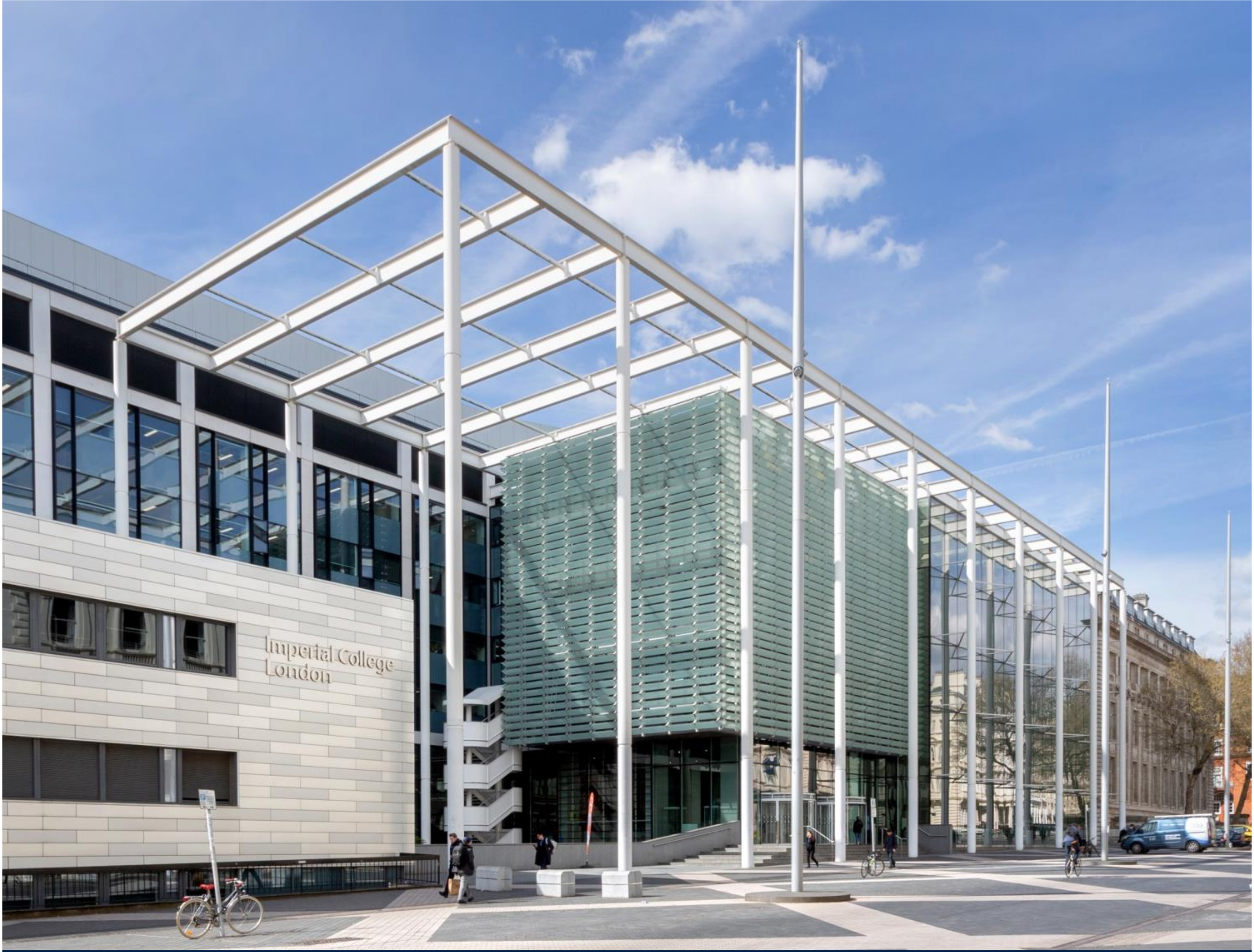

Workshop on the Mathematics of Metamaterials with Extra Dimensions

April 2-4, 2025
Imperial College London, London, UK

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About

The aim of the workshop is to gather all together the scientific community working on metamaterials with extra dimensions, considering both quasicrystalline media and space-time modulated media.

This is the fourth event in a series of meetings that started lift as the *Arctic Quasiperiodic Workshop*, which was held for the first time in Luleå, Sweden in 2022 (AQW website). In this year's edition, the scope has been expanded to include the exiting topic of space-time metamaterials.

Workshop on the Mathematics of Metamaterials with Extra Dimensions

Organizers

Marc Martí Sabaté   Bryn Davies   Elena Cherkaev   Niklas Wellander   Sébastien Guenneau

Timetable

Wednesday, 2nd of April

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11:15–11:45	**Yang Hao** Queen Mary University of London	Time-Modulated Matters: Combining Atomic Doping and Metamaterials Design for Future Electronics
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15:00–15:30	**Lorenzo Morini** Università di Cagliari	Hofstadter butterflies in phononic structures: Commensurate spectra, wave localisation and metal-insulator transitions
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Thursday, 3rd of April

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9:30–10:00	**Antonio Palermo** Università di Bologna	A theoretical framework to model the scattering of elastic longitudinal waves at time interfaces
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10:45–11:15	**Maryna Kachanovska** POEMS, INRIA - CNRS	Wave propagation in materials with smooth sign-changing coefficient
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11:45–12:15	**Eric Stachura** Kennesaw State University	The Drude-Born-Fedorov system on anisotropic fractals
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12:45–14:00	**Lunch**	
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14:30–15:00	**Paulo Piva** University of Sheffield	Band Gaps from Randomly Distributed Resonators
15:00–15:30	**Mario Lázaro Navarro** Universitat Politècnica de València	Mathematical conditions for the weak-scattering assumption in flexural waves on thin elastic plates with point-like resonators
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15:45–16:15	**Martin Wegener** Karlsruher Institut für Technologie	Metamaterials with extra twists
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14:00–14:30	**Ying Wu** King Abdullah University of Science and Technology	Spacetime modulation of flexural-gravity waves in floating thin elastic plates
14:30–15:00	**T. V. Raziman** Imperial College London	Surface plasmons in time-varying media
15:00–15:15	**Coffee break**	
15:15–15:45	**Bryn Davies** University of Warwick	Graded quasiperiodic metamaterials for fractal rainbow trapping
15:45–16:15	**Simon Becker** ETH Zurich	Fragile topology and the Thouless conjecture
16:15–16:45	**Richard Wiltshaw** Imperial College London	Quasinormal mode expansion in thin elastic plates

Wednesday, 2nd of April

Opening lecture: Light propagation in time-varying media

Sir John B. Pendry, Imperial College London.

