# Finding and Manipulating Exceptional Points in Wave-Chaotic Microwave Cavities with Tunable Metasurfaces

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Exceptional points (EP's) are locations in parameter space where the eigenvalues and eigenvectors of non-Hermitian operators become degenerate, losing one or more degrees of freedom required to describe the state of the system [1]. EP's are typically studied in the context of non-Hermitian Hamiltonians, and the splitting between energy eigenvalues show strong sensitivity to perturbations in the neighborhood of the EP, leading to potential applications as a sensor [2]. In most prior work, EP's are created through contrived and delicately adjusted model Hamiltonians, and these systems typically have only a single EP. This gives the impression that EP's are rare and exotic phenomena, of little interest to those outside a narrow research community. We focus instead on the scattering matrix, which is a function of the Hamiltonian, and study it's EP's in a multi-dimensional parameter space. By measuring wave-chaotic microwave cavities, we have discovered an enormous number of EP’s in the accessible parameter space, and demonstrated that scattering EP’s are generic features of complex scattering systems.

In this work we use a variety of one-, two-, and three-dimensional microwave cavities having no special symmetries, but endowed with tunable metasurfaces [3] and phase shifters [4]. These metasurfaces allow us to observe and electronically manipulate numerous scattering matrix EP’s. This capability has enabled us to explore new phenomena of exceptional points, such as encircling multiple EP’s by purely electronic means, and seeing how the eigenvalue topology changes as different numbers of EP’s are enclosed in the loop. We also find that by using two metasurfaces we can collide and annihilate pairs of exceptional points, as well as bring pairs of new EP’s into existence. This gives us the opportunity to explore “EP dynamics” and to develop new insights into the topological properties of the parameter spaces that host EP’s. We also explore applications of these abundant EP’s.

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