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DEPARTMENT OF PHYSICS

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The AI revolution... worth a Nobel prize in physics (?)

This year's Nobel prize in Physics was unique... and quite surprising for several reasons

Last October 8, Professor Hans Ellegren, Secretary General of the Royal Swedish Academy of Sciences, announced the names of the winners of the Nobel Prize in Physics corresponding to the year 2024. As announced, 'the Nobel this year it's about machines that learn'. The lucky ones were professors John J.Hopfield, of Princeton University, and Geoffrey E. Hinton, of the University of Toronto, 'for the fundamental discoveries and innovations that enable machine learning with artificial neural networks'.

> John J. Hopfield
>> Geoffrey E. Hinton

This announcement was quite surprising for several reasons. One of them is that Hinton is the first scientist to get a Nobel prize in physics, having previously been awarded with the Turing prize in 2018, the equivalent of the Nobel but for computer science. And this year's Nobel is unique. It is obvious the impact that the popularly called Artificial Intelligences have today, mostly based on the use of neural networks, an example of which is the omnipotent ChatGPT. But this is the result of the evolution of a field born in the middle of the last century, when the theoretical foundations of the neural networks theory, which form the core of most current generative models, were, established.

This year's two awardees made fundamental contributions in this area, even though none of them participated in developing the actual concept of an artificial neural network. This dates back to 1943 when McCulloch & Pitts proposed in the Bulletin of Mathematical Biophysics the first simple model of an artificial neuron, followed by the introduction by Frank Rossemblatt in the

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journal Psychological Review of the simple Perceptron as a probabilistic model for Information storage and organization, capable of adjusting its parameters or learning, based on the data supplied.

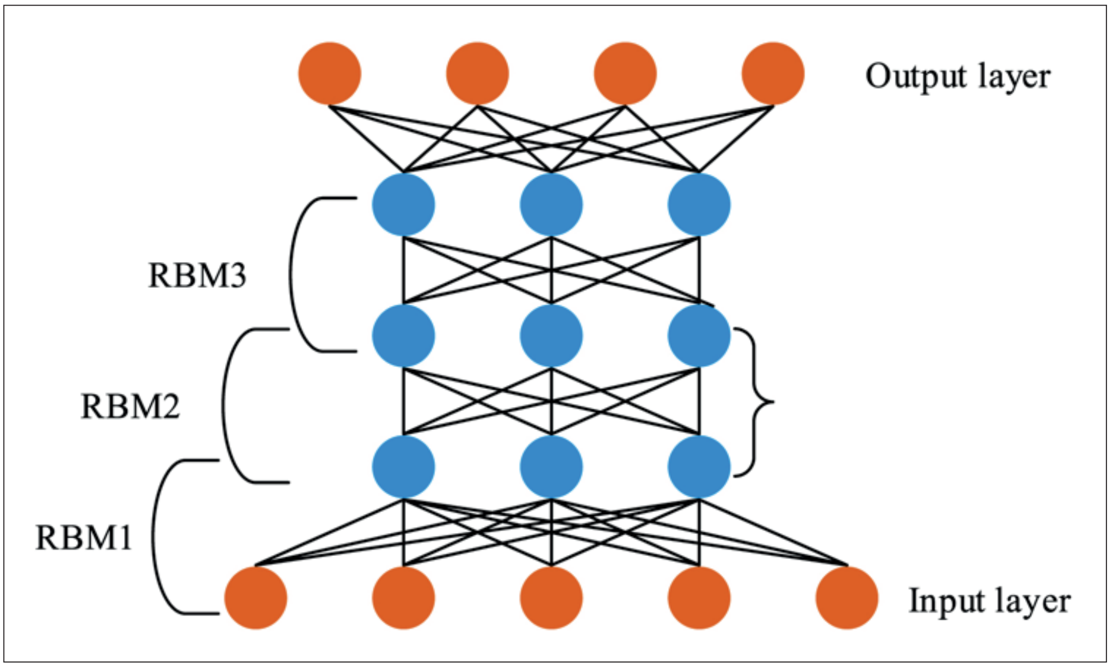
Professor Hopfield, however, made a fundamental contribution to the field, from a physics perspective. He was the first to properly formalize the concept of associative memory formulated from an energy function point of view in a by now famous manuscript published in the Proceedings of the National Academy of Science in the USA in 1982 entitled "Neural Networks and Physical Systems with Emergent Collective Computational Abilities". In his model, the states that the network stores and returns correspond to its local minima, which become attractors of the network dynamics. This opened a door to the study of the field that other scientists, such as Shun'ichi Amari or Daniel J. Amit, properly extended.

