CLEARED
For Open Publication

Mar 17, 2020

Department of Defense
OFFICE OF PREPUBLICATION AND SECURITY REVIEW

Future Directions Workshop:

Topological Sciences

July 30–31, 2019
Arlington, VA

David Goldhaber-Gordon, Stanford University

Mikael C. Rechtsman, The Pennsylvania State University

Nadya Mason, University of Illinois, Urbana-Champaign

N. Peter Armitage, The Johns Hopkins University

Prepared by:
Kate Klemic, *VT-ARC*
Jason Day, *OUSD(R&E)*

Future Directions Workshop series
Workshop sponsored by the Basic Research Office, Office of the Under Secretary of Defense for Research & Engineering

VT-ARC
Virginia Tech
Applied Research Corporation

Contents

> Innovation is the key to the future, but basic research is the key to future innovation.
>
> –Jerome Isaac Friedman, *Nobel Prize Recipient (1990)*

Preface

Over the past century, science and technology has brought remarkable new capabilities to all sectors of the economy; from telecommunications, energy, and electronics to medicine, transportation and defense. Technologies that were fantasy decades ago, such as the internet and mobile devices, now inform the way we live, work, and interact with our environment. Key to this technological progress is the capacity of the global basic research community to create new knowledge and to develop new insights in science, technology, and engineering. Understanding the trajectories of this fundamental research, within the context of global challenges, empowers stakeholders to identify and seize potential opportunities.

The Future Directions Workshop series, sponsored by the Basic Research Directorate of the Office of the Under Secretary of Defense for Research and Engineering, seeks to examine emerging research and engineering areas that are most likely to transform future technology capabilities. These workshops gather distinguished academic researchers from around the globe to engage in an interactive dialogue about the promises and challenges of each emerging basic research area and how they could impact future capabilities. Chaired by leaders in the field, these workshops encourage unfettered considerations of the prospects of fundamental science areas from the most talented minds in the research community.

Reports from the Future Direction Workshop series capture these discussions and therefore play a vital role in the discussion of basic research priorities. In each report, participants are challenged to address the following important questions:

- How will the research impact science and technology capabilities of the future?
- What is the trajectory of scientific achievement over the next few decades?
- What are the most fundamental challenges to progress?

This report is the product of a workshop held July 30-31, 2019 at the Basic Research Innovation Collaboration Center in Arlington, VA on the future of Topological Sciences research. It is intended as a resource to the S&T community including the broader federal funding community, federal laboratories, domestic industrial base, and academia.

Executive Summary

Over the past ten years, there has been an explosion of research into a new class of exotic materials with topological behavior that have transformed what had been thought possible in condensed matter physics, electronics, quantum science, and more. These topological materials show a remarkable robustness to distortion and defects that could enable a new generation of electronics, sensors, and optical components with greatly reduced size, weight, and power (SWaP) and sensitivity.

To examine the potential of topological materials, a workshop was held on July 30-31, 2019 at the Basic Research Innovation Collaboration Center, in Arlington, VA. Sponsored by the Basic Research Office of the Office of the Under Secretary of Defense for Research and Engineering, the workshop gathered more than 26 distinguished researchers from academia, industry, and government from the condensed matter physics, photonics, and electronics communities for unfettered discussion and debate on the current and future status of research in topological sciences. This report is the product of those discussions, summarizing the current research challenges, opportunities, and trajectory for topological science research over the next twenty years.

The participants discussed recent advances in both electronic and bosonic/classical topological systems to identify opportunities and challenges for using these topological materials in future technologies.

Electronic Topological Systems

Recent advances in electronic topological materials include the discovery of new classes of topological insulators (such as topological crystalline insulators, axion insulators, higher order topological insulators), topological semimetals, and topological superconductors.

Opportunities

The participants expect these new materials to generate opportunities for a range of new electronic devices. They identified these devices, new states of matter, and other opportunities in topological electronics as:

- Transistors and switches with greater functionality
- Passive devices with lower interconnect resistance, increased transparency, and smaller footprint
- Magnetic and spin-related devices with higher efficiency and less sensitivity to interference
- Quantum computation systems that are robust against decoherence
- Correlated electronic systems with new topological states of matter
- New phenomena in heterostructures and their emergent phenomena
- New calculational schemes for predicting topological materials

Challenges

The participants defined the key challenges for electronic topological systems as:

- Material design and fabrication quality that allow high temperature operation
- Heterostructure fabrication and measurement that allow new topological states
- Identification of topological states enabled by strong interactions
- Developing novel experimental approaches for measuring topological effects and in particular strongly interacting variants

Bosonic/Classical Topological Systems

Bosonic/classical topological systems include photonic, mechanical, acoustic, polaritonic, atomic, and geophysical systems. Topological properties in these systems can overcome the limitations associated with fabrication disorder and enable device miniaturization and lower manufacturing costs. The potential applications of topological “bosonics” are different from, but complementary to those for electronic devices. Nonetheless, one key starting point is similar: a need for transport without disruption by defects and disorder.

Opportunities

The workshop participants identified the key opportunities for bosonic/classical topological systems as:

- Nonlinear and interacting states: more compact and energy-efficient use of light on photonic chips; robust quantum simulation of many-body states
- Topological bosonics in three dimensions: disorder-insensitive mechanical and photonic devices with smaller footprint and new functionalities based on going beyond 2D
- Higher-order topological systems: protecting cavity and hinge modes for manipulating quantum information and novel on-chip laser designs
- Bound states in the continuum: large-area devices (lasers, metasurfaces) with minimal radiative loss for maximal efficiency in lasers and chemical and biological sensors
- Synthetic dimensions: realizing new physics and device implications that can only be realized beyond three spatial dimensions
- Quantum topological bosonic states: manipulating and transmitting highly fragile entangled particles with minimal sensitivity to disorder

Challenges

The key challenges for bosonic/classical topological systems include:

- Comprehensive theory for nonlinear and non-Hermitian topological waves
- Development/identification of new technologies in which topological protection can be exploited
- Development of magneto-optical materials and their incorporation into non-reciprocal topological devices
- Scalable 3D fabrication processes to manufacture topological materials

The participants were optimistic about the potential of topological systems to impact future technologies with continued advancement in prediction and discovery of new topological materials. The near-term of this nascent field will see remarkable improvement in theory, design, and manufacture of topological systems with prototypes within ten years and full systems within twenty years. The range of envisioned long-term capabilities for electronic and bosonic/classical systems include:

Electronic Topological Systems Long-term Capabilities

- Large-scale production and first demonstration of compute-in-memory using topological magnetic memories
- Control of correlated topological states that will enable room temperature orbital magnetism and superconductivity
- Room temperature dissipationless interconnects, metrology, and magnetic devices
- Room temperature topological effects for topological quantum computation, which may break through bottlenecks in scaling the existing qubit paradigms
- Measurements of entanglement entropy for solid-state systems
- Large-scale quantum electronics that incorporate a network of quantum transport interconnects
- Robust high temperature topology sensitive electromagnetic effects

Bosonic/Classical Topological Systems Long-term Capabilities

- Topological quantum computing with light
- Topologically robust and bright sources of single and entangled photons
- Defect-tolerant self-assembled subwavelength photonic devices
- Narrow-line and high power lasers based on type-I Weyl points in 3D photonic crystals
- Highly defect-tolerant semiconductor topological lasers for telecommunications
- Topologically protected quantum communication
- Orders-of-magnitude, smaller-footprint on-chip optical devices due to robust topological slow light

Introduction

Historically, new materials and heterostructures have enabled revolutionary scientific and technological changes, from carbon composites for fuel-efficient aircraft to high-purity, precise doping of semiconductors for modern computing to novel III-V heterostructures for both solid state lasers and correlated quantum Hall physics. In recent years there has been a revolution in our understanding of the classification of materials. In much the same way as a donut and a coffee cup "look the same" to a topologist because each has a single hole (Figure 1), but neither looks the same as a ball with no hole, these new materials are characterized by topological properties of their electronic states. The unusual properties that are robustly stabilized in topological materials will enable a new generation of electronics, sensors, and optical components for a range of technological applications.

In late 2018, the topological field lost a leader, Shoucheng Zhang, who inspired many with his intuitive pictures of new scientific phenomena and his visions of how those phenomena might impact technology. For readers who wish to come up to speed before embarking on the present report, the organizers recommend Zhang's review article (Qi, et al., 2010) as well as other semipopular accounts (Kane and Moore, 2011; Moore, 2010). For a deeper but still accessible account, see (Hasan and Kane, 2010). For a semipopular review of topological photonics, see (Lu, et al., 2014).

Excitement for this field is driven by the rapid pace of prediction and discovery of interesting and functional behavior from exotic new materials—such as 3D topological insulators, quantum anomalous Hall systems, Weyl and Dirac semimetals (linear band touchings), Luttinger semimetals (quadratic band touchings), and spin liquids—that promise to transform what had been thought possible in condensed matter physics, photonics, electronics, quantum science, and more. Table 1 notes some of the most common topological materials. To date almost ten thousand materials—fully a quarter of those in a broad database of inorganic crystals—have been computationally determined to have topological properties (Zhang, et al., 2019) (Vergniory, et al., 2019). Further, the exploration of topological materials has inspired design of engineered artificially structured materials with analogous properties for photons or other bosonic waves, as opposed to electrons. We have moved from finding topological materials to designing such materials.

Development of Topological Materials

The modern focus on topological materials grew out of a framework developed by Thouless and collaborators (TKNN) in the 1980s, who were trying to understand the remarkable quantization of the quantum Hall effect (Thouless, et al., 1982) in which a 2D electron gas in an applied magnetic field showed a Hall conductance equal to a combination of fundamental constants of nature (von Klitzing, et al., 1980). TKNN showed mathematically that for any 2D material, as long the Fermi energy is in an energy "gap", the Hall conductance is quantized; it can take on only certain discrete values. Also in the early 1980s, Michael Berry developed his now-famous geometric phase in adiabatic quantum mechanics (Berry, 1984) and shortly thereafter Barry Simon recognized that the TKNN expression could be written as the integral over all momentum states of the "Berry curvature" associated with the Berry's phase (Simon, 1983). Quantities like (Berry) curvature are geometric, but their integrals over an entire surface (in real space, momentum space, or parameter space) can be topological. This shows how some quantities can be sensitive only to material's general class, not its details. This categorization of quantum Hall states by the global integrals of the Berry curvature is directly analogous to labeling coffee cups as similar to donuts but not to balls: the local curvature of a shape can vary wildly, but the integral of the Gaussian curvature depends only on the number of holes in the shape, irrespective of the geometric details.

Figure 1 Topological equivalents (Hood, 2016).

