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Algebra, topology, and the solid state: New perspectives on insulators and semimetals

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The interplay of topology and geometry has been – and continues to be – a rich area of study for condensed matter physics. Recently, we have realized that spatial symmetries allow for the stabilization of topological phases much more exotic than those that can be found with time-reversal symmetry alone. Examples include topological crystalline insulators, "hourglass Fermion" phases, and Dirac and double-Weyl semimetals. However, a complete and unified theory of these phases is still missing. In this talk, I will examine topological metals and insulators stabilized by any of the 230 crystal symmetry groups. I will develop a topological band theory that relates the symmetry properties of real space Wannier functions to the global topology of energy bands in momentum space. From this I will derive a predictive classification of topological crystalline phases, well suited for both predictions and ab-initio materials searches. Focusing first on insulating phases, I will show how our topological band theory sheds new light on old topological insulators, before moving on to present a new slew of topological insulators that we have predicted with our method. Additionally, I will show how non-symmorphic crystal symmetries can protect topological insulators with novel surface states, through symmetry constraints on the band structure; this includes a new toplogical phase whose surface spectrum consists of a single four-fold degenerate Dirac fermion. Moving on to topological semimetals, I will show how these same non-symmorphic symmetries require the existence of gapless free-fermion excitations unlike any found in high-energy physics. This includes the first natural generalization of the Weyl fermion, described by a kS Hamiltonian.