Ferran Mazzanti is an associate professor of the CCQM research groups, working both in Quantum Many-Body physics and Machine Learning problems. His main research activities include the study of Bose-Einstein condensates at low temperatures, and on the analysis of the structural properties of Restricted Boltzmann machines.

On the other hand, Geoffrey Hinton's contributions to the field are abundant (hence the multiple condecorations). He was one of the creators of the Boltzmann Machine networks in 1985, together with D. Ackley and G.E. Sejnowski. A Boltzmann Machine network is a successful generative model that learns the joint probability distribution of the given data and is able to generate new examples following the same distribution. Different versions of these models exist, some of them with a very easy-to-train version, as the Restricted Boltzmann Machine. For reference, the latter forms the basis of the so-called Deep Belief Networks of 2006, the first successful deep network model with many intermediate layers that could be efficiently trained to handle a huge amount of data. A schematic of this network is shown below. They could be efficiently trained to handle huge amounts of data. Remarkably, these networks were also designed by Professor Hinton, together with Simon Osindero and Yee-Whye Teh. And they also published in 2006 a fast and efficient training algorithm for them in the Neural Computation journal.

And where has all this led today? Well, it turns out that the plasticity of neural networks to process large amounts of data is so great that the field has experienced an explosion of models and topologies. In case anybody is interested, just take a look at *https://www.asimovinstitute.org/neural-network-zoo/*. The future of these tools in science and in our lives is undeniable.

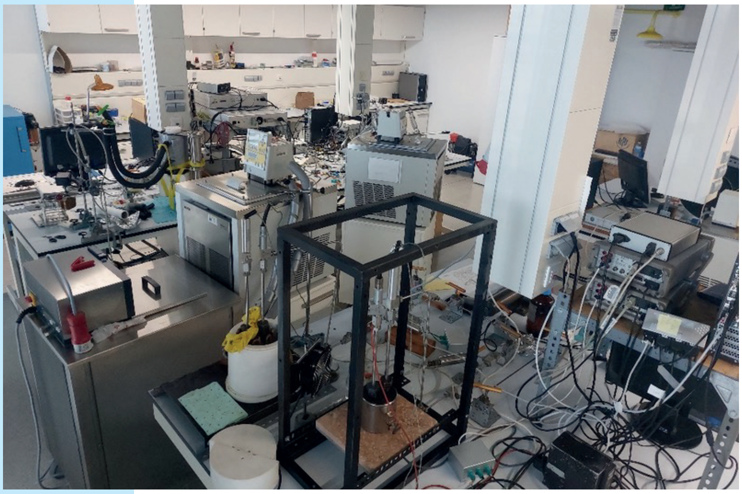
A final thought: do you like music? Google or duckduckgo the word SUNO. It's fun. □



European Project about the first steps towards sustainable refrigeration

> European Consortium involving institutions from France, Slovenia, United Kingdom, and Spain, has been awarded a 3.4M euros EU grant for the next 4 years to develop a new all-solid refrigeration technology based on the energy exchanged during spin transitions driven by pressure: the FROSTBIT project.

In 2019, refrigeration systems worldwide emitted as much greenhouse gas as the European Union.



This impact is largely due to the frequent leaks of refrigerant fluids, which represent, for example, 30% per year of the fluids consumed by the cold storage rooms of a supermarket.