<table>
<tr><td rowspan="2">Layered Chalcogenides</td><td colspan="20">3D Topological Insulator:
Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, Bi_2Te_2Se, $(Bi,Sb)_2Te_3$, $Bi_{2-x}Sb_xTe_{3-y}Se_y$, Sb_2Te_2Se, $TlBiSe_2$, $TlBiTe_2$, $TlBi(S,Se)_2$, $PbBi_2Te_4$, $PbSb_2Te_4$, $GeBi_2Te_4$, $PbBi_4Te_7$,</td><td colspan="20">2D Topological Insulator:
1T'-WTe_2</td><td colspan="20">*Magnetic 3D Topological Insulator (Axion Insulator):*
Cr doped $(Bi_{1-x}Sb_x)_2Te_3$, V doped $(Bi_{1-x}Sb_x)_2Te_3$, $MnBi_2Te_4$</td></tr>
<tr><td colspan="20">Weyl Semimetal:
T_d-WTe_2, T_d-$MoTe_2$</td><td colspan="20">Higher-Order Topological Insulator:
1T'-WTe_2, 1T'-$MoTe_2$</td><td colspan="20">**Higher-Order Topological Superconductor:**
$MoTe_2$, $FeTe_{1-x}Se$</td></tr>
<tr><td>Other Chalcogenides</td><td colspan="20">2D Topological Insulator:
(Hg,Cd)Te Quantum Wells</td><td colspan="20">Topological Crystalline Insulator:
$Pb_{1-x}Sn_xTe$</td><td colspan="20">*Chern Insulator:*
Mn doped HgTe</td></tr>
<tr><td>Pnictides</td><td colspan="20">3D Topological Insulator:
$Bi_{1-x}Sb_x$</td><td colspan="20">Weyl Semimetal:
TaAs, TaP, NbP, NbAs</td><td colspan="20">Dirac Semimetal:
Cd_3As_2, MoP</td></tr>
<tr><td>Heusler and Half-Heuslers</td><td colspan="40">*Magnetic Weyl Semimetal:*
GdPtBi, NdPtBi, LuPdBi, Co_2MnX (X = Si, Ge, Sn), Co_2TiX (X = Si, Ge, Sn)</td><td colspan="20">Quadratic Band Touching:
YPtBi, ScPtBi</td></tr>
<tr><td rowspan="2">Oxides</td><td colspan="20">Dirac Semimetal:
$SrIrO_3$</td><td colspan="20">Quadratic Band Touching:
$Pr_2Ir_2O_7$</td><td colspan="20">Double Dirac Semimetal:
$Sn(PbO_2)_2$, Pb_3O_4, $Mg(PbO_2)_2$, Bi_2AuO_5</td></tr>
<tr><td colspan="20">Kramers-Weyl Semimetal:
Ag_3BO_3</td><td colspan="20">**Topological Superconductor:**
Sr_2RuO_4</td><td colspan="20">Magnetic Weyl Semimetal:
$Nd_2Ir_2O_7$</td></tr>
<tr><td>Elemental</td><td colspan="15">2D Topological Insulator:
monolayer hexagonal-Sn, Sb</td><td colspan="15">Weyl Semimetal:
Se, Te (under pressure)</td><td colspan="15">Quadratic Band Touching:
β-Sn</td><td colspan="15">Higher-Order Topological Insulator:
Bi</td></tr>
<tr><td>Graphene and non-graphene-based moirés</td><td colspan="15">2D Topological Insulator:
$MoTe_2/MoTe_2^*/WTe_2$</td><td colspan="15">**Superconductor in Topological Bands:**
Magic angle twisted bilayer graphene</td><td colspan="15">*Chern Insulator:*
Magic angle twisted bilayer graphene/hBN, ABC trilayer graphene/hBN</td><td colspan="15">2D Topological Insulator:
Magic angle twisted bilayer graphene</td></tr>
<tr><td rowspan="2">Other</td><td colspan="12">2D Topological Insulator:
BiH_3</td><td colspan="12">Weak 3D Topological Insulator:
β-Bi_4I_4</td><td colspan="12">Topological Kondo Insulator:
SmB_6, YbB_{12}</td><td colspan="12">Dirac Semimetal:
Na_3Bi</td><td colspan="12">Triple Point Dirac Semimetal:
WC</td></tr>
<tr><td colspan="12">Double Weyl Semimetal:
$SrSi_2$</td><td colspan="12">Double Spin-1 Weyl Semimetal:
RhSi</td><td colspan="12">*Magnetic Weyl Semimetal:*
Mn_3Ge, Mn_3Sn</td><td colspan="24">Topological Crystalline Insulator:
α-Bi_4Br_4</td></tr>
</table>

Table 1 Topological Materials, categorized by broad classes. 3D topological insulators (blue), 2D topological insulators (yellow), topological semimetals (orange), higher-order topological insulators (green), topological crystalline insulators (pink), and topological superconductors (purple). Magnetic materials are indicated by italics and superconductors by boldface. Inspired by a table of 2D materials in (Geim & Grigorieva, 2013).

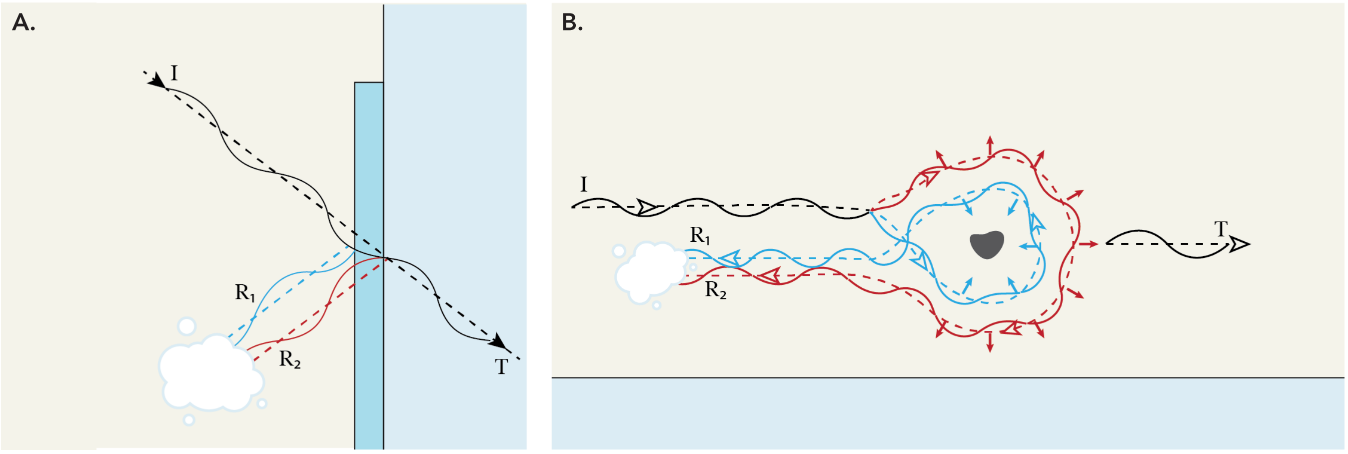

Figure 2 Topological protection is analogous to an anti-reflective coating on a glass slab. (a) Anti-reflective coatings are designed with a precise thickness so that reflected waves R1 (blue) from the front of the coating and R2 (red) from the back of the coating are perfectly out of phase and therefore interfere destructively, leaving only perfectly transmitted wave T. (b) In a 2D topological insulator, electrons can propagate along the edge in either direction. If they hit an obstacle (akin to the boundary of a glass slab) they can reflect in two different ways (blue and red). Unlike with antireflection coatings, no fine-tuning is necessary: Spin-momentum locking guarantees that the two ways of reflection perfectly destructively interfere, so electrons cannot reflect but must instead perfectly transmit past the obstacle (adapted from (Qi & Zhang, 2010)). For simplicity, spin direction is indicated only during the collision process.

Quantum Hall systems have unusual properties because of their non-trivial topology. In particular, the edges of a quantum Hall system can support special dissipationless one-way transport, that have properties that follow from the topological properties of the bulk. The robustness of the resulting resistance quantization plays a key role in the international system of units. A theoretical breakthrough was realizing that related behavior could occur even without a magnetic field to determine the direction of edge conduction. In 1988, Haldane showed that the essential ingredient for a topological state like a quantum Hall system was not the magnetic field itself, but rather breaking "time reversal symmetry", a property of nature that physicists normally rely on without thought: if we film a movie of a particle's motion, then playing it back, the viewer cannot distinguish whether it was played forward or backward in time. Haldane's toy model for a "Chern insulator" demonstrated how quantum Hall-like phenomena could occur without a global magnetic field (Haldane, 1988). So far, the development of topological materials followed a familiar path: an unexpected phenomenon is experimentally discovered in a new or very clean material (here, quantum Hall effect seen in high-quality 2D electron systems hosted in Si/SiO2 heterostructures developed for the semiconductor industry.) This is followed, typically over a few years, by theory providing understanding and predictions for valuable new experiments, but not prediction of a new class of materials. Yet nearly 20 years after Haldane's elegant but apparently entirely academic demonstration, the story of topological materials took an unprecedented turn: the theory initially developed to understand one experimental discovery led to the proposal of novel phenomena in a different material. In 2005, Kane and Mele linked Haldane's long-fallow model to a somewhat more realistic material system: if graphene had strong spin-orbit coupling, it could act like a Chern insulator, but with two counter-propagating edge states related to each other by time-reversal symmetry. These states were also robust against backscattering, as described in Figure 2 (Kane & Mele, 2005a) (Kane & Mele, 2005b).

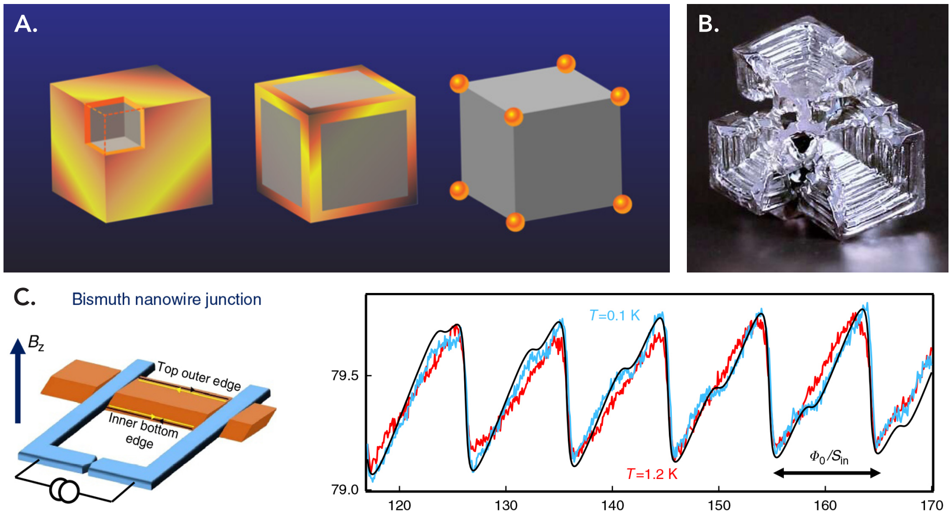

Figure 3 Topological Surface States. (a) A 3D topological insulator has insulating bulk and conducting surface states (left, with cutout to show insulating bulk) but more recently it's been realized that 1D edge ("hinge") states (center) or 0D corner states (right) could also be protected. (b) Bismuth displays such higher-order protected states, as revealed in (c) sawtooth rather than sinusoidal pattern of supercurrent measured through a Bi nanowire (adapted from (Parameswaran & Wan, 2017) (Paiste, 2019) (Murani, et al., 2017)).