Recent experiments demonstrate ultra-fast modulation of refractive indices opening up the field of space-time modulation. Breaking time invariance presents new challenges to theory with the removal of conservation of energy/frequency. New conservation laws are emerging which deepen our understanding of these systems. A recent review can be found here. Typically space -time structures involve no physical movement of material meaning that movement at any speed can happen without violating causality. This removes many theoretical obstacles to theoretical treatment. Many new phenomena are being found such as novel amplification mechanisms that work by squeezing lines of force together. Some systems can be regarded as reversible heat engines capable of heating or cooling radiation incident upon them. Quantum aspects of 4D systems are rich field of study particularly for systems in uniform motion which obey PT symmetry and therefore have some elements in common with traditional QED but with the difference that frequency is not conserved. In particular transitions between positive and negative frequencies can be induced and are associated with spontaneous emission of radiation as photon pairs. By analogy between a refractive index and gravitational metrics, systems have been found which model the Schwarzschild singularity and emit Hawking-like radiation. Other systems that make travelling-wave modulations of a medium's impedance but leave the speed of light a constant, are analogous to the interaction of gravitational waves with electromagnetic fields.

Wave propagation across a time-modulated imperfect interface

Bruno Lombard, LMA-CNRS.

Time modulation of the properties of a propagation medium offers interesting possibilities for wave control, without resorting to non-linear mechanisms. Examples include parametric amplification, harmonic generation and non-reciprocity. As time modulation of volume properties is difficult to achieve experimentally, we focus here on the special case of time-varying jump conditions, for which experimental results have recently been proposed. Diffracted wave properties (energy evolution, harmonics) are studied. A numerical method is developed to simulate transient effects in fine detail. Numerical experiments are proposed to validate the method and illustrate the expected theoretical results.

Symmetry and topology in networks of acoustic waveguides

Vincent Pagneux, LAUM - CNRS

In this work, networks of slender acoustic waveguides exhibiting different symmetries (mirror, chiral or hidden) are examined. In these systems, it is shown how eigenfrequencies [1-4] or scattering properties [5] follow interesting broadband properties inherited from the symmetries and associated topological aspects.

[1] A. Coutant, V. Achilleos, O. Richoux, G. Theocharis & V. Pagneux, Robustness of topological corner modes against disorder with application to acoustic networks. Physical Review B, 102(21), 214204 (2020)

[2] A. Coutant, A. Sivadon, L. Zheng, V. Achilleos, O. Richoux, G. Theocharis & V.Pagneux, "Acoustic Su-Schrieffer-Heeger lattice: A direct mapping of acoustic waveguide to Su-Schrieffer-Heeger model," Phys. Rev. B 103, 224309 (2021)

[3] A. Coutant, V. Achilleos, O. Richoux, G. Theocharis & V. Pagneux, Subwavelength Su-Schrieffer-Heeger topological modes in acoustic waveguides. The Journal of the Acoustical Society of America, 151(6), 3626-3632 (2022)

[4] M. Röntgen, X. Chen, W. Gao, M. Pyzh, P. Schmelcher, V. Pagneux, V. Achilleos & A. Coutant, Topological states protected by hidden symmetry. Physical Review B, 110(3), 035106 (2024)

[5] A. Coutant, L.Y. Zheng, V. Achilleos, O. Richoux, G. Theocharis, & V. Pagneux, Topologically invisible defects in chiral mirror lattices. Advanced Physics Research, 2300102 (2024)

Time-Modulated Matters: Combining Atomic Doping and Metamaterials Design for Future Electronics

Yang Hao, Queen Mary University of London

Recent breakthroughs in time-modulated materials based on ferroelectrics, piezoelectrics, phase-change materials (PCMs), and metamaterials have enabled unprecedented control over electro-magnetic, acoustic, and quantum wave dynamics. By leveraging structural anisotropy and atomic doping, researchers have enhanced tunable polarisation, loss reduction, and broadband response, pushing beyond traditional material limitations. One emerging paradigm is meta-ferroelectrics, where artificial dipole moments, engineered through metamaterial structuring, mimic and even surpass conventional ferroelectric behaviours, achieving enhanced tunability for applications in nonlinear optics, RF circuits, and reconfigurable photonics. Similarly, doped ferroelectric and piezoelectric materials enable ultrafast, low-power switching for 6G adaptive antennas, and energy-efficient transistors. Meanwhile, hybrid PCMs with doped VO_2 now offer femtosecond-scale optical modulation, paving the way for ultrafast LiDAR and optical computing.

Despite these advancements, traditional trial-and-error materials discovery remains slow and resource-intensive. To accelerate the design of functional materials, our recent work integrates machine learning (ML)-driven material discovery with robotic-assisted lab automation, enabling autonomous synthesis, high-throughput characterisation, and AI-driven performance prediction. Our ML models leverage neural networks to predict material properties, optimise doping strategies, and design meta-atoms with minimal experimental iterations. In parallel, our robotic platforms automate material processing and testing, significantly reducing development cycles from months to weeks. By merging computational intelligence, robotics, and tunable material engineering, we establish a closed-loop, self-learning materials innovation framework. This convergence of AI, automation, and material science will drive the future of adaptive communication, computing, and quantum systems.

Modal approximations for plasmonic resonators in the time domain and application to super-localisation

Alice Vanel, Institut Fresnel - CNRS.

We present recent results on the spectral analysis of the singular integral operator associated with Maxwell's equation. The operator is neither compact nor self-adjoint in the general case. However, in the electrostatic case (zero frequency), it is possible to obtain a modal decomposition for the singular integral operator. We use Kato's perturbative spectral theory and recent results on the analysis of the Neumann-Poincaré operator to show that the decomposition remains valid outside the electrostatic case and how to treat the essential spectrum. We also show how these theoretical results can be applied to solve practical problems arising in nanophotonic imaging experiments.

Space-time metamaterials for light

Riccardo Sapienza, Imperial College London.

Metamaterials have revolutionised the way we control light transport and generation. Yet, to date, they rely on static and passive architectures, only redistributing incident wave energy - for example a metalens that focuses light or a cloak that makes an object invisible. The next frontier is to control metamaterials in space and time and make waves from the past and future to interact.

I will discuss our first steps towards temporal control and experiments on double-slit time diffraction at optical frequencies in time-varying metamaterials [1] and how we can extend the modulation of the linear refractive index to the modulation of the nonlinear response [2]. Intertwining space and time, I will discuss the observation of the temporal version of coherent perfect absorption [3] and scattering of light from optical modulations traveling faster than the speed of light [4] and how this will enable us to simulate more complex phenomena.