The project FROTSBIT aims to develop an all-solid system based on spin transition material, and it is funded by the European Innovation Council (EIC). FROSTBIT has a budget of 4 million euros for a four-year duration. FROSTBIT brings together various European research groups, combining expertise ranging from the synthesis of materials using green chemistry processes to the characterization of the barocaloric properties of the resulting materials. In particular, **the Group of Characterization of Materials at the Department of Physics of the UPC** will perform the characterization of the thermal response of the materials to pressure changes, both in powder and ceramic form. ☐

The Research Center for Multiscale Science and Engineering (CCEM) celebrates obtaining the accreditation of María de Maeztu Unit of Excellence

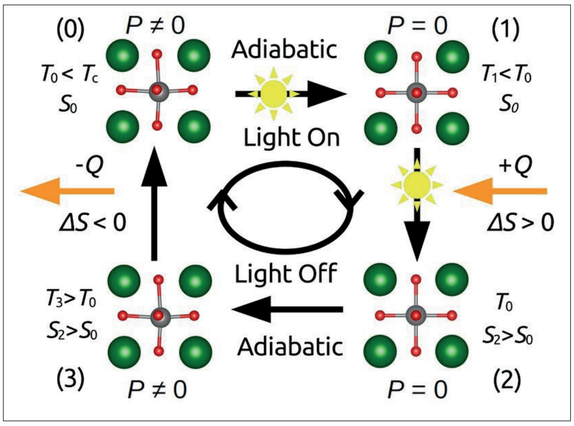
> The Research Center for Multiscale Science and Engineering (CCEM) directed by Professor Josep Lluís Tamarit from the Department of Physics organized the meeting that brought together a large part of the scientific community of the Diagonal-Besòs Campus.

On November 14, the Assembly Hall of the Diagonal-Besòs Campus was filled to celebrate a shared success: obtaining the María de Maeztu Unit of Excellence accreditation, granted by the Ministry of Science, Innovation and Universities in the 2023 call. The CCEM has thus become one of the seven research centers that have received accreditation in this call, thus becoming part of a prestigious group of 66 centers and research units that lead the best science, at a national and international level.

The CCEM promotes cutting-edge research in materials science, in the field of micro and nanoengineering, nanotechnology, and nanoscience, and constitutes a multidisciplinary hub formed by eight research groups. ☐

Harnessing Light for Next-Generation Solid-State Cooling Technologies

> Solid-state cooling has the potential to provide a more energy-efficient and environmentally friendly solution compared to traditional refrigeration, which typically depends on thermodynamic cycles using greenhouse gases. However, existing solid-state cooling technologies, which rely on caloric effects (changes in temperature under external fields), face significant challenges that limit their practical use in everyday refrigeration devices. One major obstacle is that the temperature conditions for operation need to be very close to specific phase-transition points. Unfortunately, these phase transitions rarely happen near room temperature.



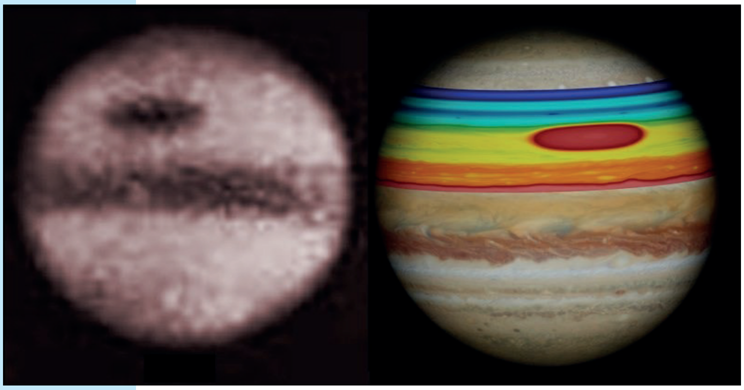
Researchers from the Physics Department of the UPC under the supervision of Dr. Claudio Cazorla presented theoretical evidence for the existence of giant photocaloric effects induced by light absorption. They used advanced simulation techniques to explore an alternative approach: using light to drive phase transitions in specific materials known as polar oxide perovskites. These materials have unique properties that allow them to undergo phase transitions when exposed to light. Material experiences significant temperature changes when exposed to light, across a broad temperature range that includes room temperature. These results suggest that light-driven phase transitions could provide a more flexible and effective way to achieve solid-state cooling across a wide temperature range. □

Reference:
Rurali, Riccardo, et al. Giant photocaloric effects across a vast temperature range in ferroelectric perovskites. *Physical Review Letters*, 133 (11) 116401, 2024.