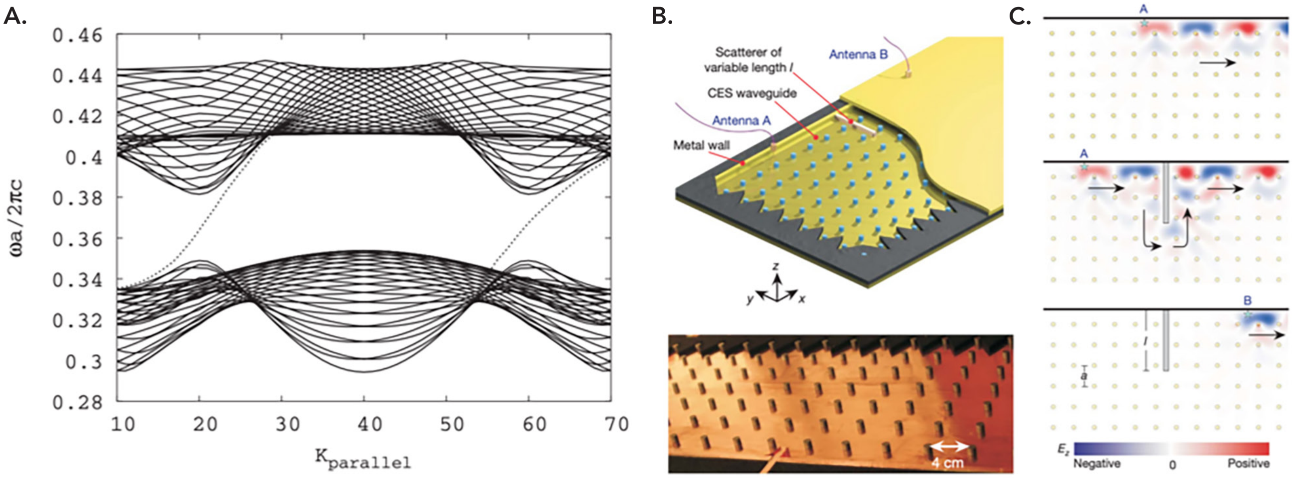

Figure 4 Topology in Gyromagnetic Photonic Crystals. (a) A photonic band structure: dotted lines represent edge states that propagate in only one direction as a result of an applied magnetic field. (b) Schematic diagram and picture of such a photonic crystal in the microwave regime. (c) Simulations showing how microwaves pass by a defect in this photonic crystal, unimpeded (adapted from (Raghu & Haldane, 2008) (Wang, et al., 2009)).

A specifically-engineered semiconductor heterostructure for achieving this effect was proposed soon after (Bernevig, et al., 2006), and quickly realized experimentally (König, et al., 2007). Within a few years, several groups also predicted the stability of 3D versions of these time-reversal symmetric systems that had protected 2D metallic surface states (Fu, et al, 2007), which were again soon verified by experiments on multiple materials $Bi_{1-x} Sb_x$ (Hsieh, et al., 2008). There was soon an explosion of theoretical work that classified multiple types of topological insulators distinguished by the presence or absence of time-reversal symmetry, particle-hole symmetry, point group, and sublattice (or "chiral") symmetry (Ryu, et al., 2010).

In the past decade, predicted and discovered topological systems have moved beyond bulk crystals and heterostructures to layered 2D materials, and from band insulators to semi-metals. These systems may be characterized by protected conducting bulk, surfaces, edges, or corners (Figure 3). There are many kinds of topological systems with distinctions possible to be made between topological insulators and topological semimetals, symmetry protected topological phases, long range entangled topologically ordered systems, and even topological magnets in the form of spin-liquids (Balents, 2010) (Broholm, et al., 2020).

New approaches to discovering topological materials, particularly quantum chemistry techniques allowing for scanning of materials databases, have led to an explosion in the number of potential topological materials, from dozens to thousands (Zhang, et al., 2019) (Vergniory, et al., 2019) (Tang, et al., 2019). In parallel, researchers have realized that topology may not be fully determined by non-interacting band structures alone. Instead, interactions can drive symmetry breaking phase transitions that can cause or destroy topological behavior. Interactions may even drive qualitatively new topological phases of matter, as in the case of the fractional quantum Hall phases that arise in very clean 2D electron gases in strong magnetic field (Stormer, 1999).

Development of Bosonic and Classical Topological Systems

A breakthrough in expanding the context for topological physics came in the mid-2000s, when Haldane and Raghu first pointed out that topological robustness against disorder could apply not only to electronic transport, but to photonic transport as well (Haldane & Raghu, 2008) (Raghu & Haldane, 2008). Specifically, they predicted that carefully-engineered photonic crystals made of magneto-optical materials could have topologically non-trivial bands and thus host edge states that propagate unidirectionally along their boundaries, leaving no possibility for backscattering (Figure 4a). This led to the understanding that much of the physics associated with the quantum Hall effect was not fundamentally quantum, but rather a very general wave phenomenon. Soon after this realization, the group of Marin Soljačić experimentally demonstrated this effect in centimeter-scale photonic crystals for electromagnetic waves in the microwave regime (Figure 4b and c) (Wang, et al., 2009). The next challenge was to demonstrate this phenomenon for light, whose orders of magnitude shorter wavelength would require patterning on the nanoscale. Direct implementation of the Haldane-Raghu model on this scale was also challenging because the magneto-optical response in the IR and optical regimes is so weak that it does not support breaking time-reversal symmetry strongly.

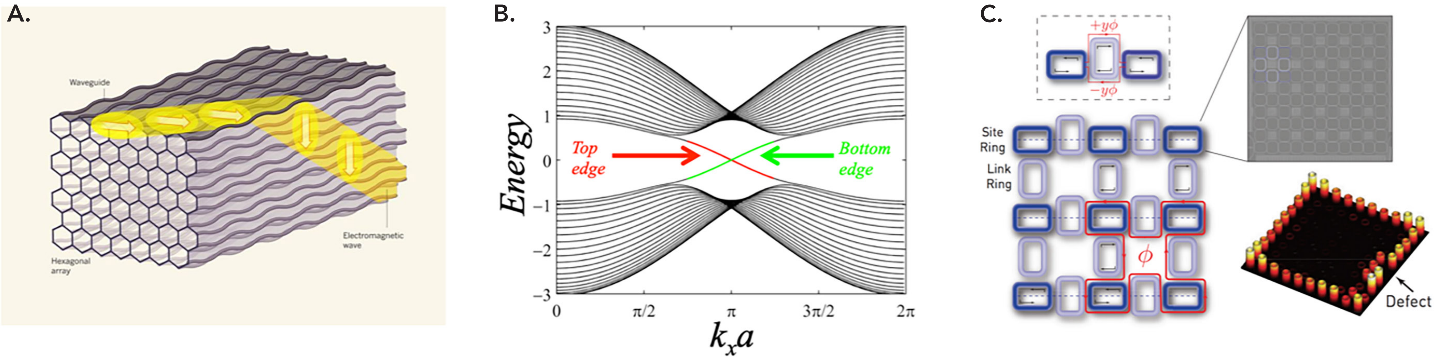

Figure 5 Examples of Photonic Topological Systems. (a) Schematic diagram of photonic topological insulator made of a waveguide array. (b) Typical edge state band structure: since counterpropagating edge states are on opposite sides (top and bottom edges), backscattering is disallowed. (c) Another example of a photonic topological insulator using photonic ring resonators (adapted from (Chong, 2013) (Rechtsman, et al., 2013) (Mittal, et al., 2018)).

This problem was eventually circumvented in 2013 in two distinct ways: chiral edge states were observed by (1) using a 3D helical photonic structure in the paraxial regime, where time-reversal symmetry was effectively broken in a 2D plane (Rechtsman, et al., 2013); and (2) using an array of coupled ring resonators (Figure 5) to implement two "copies" of the quantum Hall Hamiltonian, avoiding breaking time reversal symmetry (Hafezi, et al., 2013). Thus, the prediction and demonstration of protected edge states for photons from the microwave to the optical, along with demonstrations of optical topological phenomena in one dimension (Malkova, et al., 2009) (Kraus, et al., 2012) (Kitagawa, et al., 2012), brought about the field of topological photonics (Lu & Joannopoulos, 2014) (Khanikaev & Shvets, 2017) (Ozawa, et al., 2019).

It was soon realized that systems beyond optical and electronic can exhibit topological states. As a general wave phenomenon, topological protection can be observed for mechanical vibrations and sound waves as well. Parallel to topological photonics, this emerging field can be called "topological phononics". A series of seminal theoretical (Prodan & Prodan, 2009) (Kane & Lubensky, 2014) (Yang, et al., 2015) (Mousavi, et al., 2015) (Paulose, et al., 2015) and experimental (Nash, et al., 2015) (Süsstrunk & Huber, 2015) works laid the foundations for the study of the topological properties of mechanical and acoustic waves (see Figure 6). Phononic systems naturally give rise to strong nonlinearities, a compelling advantage over photonic systems. Topological phenomena are truly universal, a testament to this is the new understanding of equatorial waves as topologically protected chiral states (Delplace, et al., 2017), where time-reversal breaking arises due to the rotation of the earth. More than that, topologically-protected edge states have also been predicted (Karzig, et al., 2015) (Yuen-Zhou, et al., 2016) (Nalitov, et al., 2015) and observed (Klembt, et al., 2018) in exciton-polariton condensates and various topological phenomena have been studied in a range of ultracold atomic systems (both bosons and fermions) (Atala, et al., 2013) (Aidelsburger, et al., 2015) (Jotzu, et al., 2014).