[1] Romain Tirole, Stefano Vezzoli, Emanuele Galiffi, Iain Robertson, Dries Maurice, Benjamin Tilmann, Stefan A Maier, John B Pendry, Riccardo Sapienza, Double-slit time diffraction at optical frequencies Nature Physics 19 (2023), 999.

[2] Romain Tirole, Stefano Vezzoli, Dhruv Saxena, Shu Yang, TV Raziman, Emanuele Galiffi, Stefan A Maier, John B Pendry, Riccardo Sapienza, Second harmonic generation at a time-varying interface, Nature Comm. s41467-024-51588-z (2024).

[3] Optical coherent perfect absorption and amplification in a time-varying medium Authors: Emanuele Galiffi, Anthony C. Harwood, Stefano Vezzoli, Romain Tirole, Andrea Alù, Riccardo Sapienza, arXiv:2410.16426 (2024).

[4] Super-luminal Synthetic Motion with a Space-Time Optical Metasurface A. C. Harwood, S. Vezzoli, T. V. Raziman, C. Hooper, R. Tirole, F. Wu, S. A. Maier, J. B. Pendry, S. A. R. Horsley, R. Sapienza, arXiv:2407.10809 (2024).

Wave propagation in random multi-scale media and quantitative ultrasound imaging

Laure Giovangigli, Poems, ENSTA

"Due to the technical progress in sensors manufacturing during the last decades and the access to now extensive computational resources, the research in ultrasound imaging focuses now on refining the reconstruction algorithm and the underlying mathematical model. In composite materials, the measured echoes come from nu- merous unresolved scatterers. In this work we first aim at providing a mathematical framework for wave propagation in such random multi-scale media. We derive a quantitative asymptotic expansion of the measured field with respect to the size of the scatterers using stochastic homogenization [2]. We also present numerical simulations to illustrate our results. Secondly we use this asymptotics of the scat- tered field to justify the estimators of the effective speed of sound inside complex media introduced by A. Aubry [1]. By analyzing the dependence of the imaging functional with respect to the backpropagation speed, we build an estimator of the sound speed in the random multi-scale medium. We then confront our results with numerical simulations and experimental results.

[1] F. Bureau, Multi-dimensional analysis of the reflection matrix for quantitative ultrasound imaging, theses, Université Paris sciences et lettres (2023).

[2] J. Garnier, L. Giovangigli, Q. Goepfert and P. Millien, Scattered wavefield in the stochastic homogenization regime, (2023)."

Quasiperiodic composites: homogenization and spectral properties

Elena Cherkaev, University of Utah.

From quasicrystalline alloys to twisted bilayer graphene, materials with a quasiperiodic structure exhibit unusual properties that drastically differ from those with periodic structures. A key feature of quasicrystalline microgeometry is a long-range order in the absence of periodicity. Quasiperiodic geometries can be modeled using the cut-and-projection method that restricts or projects a periodic function in a higher dimensional space to a lower dimensional subspace cut at an irrational projection angle. Homogenized equations for the effective behavior of a quasiperiodic composite can be derived by cutting and projecting a periodic function in a higher dimensional space. Using equations for the local problem in the higher dimensional space established in the homogenization process, we develop the Stieltjes analytic representation of the effective properties of quasiperiodic materials; this representation determines the spectral characteristics of fields in quasicrystalline composites and can be used to derive bounds for the effective properties. Numerical simulations using this representation show that slight changes in the parameters characterizing the quasiperiodic geometries (twist angle of moir'e structures) create a transition from order to disorder accompanied by band gaps, field localization, and mobility edges analogous to Anderson transitions. A joint work with Niklas Wellander and Sebastien Guenneau.

Hofstadter butterflies in 1D phononic structures: commensurate spectra, wave localization and metal-insulator transition

Lorenzo Morini, Università di Cagliari.

We propose a simple and easy-to-implement phononic system whose spectrum exactly corresponds to the Hofstadter butterfly detected in several studies concerning the dynamical properties of one-dimensional structured media [1]. The system consists of masses that are coupled by linear springs and are mounted on cantilever beams whose cross section (and, hence, stiffness) is modulated. We show that this system is the simplest version possible to achieve the Hofstadter butterfly exactly; in particular, we demonstrate that the local resonances due to the beams are an essential component for this achievement. We survey the various approaches to producing spectral butterflies, including Bloch spectra for rational parameter choices, resonances of finite-sized systems and transmission coefficients of sections of finite length. Numerical results show for finite-sized systems the transition from a banded to an unbanded spectrum where most of the states are grouped in very narrow sets such that it is difficult to define them as a band is governed by the amplitude of the beams stiffness modulation. We study the localization of the modes by calculating the inverse participation rate, and detect a phase transition characterized by a critical value of the stiffness modulation amplitude, where the state of the system changes from mainly extended to localized, similarly to a metal-insulator phase transition [2, 3]. The transmission coefficient for sections of finite length is benchmarked through the comparison with Bloch spectra of the same finite-sized systems. The obtained numerical results offer a practical strategy to realize experimentally a system with similar dynamical properties.

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[2] S. Y. Jitomirskaya, vol. 150, no. 3, pp. 1159–1175, 1999.

[3] J. R. M. Silva, M. S. Vasconcelos, D. H. A. L. Anselmo, and V. D. Mello, Journal of Physics: Condensed Matter, vol. 31, no. 50, p. 505405, 2019.

Time Varying Resonators in Acoustic Waveguides: A Transfer Matrix Formalism for Space-time Modulated Metamaterials

Gregory Chaplain, Exeter University

The transfer matrix method remains a simple yet powerful tool for modeling acoustic systems, particularly in a closed waveguide geometry. Here we present a generalisation of this method based on the theory of mode matching, that incorporates the effect of ultra–fast temporal variations in the geometry, applying it to a system of side-branching resonant cavities (quarter wavelength resonators) fixed to an acoustic waveguide, modulated through alteration of the cavity length. We calculate propagation in a waveguide containing single and multiple resonators, including a fully periodic array. In particular we predict the generation of additional Doppler-like terms in the reflected and transmitted fields that leads to modification of the band structure (in the periodic case) and introduces non-reciprocity in the finite case. Additionally, we compare our results to finite element simulations of space-time modulated acoustic crystals.

Effective medium theory for time-modulated subwavelength resonators

Liora Rueff, ETH Zurich.

