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Highlight

Topological Materials Go Meta

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In the 18th century, Leonhard Euler showed that no single path could be constructed through the city of Köningsburg that crosses each of its seven bridges only once. The impossibility of constructing such a path was an inherent property of Köningsburg, due to the geometric organization of its islands and connecting bridges (Figure 1a). This Seven Bridges problem is considered to be one of the earliest accounts of topology. Topology is a geometric property of an object that is unaffected by a continuous deformation of that object. It provides a fundamental framework within which to classify similarity versus dissimilarity. In case of the Seven Bridges problem, one could easily imagine a dissimilar (yet bridge-heavy) city where a path can be traced out yielding all single crossings.

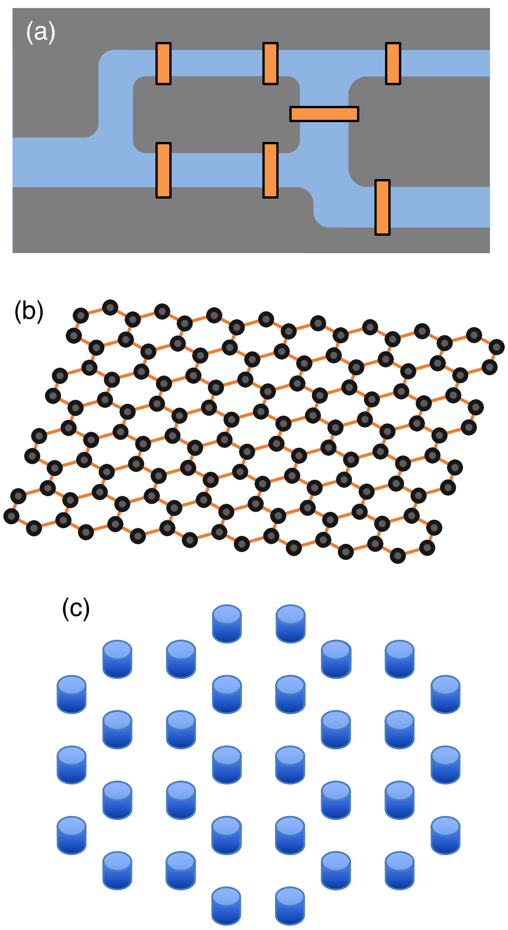

Figure 1. (a) Schematic depiction of Koningsburg and its seven bridges. (b) Atomic structure of graphene. (c) Schematic depiction of an optical MM incorporating the same honeycomb structure as graphene.

The same way the organization of bridges impacts the traffic flow of a city, topology broadly speaking has a profound impact on the dynamical behavior of an object. For this reason, topology has firmly established itself in physics, materials science, and chemistry as an abstract property governing the motion of electrons, light, and acoustic waves. A particularly compelling example is provided by topological insulators, which are materials whose quantum mechanics involve a topology that enables sustained electron motion at the edges against insulating behavior within the bulk. Predicted in the 1980s, topological insulators have seen experimental realizations in the last two decades. Moreover, during this time, efforts to harness topology in order to steer quantum dynamics have seen increased successes beyond topological insulators, leading to a variety of "quantum materials" with emergent behaviors.

In controlling dynamical behaviors through topology, a vast materials design space is available, defined by the selection of atoms on one hand, and their crystallization on the other. Further opportunities, however, are to be found in the realm of metamaterials (MMs). MMs involve a patterning of subwavelength building blocks, referred to as meta-atoms, allowing for the manipulation of optical and acoustic waves not possible by means of conventional materials. Through engineering, meta-atoms can be endowed properties out of reach to the periodic table, while MM patterns can be designed at will, beyond what is possible through crystallization. Great strides made in their fabrication techniques have propelled MMs to the forefront of materials research, while at the same time there is increasing appreciation of topology control afforded by their extreme tailorability. As such, MMs offer a new and complementary platform for the study and engineering of topological phenomena. This line of inquiry has been astutely summarized by Xiang Ni, Simon Yves, Alex Krasnok, and Andrea Alù in a recent review [DOI: 10.1021/acs.chemrev.2c00800].

