Multiple Dimensions in Heterogeneous Structures: From Spectral Properties to Mesoscopic Behavior

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Dimension is a fundamental concept linking the geometry of a structure to its physical and dynamical properties. In complex and heterogeneous systems, however, a single notion of dimension is often insufficient to capture behavior across different scales. While the spectral dimension governs asymptotic diffusion, density-of-states singularities, and critical phenomena in the thermodynamic limit, finite-size and mesoscopic dynamics may be controlled by distinct geometric features.

In this talk, I will review classical results on the spectral dimension of physical graphs and its role in transport and collective phenomena on disordered structures. I will then discuss recent results showing that in heterogeneous networks the dimension controlling the slowest relaxation modes—the Fiedler dimension—can decouple from the spectral dimension. As a consequence, systems with identical thermodynamic scaling and asymptotic diffusion properties may exhibit markedly different equilibration times. This separation emerges naturally in composite and strongly inhomogeneous architectures, where large-scale behavior and mesoscopic dynamics are governed by different geometric mechanisms. More generally, these results highlight the importance of mesoscopic geometry in determining the dynamical properties of complex materials and networks.