The age of Jupiter's Great Red Spot is determined

> Researchers from the Physics Department of the UPC have analyzed historical observations from the 17th century of Jupiter's Great Red Spot in collaboration with the Barcelona Supercomputing Center (BSC) and the University of the Basque Country (UPV/EHU)

Jupiter's Great Red Spot is a huge anticyclonic eddy around the periphery when winds are blowing at 450 km/hr. It is the largest and longest-lived vortex of all existing in the atmospheres of the planets of the solar system, but its age is the subject of debate and the mechanism that gave rise to its formation remains hidden.



In order to find out how this immense whirlpool was formed, the researchers have carried out numerical simulations on the MareNostrum of the BSC-CNS. They have explored different mechanisms to explain the genesis of the spot, including the eruption of a gigantic superstorm, or the merging of multiple smaller vortices generated by wind shear. The results indicate that, although in both cases an anticyclone forms, it differs in shape and dynamic properties from those of the current GRS.

In a third group of numerical experiments, the team of scientists has explored the generation of the spot from a known instability in the winds that is able to generate an elongated cell that closes and traps them. This cell would be a nascent Red Spot, the subsequent shrinking of which would give rise to the compact and rapidly rotating spot seen today. □

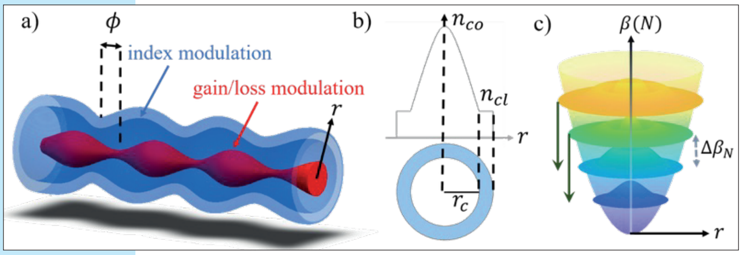
Reference:
Sánchez-Lavega, A., García-Melendo, E., Legarreta, J., Miró, A., Soria, M., & Ahrens-Velásquez, K. (2024). The origin of Jupiter's Great Red Spot. Geophysical Research Letters, 51, e2024GL108993.

Thesis 1

Non-Hermitian mode management in optical fibers and waveguides

> Mohammad Nayeem Akhter defended his thesis co-supervised by Kestutis Staliunas and Muriel Botey on December 20, 2024 at Campus Terrassa. Entitled "Non-Hermitian mode management in optical fibers and waveguides", the thesis presents a novel approach to tailor optical beam transformations in graded-index multimode fibers through non-Hermitian mode management.

Recently, MultiMode Fibers (MMFs) have gained a resurgence of interest due to their demand in optical communications, high-power lasers, and dynamic fields of optical sensing and imaging. MMFs exhibit rich and complex spatiotemporal phenomena, and one of their main drawbacks is the poor quality of the propagated beam. Any beam injected in such fibers spontaneously evolves toward a multimode configuration generating speckle formation at the output. This randomness results from the different values of propagation constants of the fiber modes causing random mode phase shifts during propagation. Generally, conventional methods do not efficiently reduce turbulence, since they generally broaden the angular spectra. This thesis uncovers a novel approach to tailoring optical beam transformations in GRaded INdex MultiMode Fibers through non-Hermitian mode management.



More specifically, the authors present a potentially transformative approach that enables effective mode-cleaning while reducing turbulence. The proposal is based on the introduction of a periodic non-Hermitian modulation, by simultaneously engineering the refractive index and the gain/loss coefficient along the fibers or waveguides, allowing a precise control of the mode coupling. This scheme leads to mode-cleaning in linear and active nonlinear fibers, as a main potential application. ☐

Thesis 2

Study of the coherence of a semiconductor laser with feedback

> Maria Duque defended her thesis co-directed by Cristina Masoller and Jordi Tiana on December 5 at the Terrassa Campus. Entitled "Experimental study of the coherence of the light emitted by a semiconductor laser with optical feedback", the thesis studies the appearance and evolution of coherence during laser start-up in different optical feedback scenarios. In addition, the impact of sinusoidal modulation in the injection current on the coherence of lasers is investigated and includes a chapter on the impact of optical injection.