In this talk I will present an effective medium theory for subwavelength resonator systems with a general form of time-dependent parameters. We show that the resonators can be accurately described by a point-scattering formulation when the width of the resonators is small. In contrast to the static setting, where this point interaction approximation yields a Lippmann-Schwinger equation for the effective material properties, the mode coupling in the time-modulated case instead yields an infinite linear system of Lippmann-Schwinger-type equations. The effective equations can equivalently be written as a system of integro-differential equations. Moreover, we introduce a numerical scheme to approximately solve the system of coupled equations and illustrate the validity of the effective equation.

Wave propagation in time-modulated media through the lens of homogenisation

Marie Touboul, POEMS-CNRS.

We focus here on the low-frequency homogenisation of space-time modulated materials. We first consider the case of travelling-wave modulations with in-phase modulations of the two parameters of the wave equation. As time modulation of volume properties is difficult to achieve experimentally, we then focus on the case of time-varying jump conditions. In both cases, effective models are proposed and their properties due to time modulations are analised (non-reciprocity, occurrence of k-gaps,. . .) and some numerical illustration and validation are proposed.

Thursday, 3rd of April

Locally Resonant Mosaic Plates

Ping Sheng, Professor Emeritus, HKUST and Associate of Clare Hall, Cambridge University.

Bandgaps constitute the central feature of photonic and phononic crystals. They enable a diverse range of novel phenomena and applications for electromagnetic and acoustic waves. However, the zero-frequency bandgap, defined here as the absence of wave states within a frequency range extending just above zero to a finite frequency, is generally regarded as not realizable for the Bragg mechanism since the lattice constants need to be very large to infinite. Moreover, for mechanisms other than Bragg scattering, a structure or material that displays a zero frequency gap would present a challenge to the theory of homogenization, which is predicated on the existence of low-frequency, long-wavelength excitations, for which the effective material parameters apply. A prior mathematical work [1]. has given an analytical solution of a solid plate with zero displacement boundary conditions on the periphery of periodically perforated holes. Such a configuration displays a zero-frequency bandgap which includes zero frequency; hence it would have no translational degrees of freedom and be difficult to transport. In this work, we utilize the finite-sized tiles, linked together at their corners, to create a mosaic plate system that can display static rigidity with translational degrees of freedom. Full waveform simulation results on the mosaic plate show a clear zero frequency bandgap, which are verified experimentally by laser vibrometer scanning of modes excited by a harmonic point source, as well as by comparison of sound transmission loss (TL) between the mosaic plate and a uniform plate with similar mass density. The latter comparison shows the mosaic plate to have a 13 dB advantage in TL at 50 Hz, and deviates from the mass density law over a broad low-frequency range.

References:

1. Poulton, C., Movchan, A., Movchan, N. & McPhedran, R. C. Analytic theory of defects in periodically structured elastic plates. Proceedings of the Royal Society A 468, 1196-1216 (2012).

Integral equation methods for time-modulated scattering systems

Erik Orvehed Hiltunen, Universitåt Oslo

We consider the resonance and scattering properties of a composite medium containing scatterers whose material parameters vary in time. The temporal modulation induces a coupling between wave harmonics whose frequencies differ by the modulation frequency, producing a coupled system of Helmholtz equations in the frequency domain. We develop an integral-operator approach for numerical calculation of resonances and band structure of time-dependent scatterers. We also show how the integral equation approach can be leveraged to find small-volume asymptotic formulas analogous to the classical results for the static (unmodulated) case. As an effect of broken energy conservation, we show that the scattering coefficients may blow up when (complex) resonances cross the real axis.

A theoretical framework to model the scattering of elastic longitudinal waves at time interfaces

Antonio Palermo, Università di Bologna.

In this talk, we analyze the propagation of elastic waves at time interfaces between homogeneous and spatiotemporally modulated media by developing a mode-coupling framework. We demonstrate that these interfaces enable controlled frequency and wavenumber conversion through mode redistribution and energy transfer. Specifically, we investigate the temporal scattering of elastic waves under two distinct spatiotemporal modulation regimes: subsonic and supersonic, which give rise to frequency and wavenumber bandgaps, respectively. Our findings reveal non-reciprocal energy attenuation and parametric amplification with frequency conversion at time interfaces induced by subsonic and supersonic modulation. These results advance the development of time-varying elastic materials, opening new avenues for designing one-way elastic filters, amplifiers, and frequency converters.

Wave propagation in materials with smooth sign-changing coefficient

Maryna Kachanovska, POEMS, INRIA-CNRS.

It is well known that surface plasmonic resonances appear in transmission problems with sign-changing coefficients, e.g. at the interface between a metal and a dielectric. In this case, the sign change is abrupt (i.e., the coefficient is piecewise regular). A mathematically and physically interesting situation arises in plasma physics, where the problem is described by a PDE with a sign-changing coefficient. However, in this case, the coefficient is smooth and vanishes along a curve. In the latter case, plasma resonances occur, corresponding to solutions of the underlying problem with low regularity. The key difficulty lies in their mathematical characterization: simply relaxing the regularity assumption leads to infinitely many possible solutions. In this talk we discuss this problems, and prove a limiting absorption principle for the problem and impose an appropriate radiation condition. This presentation is based on joint works with Patrick Ciarlet Jr. and Etienne Peillon.

Effective odd elasticity

Grigor Nika, Karlstad University

Elasticity typically assumes that the stress-strain relationship is compatible with a potential energy. This assumption is in general not appropriate for a range of living, driven, or active media, and odd elasticity is the theory that emerges when this assumption is removed. At first glance odd elasticity might seem incompatible with the laws of thermodynamics. In this talk we will show that odd elasticity is the multi-continuum homogenized limit derived from a thermodynamically consistent Cosserat continuum. Moreover, we will present numerical simulations using the finite element method on circularly perforated square and rectangular unit cells, to highlight the impact of the residual Cosserat (micropolar) couple modulus has on the effective coefficients.

The Drude-Born-Fedorov system on anisotropic fractals

Eric Stachura, Kennesaw State University

Fractals are ubiquitous in nature, appearing in coastlines, porous media, cracks, snowflakes, etc. In this talk, I will discuss a mathematical framework to study differential equations on anisotropic fractal solids. These are fractal structures that could have different Hausdorff dimensions in each direction and appear, for instance, in the modeling of composite structures with fractal type microstructures. I will then discuss a fractal version of a cavity eigenvalue problem for the Drude-Born-Fedorov system.