MMs can be broadly differentiated into those manipulating optical waves, referred to as optical MMs, and those

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manipulating acoustic waves, referred to as phononic MMs (seeing that phonons, i.e., nuclear wavepackets, are carriers of sound). Progress in harnessing topology has been remarkable for both classes of MMs, and in many cases implementations realized for one class have been successfully replicated in the other class. Moreover, many implementations of topological MMs are inspired by conventional (i.e., nonmeta) topological materials.

An example of a conventional topological material whose topological properties have been successfully replicated in MMs is graphene. Graphene consists of a single layer of carbon atoms organized in a honeycomb lattice (Figure 1b). Within this lattice, electrons assume quantum states with different characteristic momenta, the combination of which forms momentum-dependent "bands". At zero temperature, each band is either fully occupied or fully filled, yielding an insulating state in which no net electronic motion occurs. Importantly, a touching between bands allows thermal fluctuations to promote electrons from a filled to an unfilled band, inducing a conducting state. For this reason, graphene is referred to as a semimetal. The relevant bands in graphene feature two touching points, each assuming a conical shape as a function of the two in-plane directions of the monolayer. Moreover, the two touching points exhibit an "opposite" topology, causing electrons near each cone to have an opposite pseudospin state, among other exotic properties. This principle has drawn great attention due to both its fundamental and technological relevance.

Early after the discovery of graphene, propositions were made to replicate its honeycomb lattice by means of a photonic crystal (Figure 1c), which would mimic its topological behavior by optical means. This was motivated in part by the desire to overcome difficulties of precisely controlling atomic-scale electron dynamics within graphene by resorting to larger-scale photonic structures, while retaining fundamentally similar dynamical behaviors. Successful experimental implementations of such photonic MMs have since been realized, which were in turn followed by analogs within the realm of phononic MMs. The range of topological MMs similarly inspired by phenomena first discovered in conventional materials has come to be remarkably wide, and now includes chern insulators, floquet-based systems, and spin- and valley-hall insulators.

An interesting aspect of the recent surge in topological MMs is that it steers the study of topology back into the classical realm. Topology as a concept predates quantum mechanics, yet its application to quantum phenomena has particularly deepened its relevance, with topological insulators as a compelling example. Optical and acoustic motion, however, can be understood entirely based on classical wave dynamics. By replicating the behaviors of conventional topological material using MMs, the library of classical topological phenomena is now being expanded radically, informed by advances made within the quantum realm.

While the study of topology in quantum systems is subject to difficulties associated with atomic-level control, topological MMs allow some of these difficulties to be overcome thanks to the larger scale of optical and phononic wave phenomena. As such, topological MMs provide unique engineering opportunities as well as a platform for studying the fundamentals of topology with ramifications for related fields. One such field is chemistry. Topology is known to fundamentally impact molecular phenomena where nuclear-dependent electronic states become close in energy. In some cases, crossings of such states arise, called conical intersections, where topology turns out to directly impact the nuclear dynamics. This in turn affects transient molecular phenomena such as reactions. Not only do MMs provide a platform to study the fundamentals underlying topological effects in chemistry, chemistry in return offers opportunities to expand upon the library of existing topological MMs by harnessing chemical design principles for the optimization of MM components.

A particularly interesting example of the cross-pollination between MMs and chemistry is found in the realm of polaritonics, i.e., the hybridization of matter-based quantum excitations with optical modes. This hybridization offers new control knobs for chemical transformations and optoelectronic technologies. Endowing the optical field with topological properties through the application of MMs may offer even higher levels of control, by combining the unique physics associated with topology with that of strong light−matter coupling. Such developments cross disciplinary boundaries, and one may expect future interdisciplinary efforts to further propel the control and application of topology in chemistry, physics, and beyond.

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