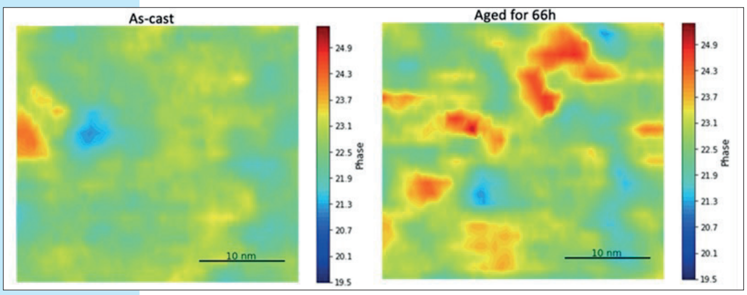
Semiconductor lasers are present in many areas of our daily lives due to their compact size, efficiency, and versatility. We find applications in telecommunications, sensors, metrology, and biomedicine. This thesis investigates the impact of optical feedback on the temporal and spatial coherence of semiconductor lasers using a technique based on random intensity patterns, i.e., speckle.and spatial coherence of semiconductor lasers using a technique based on random intensity patterns, i. e., speckle. ☐

Thesis 3

Study of the evolution of the structural dynamics during the physical aging process in a vitreous alloy

> The candidate Mehran Nabahat defended his thesis, directed by Eloi Pineda, on October 10, 2024 at the Diagonal Besòs Campus. Entitled "Dynamic Heterogeneity in Metallic Glasses: Study of Structural Relaxation, Aging, and Mechanical Properties of Vit4 alloy", the thesis presents a study of the evolution of the structural dynamics of an alloy in the vitreous state.

Metallic glasses (MGs), distinguished by their unique microstructural features and exceptional mechanical properties, offer compelling materials for exploring relaxation dynamics and related phenomena within glass science. This doctoral thesis provides an in-depth examination of the dynamic and structural heterogeneity of a glass-forming alloy, investigating the intricate relationships between its structural dynamics, thermal behavior, and mechanical properties. It has characterized how the viscoelastic behavior of these materials evolves by performing tests at high temperatures.



The observations have made it possible to determine that the spectrum of relaxation processes becomes wider as the material approaches states increasingly close to equilibrium, and, on the other hand, at lower temperatures the aging process becomes controlled by a secondary relaxation process. This study will allow a better control of the properties of metallic glasses through thermal treatments. ☐

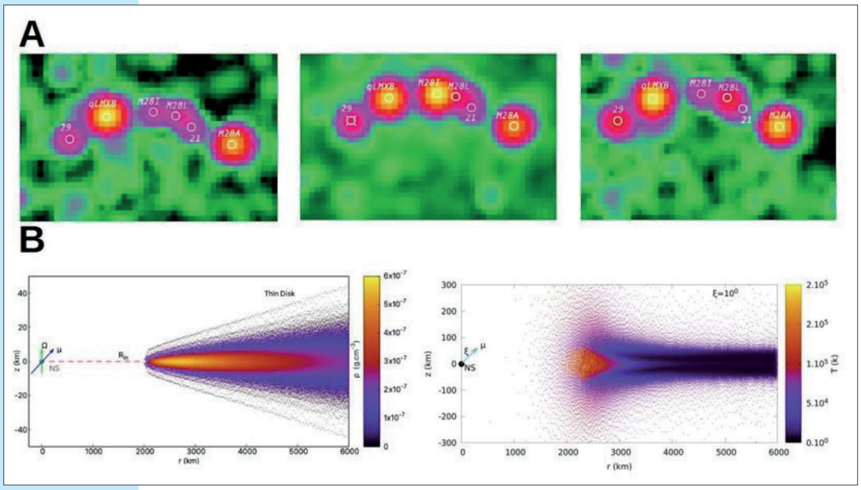
Thesis 4

Disks around ultra-fast spinning millisecond pulsars: from observations to numerical simulations

> Eda Vurgun defended her doctoral thesis entitled “Compact binary millisecond pulsars: X-ray observations and numerical simulations” on November 7, 2024 at the Besòs Campus. The thesis has been co-directed by Domingo García Senz and Manuel Linares Alegret

Millisecond pulsars (MSPs) represent a fascinating and crucial subset of rotation-powered pulsars (RPPs). They are distinguished by their exceptionally rapid rotation periods and powerful magnetic fields. These rapidly spinning neutron stars are believed to form through a process in which mass transfer from a companion star in a binary system causes the neutron star to accelerate, or “spin up” to millisecond periods. This “recycling” process not only rejuvenates the pulsar but also sheds light on the complex mechanisms of stellar evolution.