Frequency-driven wave localization in disordered metamaterials

Anastasiia Krushynska, Rijksuniversiteit Groningen

We propose a design strategy for spatially disordered metamaterials that can steer elastic waves toward multiple specific locations depending on an excitation frequency. We thus exploit the frequency as a driving parameter for wave propagation and localization and show that the frequency-controlled wave steering can be realized in rationally pruned random elastic networks. Our strategy is robust for both discrete and continuous configurations, scalable in terms of the excitation frequencies, the number of target locations, and network sizes, and is validated experimentally. These results revise the concept of path-driven wave steering and open up a viable route to develop disordered metamaterials with controllable wave steering functionalities. This can be useful for acoustic sensors, energy harvesters, lenses, and programmable acoustic media.

Band gaps from randomly distributed resonators

Paulo Sergio Piva, University of Sheffield.

Periodic metamaterials are commonly used to create band gaps within narrow frequency ranges, but expanding these gaps or designing materials with multiple band gaps can be challenging. This difficulty arises from the need to incorporate multiple length scales within a periodic structure. In this talk, we explore an alternative approach: designing band gaps without relying on periodicity. We demonstrate how arbitrary combinations of randomly placed Helmholtz resonators can be used to tailor band gaps effectively. Moreover, we derive simple, explicit formulas for the effective properties of these materials, valid across a broad frequency range. These formulas are validated through high-fidelity Monte Carlo simulations, confirming their robustness for various random resonator configurations.

Mathematical conditions for the weak-scattering assumption in flexural waves on thin elastic plates with point-like resonators

Mario Lázaro Navarro, Universitat Politècnica de València.

In recent decades, significant achievements have been made in the study of phononic crystals, driven by innovative techniques for manipulating wave propagation in complex media. A particularly relevant area of interest is materials composed of a host medium embedded with an array of point scatterers or resonators. This presentation specifically examines wave propagation in elastic plates. Using multiple scattering equations, we obtain an analytical solution to the problem in its most general form. Our goal is to establish the mathematical conditions that distinguish when an array of scatterers induces weak scattering in a plate. To achieve this, we propose evaluating the spectral radius of the scattering matrix, which exhibits a strong correlation with the classical Born approximation as applied to elastic waves. Our derivations allow us to decompose the effect of wave scattering as the product of one parameter measuring the global scattering depending on the relative position between points and another parameter depending on the local frequency-dependent behavior of each resonator.

Metamaterials with extra twists

Martin Wegener, Karlsruher Institut für Technologie.

I review our recent work on nonlocal metamaterials in elasticity, acoustics, electromagnetism, and transport. I give a brief introduction into nonlocality following Ref. [1], including different mechanisms and different mathematical ways of capturing it. Thereafter, I will focus on two groups of examples: (i) propagating elastic waves at finite frequencies [2,3] as well as frozen evanescent elastic waves [4,5] and (ii) nonlocal dc Ohmic conduction in 1D metawires [6].

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2. ‘Roton-like acoustical dispersion relations in 3D metamaterials’, Y. Chen, M. Kadic, and M. Wegener, Nature Commun. 12, 3278 (2021).

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4. ’Anomalous frozen evanescent phonons’, Y. Chen, J. L. G. Schneider, K. Wang, P. Scott, S. Kalt, M. Kadic, and M. Wegener, Nature Commun. 15, 8882 (2024).

5. ‘Observation of Floppy Flexural Modes in a 3D Polarized Maxwell Beam’, Y. Chen, J. Mc Inerney, P. Krause, J. L. G. Schneider, M. Wegener, and X. Mao, Phys. Rev. Lett., in press (2025) .

6. ‘Nonlocal conduction in a metawire’, J. A. Iglesias Martinez, Y. Chen, K. Wang, and M. Wegener, Adv. Mater., in press (2025).

Ultrasonic Hologram for Bi-directional Diffusion by Phase Controlling the Scattering Coefficients

Vicent Romero García, Universitat Politècnica de València.

In this work, we present a bi-directional asymmetric ultrasonic hologram that can simultaneously control both the reflected and transmitted wave-fields. To do that we design a surface made of a discrete spatial distribution of monolithic elements with different properties than the surrounding medium. This allows to compress two identical or different wavefield scattering patterns (for transmission and reflection) into a single monolithic object. We report an ultrasonic hologram based on Quadratic Residue sequences encoded with resonant building blocks behaving as an ideal Lambertian scatterer from both sides, with spatial autocorrelation coefficients 0.7 each one, therefore diffusing waves in both transmission and reflection. Depending on the applications, such hologram could be useful in situations where transmitted and reflected wavefields need to be controlled at the same time, such as a bi-directional diffusing system emitting and receiving equally in and from all directions (equivalent of perfect optical diffusers in optics) or as a bi-directional beam directivity selector. Such hologram could also be used directly in reflection situations for minimizing unwanted specular reflections.

The collaboration between the authors of this article was made possible thanks to Institut d’Acoustique – Graduate School (IAGS) project (ANR-17-EURE-0014) from the Laboratoire d’Acoustique du l’Université du Mans (LAUM) for the support and mobility. The authors gratefully acknowledge the ANR-RGC METARoom (ANR-18-CE08-0021). Project. N. J. and V.R.-G. acknowledge financial support from Conselleria de Innovación, Universidades, Ciencia y Sociedad Digital de la Generalitat Valenciana through project CIAICO/2022/052 of the Programa para la promoción de la investigación científica, el desarrollo tecnológico y la innovación en la Comunitat Valenciana. V.R.-G. acknowledges the partial support under Grants from MCIN/AEI PID2023-146237NB-I00, PID2020-112759GB-I00.

Friday, 4th of April

Quasiperiodic patterns of particles using standing acoustic waves

Fernando Guevara Vasquez, University of Utah.

Standing ultrasound waves can be used to drive particles immersed in a fluid into patterns. The particles cluster at minima of the potential describing the time averaged forces exerted on the particles. We give conditions under which this acoustic radiation potential is quasiperiodic and illustrate our theoretical results with both experiments and simulations. We also show how to control the transducers to translate or rotate the patterns. The same technique can be used to obtain Moiré patterns.

Homogenization of quasi-periodic conformal architectured materials

Jean-François Ganghoffer, Université de Lorraine

Quasi-periodic homogenization schemes are designed for quasi-periodic media, those without strict periodicity, but that can be mapped to a parent periodic medium. We consider more specifically non-periodic geometry designed by a conformal planar transformation of a periodic parent domain architectured media with periodically disposed unit cells.