Potential of Topological Systems

We have only begun to scratch the surface of the possible applications for topological materials. The most widely proposed application is topological quantum computing based on the potential that Majorana fermions should be present in some topological materials, heterostructures, and nanostructures. These Majorana fermions, which emerge from a combination of topological band structure, superconductivity, and sometimes magnetism, could be the basis for scalable solid-state qubits that are stable against decoherence. Topological magnetic materials may provide opportunities for energy efficiency and energy conversion, ranging from dissipationless conductors for computing or power transmission, to information processing expending dramatically less energy than the theoretical minimum

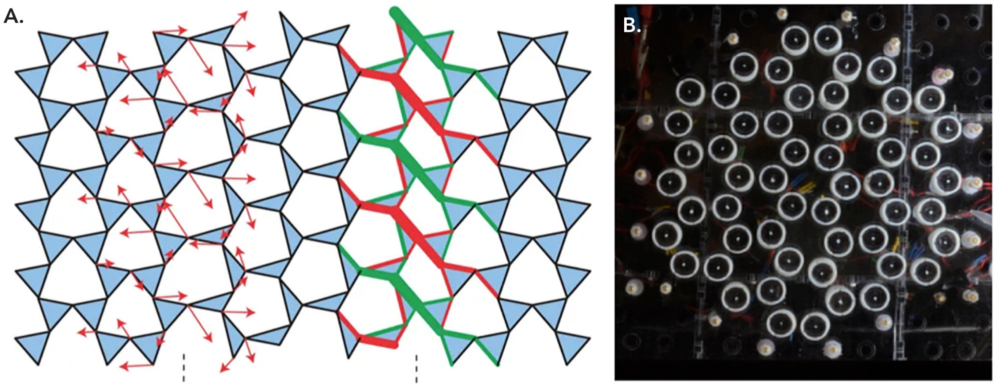

Figure 6 Phononic Topological Systems. (a) Schematic diagram of topological interface modes in mechanical isostatic lattices (Kane, 2014). (b) Bottom view of an array of coupled pendula; here, time-reversal symmetry is broken by gyroscopes inside each pendulum (Nash, et al., 2015).

for conventional transistors, to micro-Volt energy harvesting from a local environment. Topological electronic devices use topological surface or edge currents to manipulate magnetic states to store information, act as novel sensors, or enable compact nonreciprocal electromagnetic devices. Topological photonic devices will be fundamentally more resistant to fabrication disorder, and potentially have a small-footprint for wide-band operation of on-chip optical isolators and high-power single-mode lasers. Topological mechanics could allow for materials that distribute external forces on the surfaces of objects while protecting the interior.

Much work remains to be done in identifying materials possessing useful topological properties, exploring the full range of possible phenomena based on topological properties, demonstrating these topological effects, and determining how they may be exploited. In addition, there are sure to be useful properties of topological insulators, semimetals, and metamaterials that have not yet been discovered. A crucial aspect going forward will be optimizing materials, especially for transport that is robust against defects and disorder.

Workshop on Topological Systems

To explore the promise and challenges of topological science, a future directions workshop was held on July 30-31, 2019 in Arlington, VA. This workshop gathered more than 26 distinguished researchers from academia, industry and government from the condensed matter physics, photonics, and electronics communities for unfettered discussion and debate on the current research challenges, opportunities, and trajectory for topological science research over the next twenty years.

Designed primarily around small-group breakout sessions, participants engaged in open dialogues on three overarching questions:

- How might the research impact science and technology capabilities of the future?
- What are the most fundamental challenges to progress?
- What is the possible trajectory of scientific achievement over the next 10-20 years?

The two-day workshop was organized to encourage lively discussion and debate and to maximize the interaction of participants. The first day began with short, introductory presentation from the co-chairs to frame the workshop goals. The remainder of the day was spent in small group discussions on the fundamental challenges to progress and technical capabilities. These breakout sessions covered specific subdomains: solid-state electronic devices, strongly correlated electronic systems, and bosonic systems. Each session was led by an expert in the field and was followed by an outbriefing to the whole group.

The second day of the workshop began by reviewing the discussions of Day 1 followed by additional small groups to discuss any topics not covered in the first day and to map a research trajectory for each research area. At the end of the day, the participants were asked to write down their view on the most significant takeaways from the workshop that should be included in the final workshop report.

With this framework in mind, the following sections describe the research challenges and opportunities outlined at the workshop and maps a research trajectory for topological sciences over the next twenty years.

Research Advances and Opportunities in Topological Sciences

Since the theoretical predictions and experimental verification of 2D and 3D topological insulators, many new varieties of topological systems have been classified, predicted, and discovered. This section describes recent theoretical and experimental research advances and the exciting opportunities that are on the horizon for electronic and bosonic/classical topological systems.

Advances in Prediction and Discovery of Electronic Topological Materials

The topological classification of band structures has been extended to insulators (and superconductors) other than those defined in terms of the presence or absence of time-reversal symmetry, particle-hole symmetry, and chiral symmetry (Ryu, et al., 2010). These include those protected by crystal point group symmetries with discrete translations and rotations, termed "topological crystalline insulators" (TCIs). TCIs, such as SnTe, were predicted to have metallic surface states on certain high-symmetry crystal surfaces, protected by crystal symmetries rather than time reversal symmetry (Hsieh, et al., 2012). Proposals for materials which host both topological insulating electronic structures and magnetism led to proposals and the discovery of the "Chern insulators" and "Axion Insulators" both in the form of magnetically doped TIs (e.g. Cr doped $(Bi_{1-x}Sb_x)_2Te_3$) and, more recently, stoichiometric magnetic systems (e.g. $MnBi_2Te_4$) and moiré heterostructures (e.g. ABC trilayer graphene sandwiched with hBN). Recently proposed "higher-order topological insulators" have topologically protected gapless hinge states (at edges and corners) as a generalization to conventional TIs (Figure 3). Here, the boundary modes are proposed to be protected by spatio-temporal symmetries of materials, such as Bi and Bi_2TeI (Schindler, et al., 2018).

Beyond insulators, **topological semimetals** have been proposed which host protected bulk band touching points and surface "Fermi Arcs" in "Weyl semimetal" materials with broken inversion symmetry (e.g. TaAs) and broken time reversal symmetry (e.g. $Co_3Sn_2S_2$) and "Dirac semimetal" materials which preserve those symmetries (e.g. Cd_3As_2) (Armitage, et al., 2018). A variety of Weyl semimetals have been further categorized by the relationship of their energy to their momentum, includes type-II Weyl semimetal WTe_2 and $MoTe_2$ that have a "tilted" dispersion and hence open Fermi surfaces when slightly doped. These materials when isolated as monolayers represent an emerging class of 2D TIs. Four fold degenerate Dirac semimetals with linear band touchings and Luttinger semimetals with quadratic band touchings have also been realized (Armitage, et al., 2018).

Topological superconductors which support exotic boundary modes including Majorana fermions have been predicted in both bulk materials and engineered structures (e.g. hybrid structures combining superconductors, semiconductors, and/or magnets; chains of Fe atoms on superconducting surfaces).

An exciting new approach of the past few years is the development of "topological quantum chemistry" which has combined efficient rules for determining electronic topology with material databases to broadly classify the topology of thousands of materials. Interacting topological materials in which electronic correlations play a crucial role have been predicted (e.g. topological Mott insulators) with their experimental verification being an active area of current research (Zhang, et al., 2019) (Vergniory, et al., 2019) (Tang, et al., 2019). Interacting systems can reflect topology through symmetry-protected phases qualitatively similar to non-interacting topological insulators, or in a quite different way, in states with long range entanglement, such as fractional quantum Hall systems and spin-liquids (Wen, 2017).

As noted earlier, a hallmark of the last decade of research in this field was the key role of theory to predict not only the topological classes listed above, but also (through ab initio calculations) specific materials in which they could be and often were observed (Bansil, et al., 2016). These predictions motivated experimental physicists, chemists, and materials scientists to grow crystals and films of proposed topological materials. Many of the early experiments that supported theoretical proposals were based on scanning tunneling microscopy (STM) or angle resolved photoemission (ARPES) because those techniques are exquisitely surface-sensitive, can measure wavelength/momentum as function of energy, and (in case of STM) can give nanoscale lateral resolution. So even if there is disorder/doping such that the bulk is conductive one can obtain information on topology from these techniques. The balance has now changed as material quality has progressed to the point where often the bulk of a topological insulator is insulating and scattering is much reduced, so novel transport and magnetoelectric properties of topological insulators can increasingly be explored (Kushwaha, et al., 2016) (Koirala, et al., 2015) (Wu, et al., 2016).

As the field moves towards materials having increased electronic correlation, experimental exploration has begun to take the lead, inspiring theoretical studies (both analytical and computational) which aim to identify new states discovered in experiments. Further opportunities have emerged by considering hybrid systems. A new approach is to interface topological systems with another layer that brings a missing ingredient, to make new effective materials (Geim & Grigorieva, 2013).

Opportunities for Applying Electronic Topological Materials

The many properties of topological materials that are distinct from those of typical metals, semiconductors, or insulators may prove useful in electronic devices. In particular, topological materials generally manifest protected conducting states, either on the surfaces, edges, or even in the bulk (Figure 3). These states can be chiral, meaning that the current flows in only one direction. Topological insulators exhibit spin-momentum locking on their surfaces (or edges) which can lead to new types of spintronic and magnetic devices. Topological systems can be gapped or protected by symmetries, which means that a change in the system's symmetry or an external field may cause a topological phase transition, abruptly changing the properties of the system. Such topological phase transitions can be harnessed for efficient switches and ultrasensitive sensors not achievable with conventional mechanisms. Perhaps most exotically, axion electrodynamics, an exceptionally strong and quantized magnetoelectric coupling, effectively modifies Maxwell's equations in certain topological materials so that an electric charge can induce a magnetic monopole-like excitation, and vice-versa (Qi, et al., 2008) (Essin, et al., 2009) (Wu, et al., 2016). Such magnetoelectric coupling may enable more efficient nonreciprocal microwave and optical devices such as circulators. In short, distinctive properties of topological insulators suggest a range of possible topological devices having useful behaviors and properties not otherwise available. The first such device concepts are only just beginning to be realized experimentally, as described below:

Transistors and switches with more functionality. Whereas typical electronic switches (e.g., MOSFETs) involve applying voltages to semiconductors, to change the conductance from low to high, new types of switches can be created by inducing phase transitions between states in topological materials. In this case, possible tuning parameters expand beyond voltage to include electric and magnetic fields, strain, and material thickness. This may allow switching properties between conducting and insulating, topological and trivial, or dissipationless and resistive. For example, transitions from gapped topological surface states to non-gapped trivial states can be tuned by applied magnetic fields, which gap the surface states; Weyl surface states and topological Dirac edge states can be turned on and off by voltages; and 3D crystalline insulators can go through as many as five different phase changes. In some cases, the transition can be to a quantized state with robust edge conduction and bulk electromagnetic properties. The direction of the chiral edge states is reversible, and new edge states can even be introduced (Yasuda, et al., 2017) (Rosen, 2017) by manipulating the magnetic structure, which could lead to new types of switches. Related to topological switches are topological sensors, where a small change in a "sensed" parameter leads to a large change of state, i.e., tuning through a topological phase transition. Moreover, as a result of the gaplessness of topological systems, they have been proposed as long-wavelength (THz and mid-infrared) detectors (Lindner, et al., 2014).

Passive devices. Passive electronic components such as resistors, inductors, and capacitors may be advanced by new topological properties. Dissipationless topological surface states may enable interconnects that have lower resistance than copper. Topological surfaces are intrinsically thin, so topological films may be transparent and therefore useful in touch screens, to replace existing coatings such as transparent conductive oxides or carbon nanotube networks. Inductor technology is notoriously difficult to miniaturize, yet TIs patterned with magnets may induce large inductance at the nanoscale. Further, topological systems may have beneficial high-frequency responses (including reconfigurable steering of electromagnetic waves) not available in current passive electronic materials.