This thesis comprises two parts. The first part explores a population of neutron stars using X-ray observational data. Globular clusters (GCs) are known to be extremely efficient at forming MSPs and low-mass X-ray binaries (LMXBs), due to their high stellar densities. In the second part of the thesis, we study the interaction of the magnetic field of the neutron star with the nearby accretion disk, carrying out detailed magneto-hydrodynamics (MHD) simulations that incorporate realistic disk structures into the numerical simulations. Our findings showed that aligned rotators maintained stability for completing multiple orbits, while higher inclination angles led to instability at the disk. ❑



Thesis 5

Contributions to Eco-Friendly Satellite Lean Design for a Sustainable Space Environment

> Jeimmy Nataly Buitrago Leiva defended on September 16 her thesis co-directed by José Adriano Camps Carmona at the North Campus of the UPC. Entitled “Contributions to Eco-Friendly Satellite Lean Design for a Sustainable Space Environment”, the thesis presents research that proposes an eco-friendly satellite design and operational approach focused on the integration of space sustainability strategies.

Currently, half of the satellites do not reach 20% of their expected lifetime. The possibility of recycling these “zombie satellites” (ZS) with limited capabilities would lead to an optimization of this on-orbit infrastructure, reducing unnecessary launches, and being more cost-effective. In this way, it will not be necessary to launch some new satellites for these new missions, with the corresponding positive environmental and economic impact. Based on the ZS concept, this research proposed an eco-friendly satellite design and exploitation approach.

For a complete analysis of the whole satellite life process, it is necessary to integrate eco-friendly and lean manufacturing characteristics. As a result, this concept is defined to bring together the numerous efforts for a sustainable space and considers the innovative technologies to be created for this kind of standard satellites. ❑

Thesis 6

Aircraft Trajectory Estimation and Guidance Mode Identification using Bayesian Filtering Techniques

> Homeyra Khaledian defended her thesis, co-supervised by Prof. Xavier Prats and Prof. Jordi Vilà Valls, on September 19, 2024, at the Baix Llobregat Campus in Castelldefels. Entitled “Aircraft Trajectory Estimation and Guidance Mode Identification using Bayesian Filtering Techniques”, the thesis focuses on real-time aircraft trajectory estimation and real-time guidance mode identification, which are needed for achieving accurate aircraft trajectory prediction. The main objective was to characterize the estimation and guidance mode identification problem and enhance existing filtering methodologies using Bayesian techniques that rely on multiple-model approaches. The work proposes an optimal Interacting Multiple Model approach that uses Kalman filter-based methods, particularly the Extended Kalman Filter to manage the nonlinear dynamics predominant in vertical trajectory profiles. Results show that the maximum percentage error in aircraft mass estimation is minimal, and other state variables are also accurately estimated with low delays in tracking hybrid jumps and identifying guidance modes. ❑

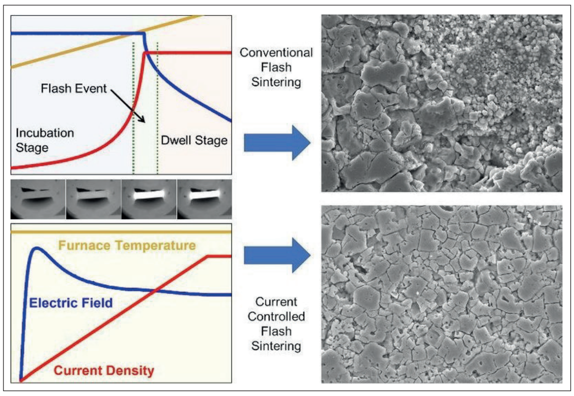
Thesis 7

Current-controlled flash sintering for ultra-fine control of the microstructure of lead-free ferroelectric perovskites

> Samuel López Blanco defended his thesis on July 3rd on the Campus Nord. Co-advised by Jose Eduardo García and Diego Alejandro Ochoa, the thesis focuses on using current-controlled flash sintering to achieve high-density, microstructure-tailored, lead-free ferroelectric perovskite oxide ceramics with enhanced functional response.