Conformal transformations are shown to play a privileged role in the design of circular macroscopic heterogeneous domains tessellated with non-periodic unit cells, obtained from a periodic parent domain architectured with these unit cells. The conditions for conformal invariance are established, leading to the general form of conformal transformation in their dependencies upon the periodic coordinates. A general theory of quasi-periodic homogenization in the framework of conformal transformations is established, leading to an expression of the tensor of quasi-periodic moduli, which are fully evaluated from the solution of the elasticity boundary value problem posed over the periodic unit cell. The influence of microcurvature distortion of individual unit cells on their effective properties is evaluated. Closed-form solutions are confronted to numerical examples issued from the finite element implementation of circular periodicity, showing overall a good agreement with the identified quasi-periodic homogenized moduli.

In situations where the grading across unit cells is too fast, the variation of unit cell geometry must be considered at the microscale, leading to the emergence of higher-order terms in the effective behavior. In the last part of the presentation, a quasi-periodic homogenization theory towards strain gradient effective media is developed, based on the notion of shape derivatives.

Active non-Hermitian acoustic metamaterials: Bridging discrete and continuous wave dynamics

Lea Beilkin, Tel Aviv University.

We design effective continuous acoustic metamaterial models derived from purely discrete mechanical metamaterial models, demonstrating their effectiveness in describing wave dynamics governed by non-Hermitian physics. Our approach employs an active acoustic waveguide with embedded actuators and sensors operating in real-time feedback loops to introduce nonreciprocity, pressure gain and loss, and non-local couplings. Using this framework, we investigate two key phenomena: non-Hermitian tunneling and accelerated wave packets. In the first case, an artificial interface within the waveguide creates an asymmetric barrier where modes accumulate due to the non-Hermitian skin effect, yet under specific conditions, waves tunnel through, forming a quiet zone. In the second case, we achieve group velocities exceeding the speed of sound without modifying the waveguide geometry or introducing passive inclusions. By tuning control couplings within a stable parity-time-symmetric regime, we enhance wave propagation while maintaining system stability. These results bridge the gap between discrete metamaterial models and continuous wave physics, offering new strategies for acoustic wave control through active non-Hermitian engineering.

Transient regimes and imperfect temporal interface for gravity induced waves in chiral waveguides

Ian S. Jones, Natasha V. Movchan and Alexander B. Movchan, University of Liverpool.

The idea of temporal interfaces for waves is very attractive, and it is important to refer to the paper by M. Fink [1] who analysed temporal interfaces and developed a range of very nice physical applications in problems related to wave focussing. Furthermore, the theory of "dynamic materials" was developed by K.A. Lurie [2]. In the paper [3], K.A. Lurie and S.L. Weeks studied waves in spatio-temporal material composites with rectangular microstructures.

NVM and ABM were introduced into this exciting topic by Prof G.W.Milton during their visit to the Department of Mathematics, University of Utah back in 2016. G.W.Milton and O.Mattei have published wonderful work [4, 5, 6] on the analysis of field patterns for waves in media, including both temporal and spatial interfaces. In [7], the notion of frontal waves was introduced for media with temporal laminates and imperfect chiral interfaces; special attention is also given to resonant cases characterised by blow up.

The main focus of the talk is on gravity induced waves in temporally stratified media. It is based on the results of the paper [8], which includes analysis of an elastic chiral waveguide, subjected to gravity, where a coupling between different velocity components is assumed through the gyroscopic action. An elementary example is a chain of gyroscopic pendulums connected by elastic links. The importance of gravity and chirality on the dispersion of waves is demonstrated for several regimes, including singular perturbations leading to formation of boundary layers. In the transient regimes, we also analyse chiral imperfect temporal interfaces in the waveguide subjected to gravity.

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Waveguiding in time-modulated elastic lattices

Emanuele Riva, Politecnico di Milano.

The propagation of elastic waves in homogeneous materials is typically dictated by fixed, non-tunable dispersion properties, limiting the control over wave trajectories. However, by introducing spatial or temporal modulation, it becomes possible to dynamically shape wave propagation through local adjustments of the dispersion. I will begin by discussing waveguiding in Hermitian elastic lattices, where slow time modulation of stiffness enables smooth frequency conversion and directional wave steering with minimal reflections. This provides a simple yet powerful framework for predictable and efficient wave control. Building on this foundation, I will extend the concept to non-Hermitian, nonlocal lattices, where breaking Hermiticity, while preserving PT-symmetry, grants additional control over the dispersion properties, unlocking new wave manipulation capabilities. These systems enable exotic effects such as wave trapping and the boomerang effect, where waves can be stopped or even guided back to their origin.

A time periodic Klein-Gordon equation

Vassos Achilleos, LAUM-CNRS.

This study delves into the exploration of wave propagation in spatially homogeneous systems governed by a Klein-Gordon–type equation with a periodically time-varying cutoff frequency. Through a combination of analytical calculations and numerical simulations, intriguing and distinctive features in the dispersion diagram of these systems are uncovered. Notably, the examined configurations demonstrate some remarkable transitions as the modulation frequency increases. These transitions encompass a transformation from a frequency gap to a wave-number (q) gap around $q = 0$, with the transition point corresponding to a gapless Dirac dispersion with an exceptional point of degeneracy. Subsequently, the q gap undergoes a bifurcation into two symmetric gaps at positive and negative wave numbers. At this second transition point, the dispersion diagram takes the form of an imaginary Dirac dispersion relation and exhibits an isolated exceptional point at the center of the $q = 0$ gap. These findings contribute to a deeper understanding of wave dynamics in periodically modulated media, uncovering tunable phenomena.

Spacetime modulation of flexural-gravity waves in floating thin elastic plates

Ying Wu, King Abdullah University of Science and Technology

In this work, we study the propagation of flexural-gravity waves in thin elastic plates floating atop nonviscous fluids, governed by a partial differential equation with Laplacian and tri-Laplacian terms. We investigate the effect of space modulation, time modulation as well as spacetime modulation on thin floating elastic plates and show the peculiarity of the phenomena of the k-band gap and the rotated k-band gap in the context of flexural-gravity waves. Elastodynamic analogs of luminal electromagnetic metamaterials and rainbow trapping materials are demonstrated.

Surface plasmons in time-varying media

T. V. Raziman, Imperial College London

Surface plasmons are collective excitations of electromagnetic fields and charges bound to the interface between a metal and a dielectric with important technological applications such as bio-chemical sensors, quantum emitter engineering, solar energy harvesting, and photocatalysis. Surface plasmon excitation requires in-plane wave momenta beyond what can be sustained by propagating light, necessitating various techniques of spatial structuring of media to excite and detect surface plasmons.