Magnetic and Spin-related devices. Properties such as spin-momentum locking, the magnetoelectric effect, and strong spin-orbit coupling give topological systems unique potential as magnetic and spintronic devices (Figure 7). Topological insulators have demonstrated large charge-to-spin conversion, useful for generating spin currents and spin polarization (Mellnik, et al., 2014). For example, topological insulators seem to act as the most efficient spin-pumps for switching small magnetic particles for MRAM (magnetic random access memory), though the exact mechanism is still disputed (Han, et al., 2017). Electrically-driven magnetism via the magnetoelectric effect or spin-orbit torque tuning may be useful for memory read/write applications with topological protection against non-magnetic external signals.

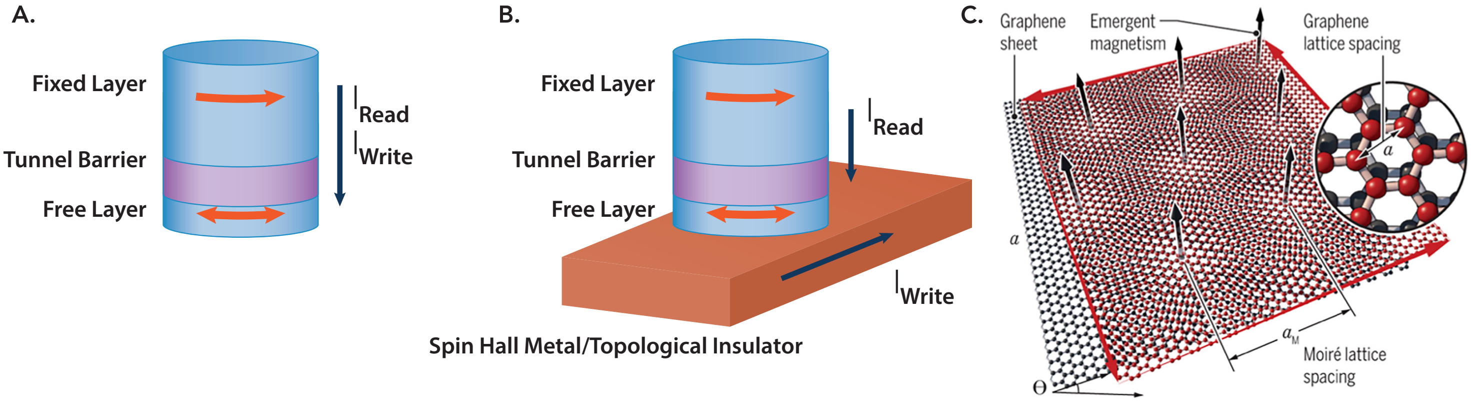

Figure 7 Topological Magnetic Memory Examples. (a) Existing commercial MRAM chips use a switching mechanism called spin-transfer torque where spin-polarized electrons cross a tunnel junction, imparting a torque to flip a small magnetic particle (the stored bit). (b) Spin-orbit torque is an alternative approach that offers a lower power and more scalable switching mechanism. In spin-orbit torque, current is driven through a material with strong spin-orbit coupling (a heavy metal or topological insulator) causing spins to diffuse into the small magnetic particle (through spin Hall effect) and thus flip the bit's magnetization. (c) Twisted bilayer graphene can be used to create a topological orbital ferromagnet. Current flowing through the plane of the sample switches the magnet without need for a reference layer or separate spin-orbit layer. The magnet works only below 10K but switching uses orders of magnitude lower current density than state-of-the-art spin-orbit torque MRAM. This may meet the need for ultralow power memory for classical computer to control classical computer. [Credits:(a) and (b) provided by Luqiao Liu at MIT; (c) Pixley & Andrei, 2019]

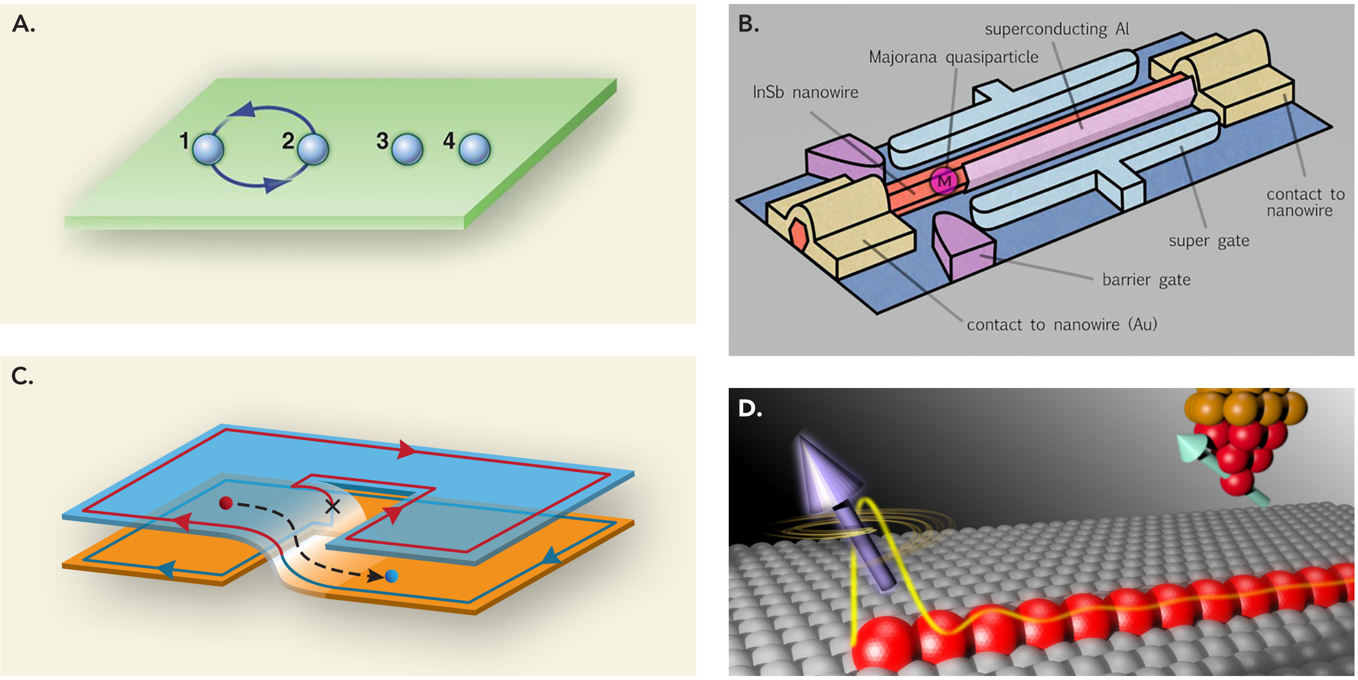

Figure 8 Majorana Fermions as Topological Qubits Examples (two Majorana modes constitute a single qubit). For conventional fermions and bosons, exchanging two of them does not change the wavefunction, except for adding a minus sign in the case of fermions. In contrast, exchanging two Majorana fermions (a) yields an entirely different wavefunction. (b) A topological superconductor wire may be engineered to host Majorana fermions at its ends by combining a semiconductor wire having strong spin-orbit coupling with a superconductor and a magnetic field. (c) Another platform for Majorana fermions is the interwoven edge states of a bilayer quantum Hall system. (d) A chain of magnetic atoms on a superconducting surface may also host Majorana fermions at each end. (Adapted from (Stern & Lindner, 2013) (Anon., 2019) (Barkeshli & Qi, 2014) (Zandonella, 2017)).

Quantum computation. Quantum computing was addressed in a recent workshop in this series, entitled Future Directions of Quantum Information Processing. As anticipated in that workshop's report, "Quantum Supremacy" has now been reported: a quantum computer appears to have performed a computation that would have been prohibitively lengthy on a classical computer. Yet this impressive achievement is still far from demonstrating a general-purpose quantum computer to run algorithms requiring millions of operations without losing coherence of the qubit states and their correlated superpositions. Qubit coherence has been improving exponentially for the past two decades, but recently shows signs of plateauing. We lack a clear roadmap for achieving the necessary coherence to allow quantum error correction and thus to run long algorithms. Topological quantum computing offers a possible path: the qubits themselves are nonlocal, so no local electromagnetic noise should be able to switch the state of a qubit. Inspired by this potential, academic and industrial researchers have been working to demonstrate a topological qubit. Encouraging spectroscopic signatures of majorana fermions (the right type of nonlocal two-state systems) have been reported in 1D semiconductor wires engineered to behave as 1D topological superconductors, and dramatic improvements in materials properties have led to concomitant improvements in electrical properties. Demonstration of coherence has so far remained elusive. A possible culprit: states within the superconducting gap, present in even the cleanest semiconductor/superconductor structures engineered to date, can couple majorana fermions that are supposed to remain fully spatially separated. But if one and two qubit gates can be achieved the topological approach may catch up with and surpass today's dominant approaches to quantum computing, by achieving ultralong coherence times.

New phenomena in correlated electronic topological materials. The vast majority of topological materials discovered so far are systems in which electrons can be considered weakly interacting. However, there is a tremendous possibility for new behavior when interactions between electrons are considered. For instance, Figure 9 shows that interactions can enhance the effect of spin-orbit coupling. In the particular model considered in (Pesin & Balents, 2010) it can stabilize a topological insulating phase and then, with increasing interactions, a topological band insulator can be turned into a "topological Mott insulator" characterized by gapless surface spin-only excitations (Pesin, 2010).

The behavior can be even richer, for example where interactions force broken symmetries and thus cause new topological functionality or totally new topological states of matter, much as fractional quantum Hall states appear due to interactions in 2D electron gases in high magnetic field. Fractional Chern insulator states have been proposed (and perhaps observed) in 2D (Regnault & Bernevig, 2011) (Parameswaran & Wan, 2017) (Bergholtz & Liu, 2013) (Sun, et al., 2011) (Spanton, et al., 2018), but the possibilities are even richer in 3D (Stern, 2016). A number of such topological systems with no non-interacting analogues have been proposed.