Mass production of ferroelectric polycrystalline materials with varied and exceptional functional properties has allowed the design of an extensive set of electronic devices capable of satisfying a wide demand in many industrial sectors and public consumption. However, the conventional sintering route is currently facing global restrictions due to its high energy consumption and environmental impact.

In this thesis, a comprehensive study of how the flash sintering parameters affect both the microstructure and functional properties of dense ferroelectric perovskite oxides was presented. Authors propose a novel approach that opens a new sintering path that is environmentally friendly, low-cost, energy-efficient, and yields extensive control over the obtained samples. □

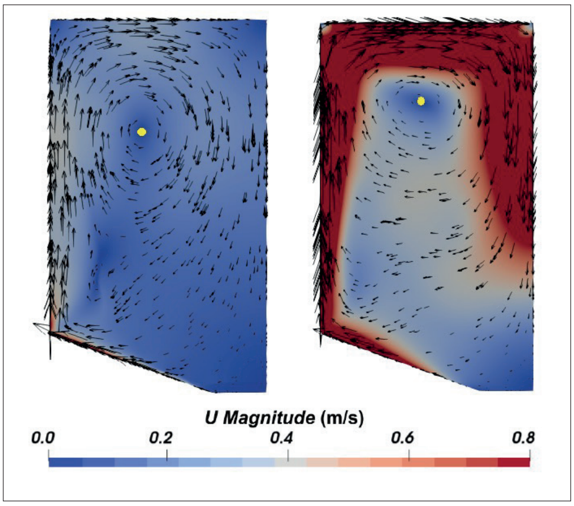


Thesis 8

Numerical Analysis of Thermally-Driven Winds in Mountain-Valley Regions

> The student Rathan B. Athota defended his thesis co-supervised by Adeline de Villardi de Montlaur and José I. Rojas Gregorio on September 19 at Campus Nord. The thesis, entitled "Numerical analysis of thermally-driven winds in mountain-valley regions", presents a numerical study of the formation of thermally-driven winds on slopes of mountain-valley systems using the open-source computational fluid dynamics software OpenFOAM. Thermal-driven winds occur in mountain-valley regions due to temperature gradients induced by the lower atmosphere's diurnal heating-cooling cycle. The contemporary energy market is particularly interested in thermal-driven winds since they exhibit greater regularity and periodicity than synoptic winds and thus can be more predictable.

A wide range of numerical simulations allows authors to investigate the influence of various wall functions on modeling thermally driven flows. To sum up, it is concluded that models can replicate the challenging atmospheric boundary layer flows with sufficient accuracy, which can help in determining the most suitable wind turbines for specific sites in mountainous regions. □



Thesis 9

Ground and Marine Resilient Integration Technology of Multi-Source Sensors for Navigation and Positioning

> Mowen Li defended his thesis co-supervised by Dr. Adria Rovira Garcia and Prof. Dr. Tianhe Xu on July 31st 2024 at Shandong University, Weihai, China. Entitled "Ground and Marine Resilient Integration Technology of Multi-Source Sensors for Navigation and Positioning", the thesis presents the resilient integration technology for the ground, marine and seamless Navigation and Positioning. Based on the integrated observations, this thesis proposes a recognition algorithm for the overwater and underwater scene which achieves scene recognition by analyzing the Global Navigation Satellite System observable satellite number, the depth and salinity measured by the Conductivity/Temperature/Depth profile, and Long Baseline sonar observable signal number. Experimental results show that the proposed resilient integration technology improves the positioning performance in all the scenes from overwater to underwater.