Time-varying media, particularly those combining spatial and temporal variations, support wave phenomena that are forbidden in static systems and can alter the frequency and momentum distribution of the light.

Here, we demonstrate theoretically that a plane wave incident on a metal with a step-like modulation of plasma frequency can excite surface plasmons at its interface. Conversely, a surface plasmon can leak into propagating waves by modulating the metal. Our theoretical treatment incorporates the dispersion in the metal and avoids numerical challenges associated with the electromagnetic space-time corner. The work introduces a new approach for controlling surface plasmons, paving the way for innovative technological applications.

Graded quasiperiodic metamaterials for fractal rainbow trapping

Bryn Davies, University of Warwick

In this work, we show that the rainbow trapping phenomenon of graded metamaterials can be combined with the fractal spectra of quasiperiodic waveguides to give a metamaterial that performs fractal rainbow trapping. This is achieved through a graded cut-and-project algorithm that yields a geometry for which the effective projection angle is graded along its length. As a result, the fractal structure of local band gaps varies with position, leading to broadband “fractal” rainbow trapping. We demonstrate this principle by designing a simple acoustic metamaterial, composed of a linear waveguide with scatterers (in the form of sound-hard rods) placed at the points determined by the graded cut-and-project algorithm. This system is characterised using theory, simulation and experiments.

Fragile topology and the Thouless conjecture

Simon Becker, ETH Zurich

I will provide a mathematical perspective on fragile topology in condensed matter physics. In dimension $d \leq 3$, vanishing Chern classes characterize the topological phases of periodic media that exhibit localized Wannier functions. However, for special symmetries I of the system, such as $C_{2z}T$ (space-time reversal), the existence of a localized set of Wannier functions that is also invariant under this symmetry I may not always exist. In systems with fragile topology, Wannier functions cannot respect both the symmetry I and the localization constraints. Nevertheless, this obstruction can be lifted by adding Chern-trivial line bundles, invariant under the I-symmetry. This allows for the construction of localized Wannier functions that respect symmetry. I will then take on a broader perspective and obtain Wannier localization in dimensions $d = 2, 3$ without symmetry constraints for Chern nontrivial Bloch bundles. For $d = 2$, we obtain the Wannier decay with Thouless exponent $O(|x|^{-2})$; for $d = 3$, we obtain the decay rate $O(|x|^{-7/3})$.

Quasinormal mode expansion in thin elastic plates

Richard Wiltshaw, Imperial College London

Elastic wave manipulation using large arrays of resonators is driving the need for advanced simulation and optimization methods. To address this we introduce and explore a robust framework for wave control: quasinormal modes (QNMs). Specifically, we consider the problem for thin elastic plates, where the Green's function formalism is well known and readily exploited to solve multiple scattering problems. By studying the associated nonlinear eigenvalue problem we derive a dispersive QNM expansion, providing a reduced-order model for efficient forced response computations which reveals physical insight into the resonant mode excitation. Furthermore, we derive eigenvalue sensitivities with respect to resonator parameters and apply a gradient-based optimization to design quasi-bound states in the continuum and position eigenfrequencies precisely in the complex plane. Scattering simulations validate our approach in structures such as graded line arrays and quasicrystals. Drawing on QNM concepts from electromagnetism we demonstrate significant advances in elastic metamaterials, highlighting their potential for tailored wave manipulation.

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Useful Information

Talks will be held at the **Lecture Theatre G.01 of the Royal School of Mines**. The building is on the South Kensington campus, with its main entrance accessible from Prince Consort Road, SW7 2PG. The building can also be accessed from Delby Court, going through Bessemer building. **Coffee breaks and lunches** will be offered at the venue.

Wi-Fi will be available during the conference; Imperial College London provides access to the eduroam network.

How to get to Imperial?

The nearest Underground station is South Kensington, on the District, Circle and Piccadilly lines.

- Plan your route with the Transport for London journey planner.

From St Pancras International
If arriving in London on the Eurostar, you can the take the Piccadilly Line directly to South Kensington (journey time 20 minutes).

From London City Airport
Take the DLR to Canning Town, then by Underground, Jubilee line to Green Park and the Piccadilly line to South Kensington (journey time 40 minutes).

From Heathrow airport
Heathrow Express, 15 mins to Paddington mainline station, then the Underground, Circle line to South Kensington.
Or take the Underground, Piccadilly Line direct from the airport to South Kensington station (50 minutes travelling time).

From Gatwick airport
Gatwick Express, 30 mins to Victoria mainline station, then by Underground, District or Circle lines to South Kensington.
Or take a national rail train to Victoria station (journey time 40 minutes) and then by Underground, Circle or District Line; westbound to South Kensington.

From Stansted airport
Stansted Express, 50 mins to Liverpool Street main line station, and then by Underground, Circle line to South Kensington.

Heathrow, Gatwick and Stansted airports are some distance from London and a taxi is not recommended for the whole journey. However, if you have to travel by taxi, establish the cost before you get in.