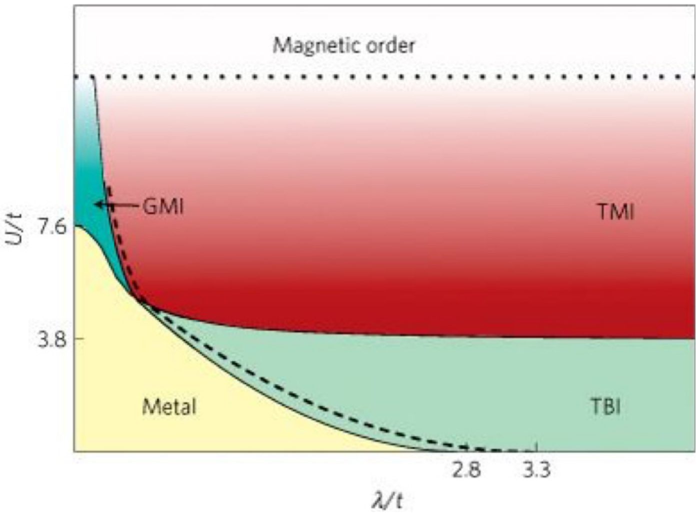

Figure 9 Correlated Topological Materials. Phase diagram for moderately strong electron-electron repulsion (as a function of Hubbard repulsion U and spin-orbit coupling λ, relative to hopping t). The four main phases include: Metal phase, Topological Band Insulator (TBI), Topological Mott Insulator phase (TMI), and Gapless Mott Insulator (GMI). The dotted line schematically separates the large-U region, where magnetic ordering is expected. As discussed in the text, long-range Coulomb interactions are expected to drive a TBI into a more-correlated TMI (Pesin & Balents, 2010).

New phenomena in heterostructures and their emergent phenomena. There has been considerable interest and results recently in various kinds of heterostructures or modified 2D systems (Mak & Shan, 2016) (Geim & Grigorieva, 2013). These systems may be layered, twisted, or stretched. Such an approach skirts the typical limits of solid-state chemistry, allowing new functionality from sandwiching of disparate layers that are not bonded together. For instance, new magnetic topological insulators can come from systems where a trivial magnetic layer is placed in contact with a topological insulator. Among other aspects, twisting provides a way to tune the relative scale of interactions. For 2D devices, there are different strategies for making useful structures including exfoliation and stacking, Van der Waals epitaxy (i.e., controllably growing disparate materials on top of each other without interlayer bonding), aligning 2D materials to create electronic superlattice structures such as moiré flat bands, and incorporating magnetic layers (both alloys and stoichiometric). Many of these devices require clean, non-oxidized surfaces and interfaces, so encapsulation is important (typically via additional insulating layers such as hBN).

New calculational schemes. As discussed above, an exciting new approach of the past few years is the development of "topological quantum chemistry" which has combined efficient rules for determining electronic topology with material databases to broadly classify the topology of thousands of materials (Zhang, et al., 2019) (Vergniory, et al., 2019) (Tang, et al., 2019). However, in some cases this approach completely fails to describe the actual behavior. For instance, Zunger et al. has recently emphasized that many materials identified as Weyl semimetals on the topological materials database are in fact insulating (Zunger, 2019). We should regard this as an opportunity to improve the approach, as well as consider how interactions can drive these systems into entirely new phases.

Advances and Opportunities in Bosonic/Classical Topological Materials

Topological protection is not an effect exclusive to electronic states in solid-state materials. Its effects can be observed in photonic, mechanical, acoustic, polaritonic, atomic, and geophysical settings. In many ways this is where the similarities end as these other wave systems are different in a fundamental way from electronic materials. To name several important differences: classical wave systems are very often not in thermal equilibrium; they can be open to the environment and often obey driven-dissipative dynamics; and in many cases, they do not conserve particle number, meaning that non-Hermitian effects are highly relevant (e.g., photons are lost due to material absorption or gained due to stimulated emission). Interactions do not originate from direct Coulomb repulsion but

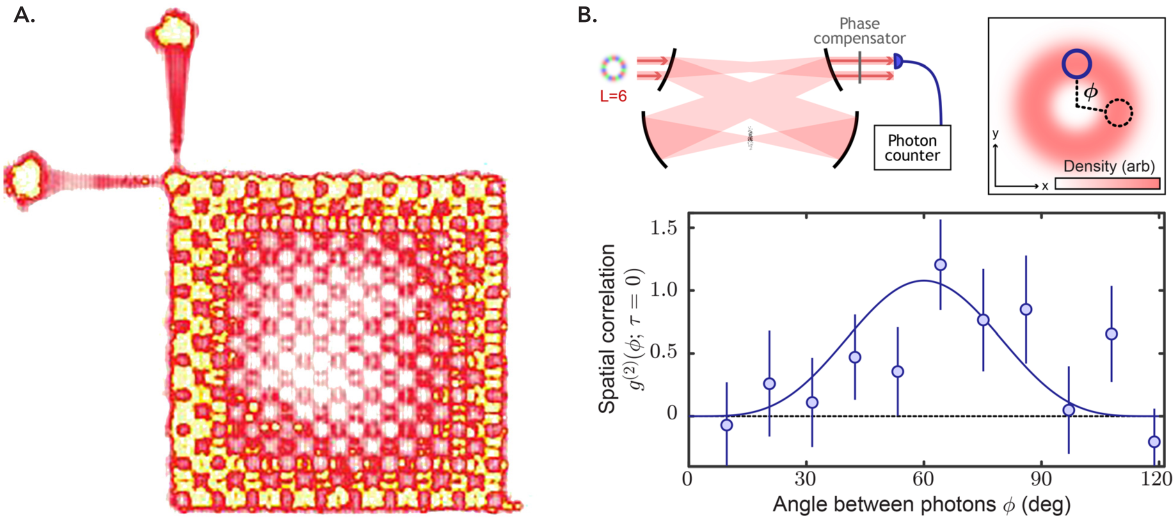

Figure 10 Topological Bosonic Systems. (a) Lasing mode in coupled-cavity photonic topological insulator laser (Bandes, 2018). (b) Schematic diagram and results for the measurement of a "Laughlin state puddle" in a Rydberg polariton system. Measured correlations correspond to those for a Laughlin state (Clark, et al., 2019).

arise due to mediation by the ambient material (e.g., nonlinear response of optical materials) and thus give rise to entirely distinct effects. Finally, but not least, typically such systems are highly tailorable and designable in a way that solid-state materials are not. Correspondingly, there have been important recent advances across these platforms that hold promise for developing new fundamental topological physics, as well as its implications for technology. We list several examples below.

Nonlinear and interacting topological bosonic systems. Pushing beyond linear dynamics into the nonlinear/interacting regime will be essential for exploring the richness of topological physics in the classical and bosonic domains. The recent observation of Laughlin states in a Rydberg polariton system (Clark, et al., 2019) is a prime example (Figure 10b). Nonlinearity and inter-particle interaction are expected to define a broad new interest in topological nonlinear optics (Mukherjee, 2019). At this point there are more questions than answers: How do solitons, nonlinear instabilities and chaos translate to the topological domain? In what ways can nonlinear topological devices be protected? How do topological systems thermalize differently from conventional systems?

Open topological bosonic systems. Conventional solid-state topological materials are based on a Hermitian description because electron number is conserved. This is not true of photonic systems, for example, with lossy elements or in those with gain, such as lasers. The study of non-Hermitian topological physics has therefore become a major topic of interest. Specific open questions include: what are the right non-Hermitian topological invariants (Zeuner, et al., 2015) (Leykam, et al., 2017) (Shen, et al., 2018), and how do they directly connect to physical observables? What are the fundamentally new topological effects that arise from non-Hermiticity (e.g., bulk Fermi arcs (Zhou, et al., 2018) (Zhen, et al., 2015) (Cerjan, et al., 2019), the non-Hermitian skin effect (Yao & Wang, 2018))? What are the new dynamics that arise from topological lasing (Figure 10a), an intrinsically non-Hermitian effect (Peano, et al., 2016) (Harari, et al., 2018) (Bandres, et al., 2018)?

Topological bosonics in three dimensions. Many topological phenomena arise in three dimensions, rather than two. As discussed above, Weyl semimetals in solid-state systems are a hallmark example. The observation of bosonic Weyl points in photonics in the microwave (Lu, et al., 2015) and optical (Noh, et al., 2017) domains, as well as in circuit-based (Lu, et al., 2019) and mechanical systems (Xiao, et al., 2015) represent the analogue of solid-state Weyl semimetals. They are endowed with similar properties: conical dispersion bands and Fermi arc surface states. That said, their potential applications are entirely different. Consider the following example. A typical trade-off in laser physics is between high power and beam quality (the larger the cavity, the more modes in a given frequency range). A type-I Weyl point has zero density-of-states and could thus be used in a laser cavity to extract high power with maximal mode purity. Pushing forward in this direction will require the development of 3D fabrication methods, including nanoscale 3D printing and infiltration. Yet another topological phenomenon that will benefit from such developments will be 3D photonic topological insulators (Slobozhanyuk, et al., 2017) (Yang, et al., 2019), which have surface states consisting of isolated Dirac cones that are resistant to Anderson localization.

Higher-order topological systems. Conventionally, a 2D quantum Hall system will give rise to protected 1D edge states, or a 3D topological insulator will give rise to protected states at 2D surfaces. Higher-order topological materials (Benalcazar, et al., 2017) (Noh, et al., 2018) (Peterson, et al., 2018) (Serra-Garcia, et al., 2018) (Mittal, et al., 2019) are those that topologically protect states more than one dimension below the ambient one. This has obvious implications for photonic devices, in particular for creating robust cavity modes in 2D and 3D integrated photonic platforms, as well as waveguides that are immune to radiative loss and backscattering. Again, this is a phenomenon that will require development of advanced 3D fabrication methods.

Bound states in the continuum (BIC). BICs are states (whether electronic, photonic, mechanical, or otherwise) that can be topologically protected against radiating despite being resonant with radiative continuum modes. These counter-intuitive states clearly go beyond the conventional topological mold that relates to bulk-boundary correspondence, and have a range of applications, particularly where large-area resonators are important; this includes low-threshold lasers, chemical and biological sensing, surface acoustic wave devices, and others. (Hsu, et al., 2016).

Synthetic dimensions. It has been shown to be possible using the exquisite tunability of photonic and atomic systems to realize physics in higher dimensions than those that are available in physical space (i.e., a maximum of 3 spatial dimensions). These “synthetic dimensions” (Jukić & Buljan, 2013) (Celi, et al., 2014) (Ozawa, et al., 2019) (Yuan, et al., 2018) allow the realization of rich new physics that may have implications for realizing new states in physical reality. An example of this (in retrospect) is the discovery of quasicrystals: aperiodic crystals that are irrational projections from higher dimensions (e.g., 6D into 3D in the case of typical icosahedral quasicrystals). The implications of synthetic dimensions for topological systems is a topic of ongoing research and relates closely to the notion of “dimensional reduction” and “dimensional extension” which are used as intuitive bases for various topological insulator models.

Quantum topological bosonic states. The dynamics of quantum states in topological materials has been of recent interest (Barik, et al., 2018) (Mittal, et al., 2018), particularly due to the experimental use and accessibility of entangled photons from the microwave to the optical regimes. Theoretical proposals have introduced the idea of robustly generating squeezed states and optical amplifiers / lasers with distinct entanglement characteristics (Peano, et al., 2016). Exploring the implications of topological protection to quantum fragility has been extensively studied in the context of electronic Majorana physics, but the bosonic / classical domain remains relatively unexplored. Although it is not expected that bosonic systems will provide a similar mechanism of protection against decoherence as Majorana fermions, other forms of topological protection for bosonic states may arise.