The integration of the above-mentioned sensors can address the limitations and disadvantages of single sensor, and achieve the more continuous, stable and reliable navigation and positioning service for the user. One multi-source sensor integrated navigation and positioning software has been developed with C++ programming language, on the basis of this thesis. □

Studying the physics of disordered solid phases

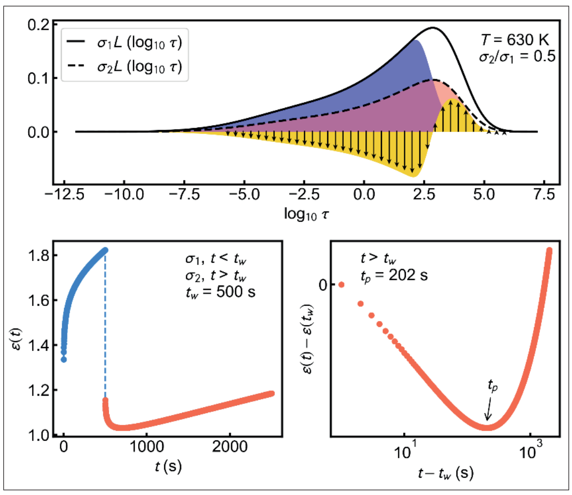
Eloi Pineda received the PhD in physics from Universitat Politècnica de Catalunya in 2002 and joined UPC as lector in 2004. He became agregat in 2008 and Full Professor in 2024. His research is focused on the study of the structure and dynamics of materials, the structural evolution of glasses and their response under mechanical stimuli. He is member of the Group of Characterization of Materials, the Institute of Energy Technologies and the Center for Research in Multiscale Science and Engineering. He is currently vice-chair for teaching in the Physics Department.

> The search for new materials with better properties is one of the main factors driving the progress of human technology. The history of humankind has been determined by the knowledge of how to synthesize and process different types of materials. The stone, bronze, and iron ages are historical periods named owing to the dominion of humans over specific materials, ancient empires, and civilizations are distinguished and classified by their ceramic and steel production methods and the recent advent of plastics, semiconductors, nanomaterials and other new materials has drastically changed our daily lives in the last 100 years. Contemporary materials science is an extremely broad and active field, which joins the efforts of physicists, chemists and engineers for developing new materials to face the most important challenges of our society.

At the molecular level, solid materials can be found either in an ordered state, with long range translational order and crystalline symmetry, or in disordered phases. The Group of Characterization of Materials, based in the Campus Diagonal Besòs, is specialized in the study of disordered phases and order-disorder phase transitions. Our group combines experimental and simulation techniques to understand the behavior of such materials and to characterize and develop new materials for health, energy and environmental uses. Among the different types of systems studied, my scientific research is mainly focused on the so-called metallic glasses or amorphous alloys.

Many solid materials are found in the glass state. Although they are solids, they show a disordered, liquid-like structure at the molecular level. Common examples of glassy materials are the window and optical glasses, based on silicates and other oxides, as well as many synthetic or natural polymeric materials based on macromolecules. They all show a continuous transition from liquid to glass upon cooling, without any structural transformation, which is one of the distinctive properties of these materials and provides the possibility of thermoplastic forming. While crystalline and liquid phases are in a thermodynamically stable or metastable states, glasses are in an out-of-equilibrium configuration. The stability of glasses over time and their solid-like appearance is only because of an extremely slow molecular mobility at room temperature, which results in almost 'frozen' structural dynamics. Some of the hallmarks of glasses are their viscoelastic behavior, inherited from the liquid state, their broad and complex spectrum of structural relaxation modes, the presence of a continuous and ample range of possible glass configurations and their spontaneous, slow structural changes known as physical aging. All these features make them fascinating materials, with a large potential to tune their physical and chemical properties by modifying their glass configuration and posing enormous challenges to understand and control their stability and time evolution.

> Materials laboratory of the Campus Diagonal Besòs.



> The broad relaxation spectrum of glasses keeps the memory of previously excited states over long timescales.

Among the different glass-forming systems, the discovery of metallic glasses revolutionized the field of physical metallurgy 50 years ago, as it was previously assumed that metallic materials could only be found in crystalline states. In our research group, we apply the unique physical and chemical properties of these metallic, disordered phases to develop new catalysts for green energy applications and to explore their properties as biomaterials for medical uses. However, our main interest is in understanding their fascinating structural dynamics, that shares the principal traits with the other glassy substances and poses a major unsolved problem in condensed matter physics. □