEn (84%). For outer race and rolling element faults, accuracy losses remain below 6%, while maintaining performance above 91% and preserving the computational gain. Although the proposed framework shows robustness across entropy measures and sampling strategies, its performance may degrade under high noise levels or in the presence of incipient faults, where fault signatures are weak and subtle dynamic changes can be partially suppressed by data reduction. Therefore, while effective for established defects, further validation under early-stage degradation scenarios is required to fully assess its suitability for predictive maintenance applications.

sciforum-175433: The decay equation: A generalization from nonextensive statistics and k-statistics based on the *q*-calculus

José Juan Peña [1], J Morales [1], Gerardo Ovando [1], J García-Ravelo [2], J García-Martínez [3]

[1] Autonomous Metropolitan University, Azcapotzalco Campus, Av. San Pablo 420, col Nueva el Rosario Azc CP 02128 CDMX, México
[2] National Polytechnic Institute, ESFM, Graduate Section, UP Adolfo López Mateos, Build 9, Zacatenco, México city, CP 07738, México
[3] Technological Institute of Higher Studies of Ixtapaluca, Biomedical Engineering Division, Ixtapaluca-Coatepec highway s/n San Juan, Coatepec District, Ixtapaluca, State of México C.P.56580, México

In this work, we propose a kind of generalization for the q-deformed calculus which consists in the deformation of the ordinary differential operator d/dx by means of a scaling operation through a parametric function f(q;x) applied to said operator in the form f(q;x)d/dx , giving rise to what could be called the q-deformed calculus (q-calculus). Based on this proposal, it is possible to construct a q-deformed arithmetic (also called q-algebra) as well as a kind of q-deformed (generalized) functions $F_q(x)=F(x_q(x))$, where F(x) is any differentiable function and $x_q(x)$ is a transformation that involves the parametric function f(q;x). Particularly, for each specific scaling function, a generalization of the q-exponential function $Exp_q(x)$ and the q-logarithmic function $Ln_q(x)$ are deduced as well as their corresponding q-algebras. In this scenario, the q-calculus is applied to the decay equation, thus generalizing the results of cases for physical phenomenal such as Newton's cooling law, radioactive half-live, simple population decay, the discharge of a capacitor, and the rate law for certain first-order molecular reactions among others. As particular cases, to exemplify the usefulness of the proposal, two different scaling functions are used to solve the case of Newton's cooling law in the context of Tsallis nonextensive statistics (q-statistics) and Kaniadakis statistical mechanics (κ-statistics). The results obtained match those already proposed in the literature. In addition, by using the *q*-deformed algebra, particularly the *q*-subtraction in the usual derivative given as a limiting of instantaneous rate of change, it is possible to generalize the results obtained before. By virtue of the generality of the method, other scaling functions can be proposed that could improve the results obtained with other statistical formalism and the involved q-calculus.

sciforum-175533: Transposing Econophysical Entropic Criteria to Scientific Time Series: An Framework for Volatility-Scaled Data Curation

Rytis Petrauskas, Renaldas Urniezius, Vytautas Galvanauskas, Karolis Mickevicius

Dept. of Automation, Faculty of Electrical and Electronics Engineering, Kaunas University of Technology, Kaunas, 51367, Lithuania

The exponential proliferation of high-frequency data acquisition across diverse scientific disciplines has exacerbated the challenge of identifying anomalous data segments. Traditional threshold-based filtering and linear frequency-domain techniques frequently fail to distinguish between stochastic signal variations, structural breaks, and genuine pathological anomalies. Drawing upon the methodology established in the analysis of financial market micro-structures specifically the interplay between entropic criteria and volatility scaling—this study introduces a cross-disciplinary framework for time series curation. In financial markets, volatility clustering and entropic phase transitions are robust indicators of regime shifts, systemic liquidity crises. By abstracting these econo-physical principles, we hypothesize an underlying mathematical isomorphism between financial non-stationarity and sensor-derived data corruption. This paper proposes an algorithmic approach that performs entropic analysis to map continuous time series. By applying unsupervised density-based classification algorithms to these isolated manifolds, the system will derive discrete, explainable "expert rules." These rules are tailored to the specific topological baseline of individual scientific datasets, thereby circumventing the opacity of conventional deep learning approaches. Validation across simulated and real-world physiological and environmental sensor networks demonstrates the framework's efficacy in isolating structural device caveats from intrinsic signal storms, advancing the reliability of downstream predictive modeling in complex, non-stationary environments which do not have expert rules explictly defined, but instead to be explored.

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

Entropy2026 Organizing Team
E-mail: entropy2026@mdpi.com
https://sciforum.net/event/entropy2026


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