Research Challenges in Topological Sciences

The research challenges to achieving the opportunities for topological systems are described in this section for both electronic and bosonic/classical systems.

Electronic Topological Systems Challenges

Challenges in making materials. A major challenge is to improve materials quality. Disorder is still a significant issue for most known compounds, where isolated topological surface or edge states are difficult to achieve because of large disorder. In single crystals, inadvertent doping through off-stoichiometry (and in thin films, layer variations) continue to be limitations toward growing materials having ideal topological properties (e.g, low disorder, a controlled Fermi level). Although there have been some successes by a few groups for growing truly insulating topological insulator crystals (Kushwaha, et al., 2016) and films (Koirala, et al., 2015), it continues to be a challenge for most groups to grow topological materials with the Fermi level reliably in the bandgap.

Many topological materials have intrinsically small band gaps and a tendency to form rare regions with even smaller gaps. This limits the observation of topological phenomenon, and the use of these materials as switches between topological regimes, to low energies. Moreover, many current materials do not exhibit topological properties at high temperatures. In chalcogenide quantum anomalous Hall systems (Chang et al., 2013), precisely-quantized Hall conductances have only appeared below 1K (Fox, et al., 2018) (Götz, et al., 2018). It will be very important to develop materials that exhibit these effects to much higher temperatures. Although it is possible that refinements to existing materials, e.g. (Mogi, et al., 2015), will eventually result in high temperature operation, it is more likely that entirely new material systems will have to be fabricated.

New measurements sensitivity to topology. There is vital need for new measurement schemes to measure topological properties. For instance, nonlinear probes of solids have been proposed to be essential probes of the intrinsic topological nature of materials (i.e., their Berry phase physics) (Sipe & Ghahramani, 1993) (Virk & Sipe, 2011) (Attaccalite & Grüning, 2013) (Morimoto & Nagaosa, 2016). As an example, the extremely large second order "shift current" response in an inversion symmetry breaking Weyl free fermion semimetal is a measure of their Berry curvature. Nonlinear effects in topological materials is a very promising but still under investigated area with little theory and even fewer experiments (Rees, et al., 2019). It is particularly promising, because it may be a unique way to access the Berry phase physics that is believed to be an essential but hard to quantify, aspect to these materials. It is unclear to what extent this nonlinear response will be affected by electron-electron interactions; this will be an important area of investigation going forward.

Measurements in the extended THz range (0.1—40 THz), targeting low energy emergent degrees of freedom, are essential. But experiments using the full complement of photon energies up through the near infrared regime will also be important. Such probes should be applied to a variety of topological insulators, Weyl semimetals, Dirac semimetals, and 2D transition metal dichalcogenides.

Challenges in fabricating and measuring heterostructures. There has been tremendous recent interest in making heterostructures of exfoliated systems by layering, twisting, and stretching known compounds (Geim & Grigorieva, 2013) (Wang, et al., 2019) (MacDonald, 2019) (Cao, et al., 2018). It is still unknown what new topological properties may emerge at interfaces, particularly in the case of difficult-to-calculate "fragile" topological states. Process limitations for many topological materials include temperature (for chalcogenides), etches, and damage by electron beams. A major limitation in hybrid and layered topological devices is understanding interfacial coupling (magnetic/strain/electrical). Further, if prepared in the usual fashion by exfoliation, samples are small (tens of microns) and hence many conventional experimental probes are unusable. Developing spectroscopies that can be applied to such small systems, e.g. THz-on-a-chip systems and micro Raman scattering, is essential (Gallagher, et al., 2019).

Challenge to experimentally realize systems that depend on strong interactions. We know that many topological phases (both topologically ordered and symmetry-protected) require strong interactions. Famous examples include the topological order realized in fractional quantum Hall states and quantum spin liquids (Balents, 2010) (Savary & Balents, 2017) (Stormer, 1999) (Tsui, et al., 1982). However, many other possible interacting topological phases have not been realized experimentally: numerous theoretically predicted topological superconductors, and 2D and 3D systems whose gapless surface states carry quantum numbers different from those of the electron (e.g. fractional electric charge, spin but not charge, etc.). In systems where interactions are weak, sophisticated approaches to predict band structures have enabled rapid identification of materials realizing a variety of topological insulators and semi-metals, vastly expanding the range of material properties at our disposal over the past decade. In interacting systems, in contrast, our ability to predict a given material's behavior is much more limited. Therefore, new theoretical approaches are needed for predicting these interacting topological phases of matter.

The recent discovery of flat bands in van der Waal (vdW) multilayers (MacDonald, 2019) (Cao, et al., 2018) suggests new approaches to realizing strongly interacting systems in diverse classes of materials, beyond localized f-electron systems and Landau levels. Flat bands should be considered a generic mechanism (i.e. an "organizing principle") to enhance the relative role of interactions. It is important to determine how we can realize materials with such properties and devices made from them. We need to identify larger classes of materials that may have this physics, beyond twisted bilayer graphene. In terms of more sophisticated approaches, theoretical methods for deterministic predictions of correlated electron physics fail for large Hilbert spaces. Theoretical treatment of correlation physics can be easier for reduced size Hilbert spaces that appear in a small isolated set of flat bands, where other bands can be neglected. It is thus of interest to develop theories that demonstrate how relevant model Hamiltonians may be realized in real materials. This may lead to the guided use of layered materials and designer bulk single crystal materials as test beds to engineer higher order interactions in the real world.

How do topology and correlations influence each other? For example, flat bands can cause strong correlations, as shown in moirés of vdW heterostructures, but correlations can clearly also influence band structures. Pesin and Balents made a specific calculation for 3D Ir-based pyrochlores (Figure 9) to show that increasing interactions enhances spin-orbit coupling and stabilizes topological insulating phases (Pesin & Balents, 2010). Similar approaches should be investigated, particularly for 2D structures. For instance, sliding charge density waves might induce topological transformations. How can one select for specific instabilities driven by a large flat-band density of states? Which ingredients stabilize flat band systems, and what is the role of other nearby electronic bands given that all energy scales (interaction, bandwidth, band gap) are comparable in some 2D moirés?

Topological Bosonic/Classical Systems Challenges

One of the key motivations for studying topological physics outside of the condensed matter context is the presence of new effects that have no direct parallel in solid-state materials. The standard linear (i.e., non-interacting) description of topological systems is the same regardless of platform, but when nonlinearity is introduced, things change dramatically. As a result, topological nonlinear dynamics is a major, mostly unexplored frontier—whether in the nonlinear Schrödinger equation, the Navier-Stokes equation, or otherwise. The topological description of linear systems is well-formulated and fully established. However, it remains a major challenge to establish a theory of topological protection of nonlinear waves. More specifically, key future questions include: what are the nonlinear phenomena that arise as a result of topological protection and only in topological systems? What is the topological description of solitons in topological band gaps? In what sense can we label nonlinear topological edge states as protected? How can photonic Laughlin states be used to probe new fractional quantum Hall dynamics, or used for protecting quantum information? What is the interplay between nonlinear/interacting dynamics and non-Hermiticity (i.e., loss and gain)? Nonlinear dynamics provides rich new frontier of exploration that would be inaccessible outside artificially structured/bosonic/classical systems. However, an overarching theory for nonlinear topological systems has not been put forward. Presumably, such a theory (or theories) will lead us to new ways in which topology and nonlinearity can be more than the sum of their parts.

Many bosonic systems are open to their environment in a way that electrons in the solid-state are not. For example, in optical devices, photons can be lost by absorption and are gained coherently in lasers. This motivates inquiry into the interplay between non-Hermiticity and topology, as described above. Despite the significant attention that this direction has received, there is still significant controversy on the ways in which non-Hermitian topological invariants manifest themselves physically. What is the most natural definition of a non-Hermitian invariant, as motivated by an experiment, akin to the Hall conductance, or non-scattering edge states? What is the new observable that arises only as a result of non-Hermiticity? Answering these theoretical questions will have direct physical implications to the description of devices such as topological lasers.

One of the most important contemporary challenges is identifying and developing the new technologies that will arise from this fundamentally new bosonic/classical topological wave dynamics. Perhaps the most commonly discussed is the potential for topological systems to provide robustness to fabrication imperfections. Nanofabrication technologies (e.g., photolithography, electron-beam lithography, among others) are ubiquitously important to innumerable devices but can be costly and are limited in production speed, yield, and resolution by imperfections. How and to what extent can topological protection thus improve speed, lower cost, and increase functionality tolerances of nanofabrication? To take a specific example, nanofabrication of integrated photonic devices by two-photon polymerization in three dimensions is highly limited by resolution constraints such that device functionality is largely limited to the mid-infrared regime. Can topological protection allow this relatively new technology to be pushed into the near-infrared / telecommunications band and visible light regimes? Perhaps tolerance to defects will push forward bottom-up nanofabrication strategies that are prone to defects that would have been impractical otherwise, such as self-assembly of colloidal particles or block-copolymers (Fruchart, et al., 2018), at the scale of 10s of nm or below. Besides resistance to scattering, it will also be important to ask whether topological protection provides some resistance to absorptive/radiative loss.

A number of proposed technologies may benefit from topological protection in a way that would be impossible in conventional systems. A new mechanism has been proposed and realized for lasers that takes advantage of the extended nature of chiral edge states (despite disorder) (Bandres, et al., 2018); a recent proposal (Guglielmon & Rechtsman, 2019) shows how such states can overcome the trade-off in slow-light systems between increased bandwidth and reduced group velocity. A major technological challenge in integrated photonic devices is the realization of optical isolators (i.e., diodes for light); topological edge states provide a novel mechanism that potentially allows for significant on-chip footprint reduction. For a number of these (and other) applications, a central challenge is to open up a large band gap in photonic crystals via time-reversal symmetry breaking. Perhaps the most straightforward way to do this is to use magneto-optical materials with large Verdet coefficients. A major challenge here (Bahari, et al., 2017) is that magnetic response is very weak in the optical frequency regime (though it can be large and effective in the microwave)

(Wang, et al., 2009). Finding high-Verdet-constant materials and/or operating at cryogenic temperatures (at least for proof-of-concept demonstrations) may be a reasonable route. Another potential route to opening topological band gaps in photonic crystals is all-optical modulation at high frequencies (He, et al., 2019). This is a major challenge due to the need for a highly nonlinear material that operates with low linear and nonlinear loss and with high modulation strength. This is both a photonic design and materials challenge: a working device will require a photonic crystal with an optimized structure and a very highly nonlinear material (lithium niobate is a preliminary candidate (He, et al., 2019)).