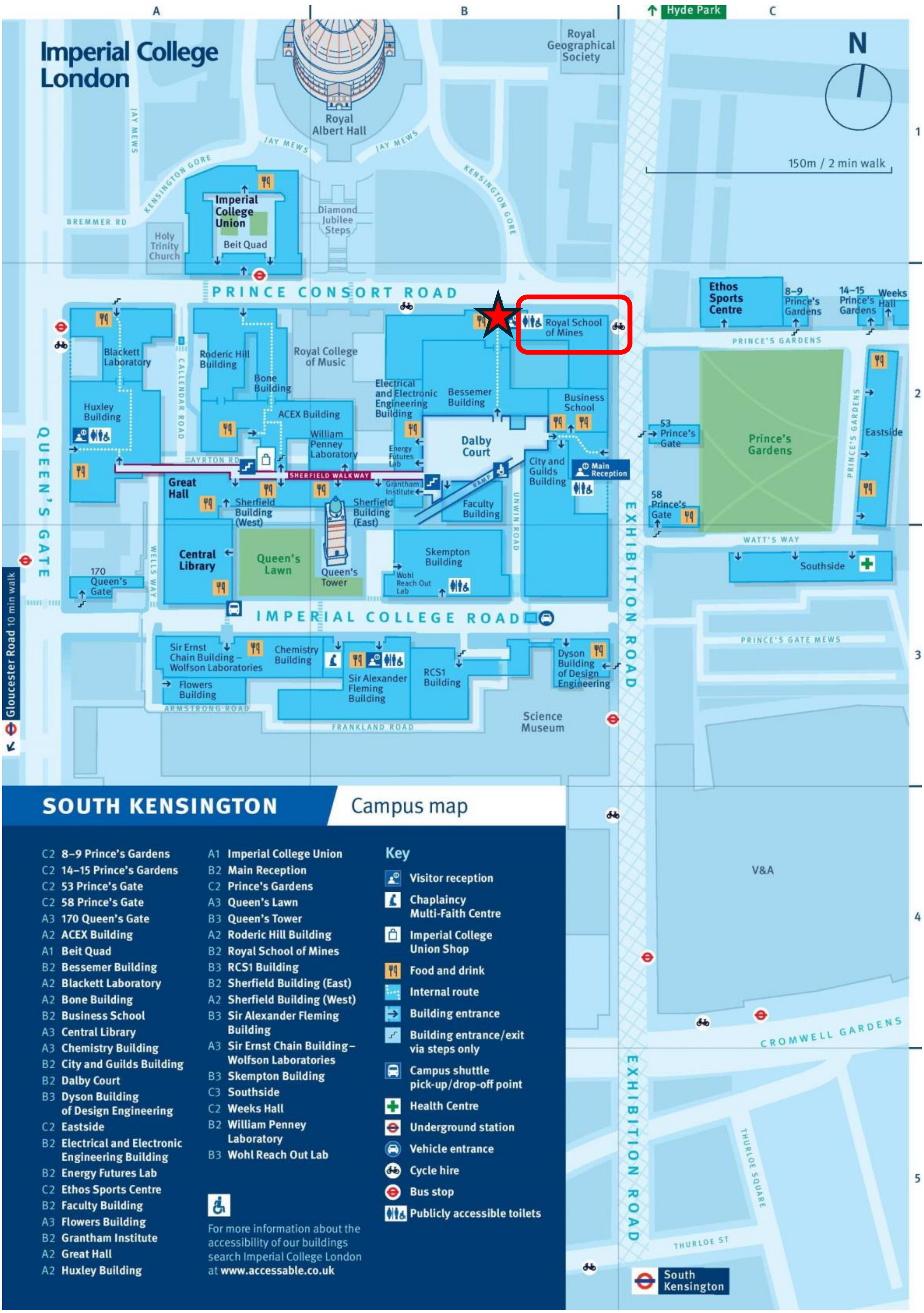
By sea
Take a British Rail train from the port of entry to London (Harwich to London journey time 1hr 30 mins; Dover to London journey time up to 2hrs) and then travel by Underground to South Kensington Station.

On foot
From South Kensington Station, the campus is only a ten minute walk. Either follow the subway signposted to the museums or walk north up Exhibition Road. The College is next to the Science Museum.

By bus
South Kensington Campus is easily accessible by bus. A number of routes pass within easy walking distance of the campus.

- Transport for London bus route maps

By car
Car parking at South Kensington Campus is severely restricted and you are advised NOT to bring a car unless permission has been given. The car park is open to the public from 18.00 to Midnight on weekdays and from 08.00 to Midnight on weekends. Please note that overnight parking is not permitted. Parking in the streets surrounding the College is at pay and display or parking meters for limited periods only.
The postcode to use for satellite navigation to the South Kensington car park is SW7 2BX . Entry is via Exhibition Road.



SOUTH KENSINGTON Campus map

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- C2 14–15 Prince's Gardens
- C2 53 Prince's Gate
- C2 58 Prince's Gate
- A3 170 Queen's Gate
- A2 ACEX Building
- A1 Beit Quad
- B2 Bessemer Building
- A2 Blackett Laboratory
- A2 Bone Building
- B2 Business School
- A3 Central Library
- A3 Chemistry Building
- B2 City and Guilds Building
- B2 Dalby Court
- B3 Dyson Building of Design Engineering
- C2 Eastside
- B2 Electrical and Electronic Engineering Building
- B2 Energy Futures Lab
- C2 Ethos Sports Centre
- B2 Faculty Building
- A3 Flowers Building
- B2 Grantham Institute
- A2 Great Hall
- A2 Huxley Building
- A1 Imperial College Union
- B2 Main Reception
- C2 Prince's Gardens
- A3 Queen's Lawn
- B3 Queen's Tower
- A2 Roderic Hill Building
- B2 Royal School of Mines
- B3 RCS1 Building
- B2 Sherfield Building (East)
- A2 Sherfield Building (West)
- B3 Sir Alexander Fleming Building
- A3 Sir Ernst Chain Building – Wolfson Laboratories
- B3 Skempton Building
- C3 Southside
- C2 Weeks Hall
- B2 William Penney Laboratory
- B3 Wohl Reach Out Lab

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- Underground station
- Vehicle entrance
- Cycle hire
- Bus stop
- Publicly accessible toilets

Partner Institutions and Sponsors

Dynamo

The project ‘Dynamo: Dynamic Spatio-Temporal Modulation of Light by Phononic Architectures’ is funded by the European Commission under the call HORIZON-EIC-2021-PATHFINDEROPEN, grant n.01046489.
The project started on 1st March 2022 and its duration is 48 months.
Dynamo deals with the fundamentals of physical acoustics to develop complex imaging applications and englobes the theoretical design, scalable fabrication and photoacoustic characterization of micro-structured surfaces for their final implementation as SLMs (Spatial Light Modulators) for imaging technology. This complex pathway requires a multidisciplinary consortium made of theoreticians and experimentalists from the domains of acoustics and photonics.

The final objective of the project is to establish a disruptive technology where the spatial modulation of optical beams reach both the spatial and temporal limits, what constitutes a true breakthrough in current technologies where only the spatial limit has been reached.

Further information be found here `https://dynamo-project.eu/`.

Meta-4D

Multiple, disruptive wave-based technologies (acoustic, elastic, radio-frequency, terahertz, and optical) would emerge if the response of the underlying materials could be modulated at will, varying throughout space and time.

META4D will simultaneously explore the fundamental physics of space-time-modulated materials and be the first to demonstrate their potential in real world applications; we will design and test a new generation of 4D (space and time) materials.

Further information be found here `https://meta4d.co.uk/`

UK Metamaterials Network

The UK Metamaterials Network connects academia, industry, governmental agencies and other professional bodies to enable the full utilisation of the UK’s metamaterials research and exploitation capabilities, from fundamental science to market-leading technology.

Further information be found here `https://metamaterials.network/`

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