In another application, higher-order topological systems can potentially be used to protect cavity modes in 2D photonic crystals, and guided modes in photonic crystal fibers. For realizing and developing 3D bosonic topological phenomena (e.g., Weyl point systems, 3D TIs, higher-order TIs that support hinge modes), it will be important to explore and improve 3D fabrication methods such as nano and microscale 3D printing (Deubel, et al., 2004). In many different contexts, realizing robust, topologically-protected wave states are bound to have a significant impact on device functionality, whether in photonics, polaritonics, acoustics/mechanics or otherwise.

> *"For robustness in applications, such as small-footprint integrated optical isolators and circulators, nonlinear devices, and topological lasers, a central challenge is to open up a large band gap in photonic crystals via time-reversal symmetry breaking."*

Research Trajectory for Topological Systems

The workshop participants outlined a research trajectory to overcome the research challenges described in the previous section, over the course of the next two decades. This section describes the research trajectory for electronic and bosonic/classical systems.

Electronic Topological Systems: Interactions + Topology

The research trajectory for solid-state topological systems is described in Table 2. A fundamental driver will be theory and experiment for systems that combine interactions and topology. As noted previously, theory and computation have powerfully guided choices of materials systems and structures for seeking topological physics, when interactions can be ignored. In comparison, our capacity to predict what interacting topological phases may appear in a particular material is extremely limited. Going forward it will be essential to improve the predictive power of theory at the intersection of interactions and topology. Because of the profound challenges involved in predicting (rather than explaining in retrospect) which phase will be the ground state in any correlated material, a fruitful approach may be to theoretically identify the ingredients required to favor strong correlations together with topologically nontrivial bands and then identify ways to engineer these combinations in heterostructures or through spatial patterning.

Looking back at what has been successful so far, there are two approaches that can guide research moving forward:

(1) The approach in theoretical works that culminated in experimental platforms to realize Majorana bound states (and potentially, someday other types of non-abelian anyons) in topological superconducting nanowires (Kitaev, 2001) (Lutchyn, et al., 2010) (Oreg, et al., 2010) (Mourik, et al., 2012). The theoretical insights about how to combine different materials have driven substantial experimental progress towards realizing these exotic excitations, opening a route to realizing topologically protected qubits.

(2) The development of a theory of engineering flat band systems in 2D moiré lattices (MacDonald, 2019) (Cao, et al., 2018). Work in this area could not predict which correlated phases would emerge (until Jarillo-Herrero's discovery of correlated insulators and superconductivity spurred more intense theoretical interest), but it did accurately indicate the conditions for producing correlated phases, which now include correlated topological phases (Chern insulators) (Spanton, et al., 2018) (Sharpe, et al., 2019) (Chen, et al., 2019) (Serlin, et al., 2019). Stimulating similar theoretical efforts to describe a broader range of interacting topological matter would open avenues to experimentally realize new types of correlated phases.

Topological protection of electron transport has been largely restricted to low temperatures, while topological protection of quantum information has not yet been demonstrated. Bringing these phenomena toward room temperature will likely require deterministic control of magnetism in topologically nontrivial band structures. This might be achieved through the epitaxial growth of magnetic topological materials or by stacking or growth of van der Waals materials to produce 2D moiré lattice bands which in turn manifest high temperature orbital magnetism.

In more detail:

(1) High temperature QAH and Weyl semimetal phases may emerge in a single stoichiometric compound such as the recently-identified topological magnet $MnBi_2Te_4$, or in heterostructures of topological materials with ferromagnetic or antiferromagnetic insulators. Such compounds, and the components of heterostructures, are likely to first be identified as bulk materials, grown and characterized as single crystals, before a small number are selected for epitaxial thin film growth. Breaking of symmetries will be an important design criterion for compounds or heterostructures. In heterostructures, magnetic exchange, superconductivity, spin-orbit coupling, and other properties will need to be transferred across interfaces, which must accordingly be extremely clean, and designed for efficient transmission.

(2) Heterostructures whose moiré lattice bands have topological character may be formed either by epitaxial growth or by van der Waals stacking. Such engineered materials may support orbital polarization (magnetism), and thus be Chern insulators at B=0, even without strong traditional spin orbit coupling, which is needed for approach (1) above. We have seen that magnetism can be controlled electrically by driving current; mechanisms for this based on bulk and/or edge conduction have been proposed but not yet tested. Pushing energy scales high enough to support room temperature correlations may require shrinking the moiré cell to 5 nm or below. We do not yet know how to make this consistent with formation of flat bands, but the many controllable structural parameters may offer a pathway to this.

If these two classes of structures yield topological order at high temperature and zero magnetic field, they may host exotic states with fractional Chern number (so far only seen at high magnetic field (Spanton, et al., 2018) or integer Chern number greater than 1 (Chen, et al., 2019). Any applications will look very different from existing technologies: a platform for realizing topologically-protected quantum computation, metrological standards that can be deployed broadly (no magnetic field needed), classical and quantum memory and logic.

Conventional low energy electromagnetic spectroscopy methods do not work in the regime where the wavelength of the light used is larger than the sample of interest: there is too little absorption or reflection to detect, or the experimental data cannot be linked quantitatively to properties of the material. This would typically be the case in THz spectroscopy where hundreds of micron wavelengths are used, but many exfoliated or heterostructure materials are tens of microns in size. Non linear or near-field spectroscopy (particularly at low frequencies), optical spectroscopy (with challenging theoretical modeling), micro Raman scattering, or scanning tunneling spectroscopy may be the best existing probes to isolate the essential Berry phase physics in many of these compounds. Development of new probes will be key, as will growth and patterning of larger-area samples.

Most important in all of this is to keep an open mind about what we might find when combining correlations with topology. Our community has consistently been surprised about the unexpected phenomena that have appeared in interacting states of matter. There is every reason to believe that profound new discoveries await us here again, as interactions are married to topology.

Table 2 Electronic Topological Systems

Research Areas	5 years	10 years	20 years
(1) Control of correlated topological states from flat band engineering	- Benchmark accurate theoretical methods for finding systems with flat bands beyond Landau levels - Realize epitaxially grown 2D flat band systems and/or mechanically stacking large-area single crystal 2D films, to host controllable topological physics - Leverage flat bands to realize robust topological states (quantum anomalous Hall effect, quantum spin Hall effect, fractional Chern insulators at B=0)	- Develop better methods for using experiment-theory feedback for accurate simulation of realistic 2D correlated systems - Identify interesting excited state properties (e.g. topo. boundary modes, at high energy density)	- Achieve room temperature orbital magnetism - Achieve room temperature superconductivity
(2) Approaches to discovering interacting topological materials in bulk systems	- Investigate ingredients required to realize, topological Mott insulators, correlated Weyl systems, spin liquids with topological surface states, spin liquids with bulk Dirac or Weyl cones	- Demonstrate robust high temperature and higher frequency results for topological effects in new materials - Identify promising material platforms, and spin liquid candidates for competitive memories, and spin detectors. Explore mechanisms for manipulation, writing and readout	- Incorporate novel topological materials in production - Achieve first demonstrations of compute-in-memory using topological magnetic memories
(3) New methods to measure and characterize low energy electrodynamic response	- Continued development of non-linear spectroscopy experiments on free-fermion systems - Advance nonlinear optical spectroscopy on interacting topological systems - Achieve further development of THz on-chip spectroscopy - Achieve further development of tools like near field IR measurements and micro Raman for understanding spectroscopic properties of van der Waals and exfoliated systems	- Understand how correlations affects nonlinear response of topological systems - Achieve fast and accurate determination and characterization of the topological properties of new and correlated materials	
(4) Identifying, detecting, or analyzing novel correlations with novel probes	- Determine right signatures and excited state properties - Apply high spatial and energy resolution techniques	- Develop techniques to manipulate symmetry breaking to control topology	- Achieve measurements of entanglement entropy in a solid-state system

Table 2 Electronic Topological Systems (Cont.)

Research Areas	5 years	10 years	20 years
(5) High temperature topological protection in intrinsically correlated materials	- Identify best materials for quantum anomalous Hall effect, 2D quantum spin Hall - Characterize interfaces for combining materials with different functionality (higher quality hetero structures) - Realize medium-temperature topologically- protected states	- Engineer best materials for the realization of high-temperature topologically protected topological states. - Achieve practical control and understanding of interfaces for combining materials with different functionality - Demonstrate prototypical devices that incorporate quantum interconnects at elevated temperatures	- Achieve room temperature QAH, high Chern number QAH for interconnects, metrology, magnetic devices - Achieve room temperature topological order (fractional Chern insulators) for topological quantum computation
(6) Detectors and devices based on topological effects	- Demonstrate non-quantitative detection of some part of the electromagnetic spectrum using topological effects, including axion electrodynamics - Demonstrate operation, frequency control, and limitations at 4K for inductors and circulators - Demonstrate electrically driven topological phase transition at cryogenic temperatures and identify ingredients and desirable parameters to make such transitions sharp and robust	- Expand the spectral range of such phenomena (e.g. from THz to near IR) - Demonstrate 80K operation of inductors and circulators; identify what limits temperature of operation and other performance (losses, imperfect nonreciprocity) - Demonstrate memory element based on Chern insulators - Build ultralow power and fast memory to operate at or below 4K - Demonstrate steeper-than-kT subthreshold slope for topological phase transition based switching	- Demonstrate topological-enabled sensing at room temperature - Demonstrate passive device operation at room temperature - Demonstrate switching of orbital ferromagnetism at room temperature - Demonstrate sub-kT subthreshold slope at room temperature
(7) Topological quantum computation	- Demonstrate coherence of Majoranas, and 1 and 2 qubit gates in semiconductor nanowire-based system - Demonstrate evidence of Majoranas in 1-2 other systems	- Compare different systems and understand limits/ scaling of coherence times with materials parameters - Demonstrate Majorana coherence in one other system - Apply compact QAH circulators operating at or below 4K to quantum computation	- Achieve 10 logical qubit topological quantum computer
(8) Spin-orbit Torque-based MRAM	- Understand mechanism of spin-orbit torque in TIs at both low and room temperature - Identify limits and opportunities for improved properties of spin-orbit torque based on new materials	- Apply these insights to achieve improved spin-orbit torque at room temperature	

Topological Bosonic/Classical Systems

The research outlook for bosonic/classical topological systems is described in Table 3. As discussed previously, topological protection is a universal wave phenomenon that, under the right conditions, can be applied not only to electronic states but all other wave states, as well. This opens the possibility of exploring and exploiting topological physics in disparate and conventionally unrelated domains, including photonics, mechanics, acoustics, atomic physics, and even geophysics (among others). In these contexts, topological behavior can be explored in the quantum (e.g., entangled photons in resonators) and the nonlinear/interacting (e.g., ultracold atoms in optical lattices or nonlinear optical waveguides) domains. Most often, such systems operate at room temperature, offering the possibility for widespread adoption of technologies based on topological designs that are more robust to disorder.

As an admittedly abstract topic of inquiry, it can certainly be a challenge to convey the importance and utility of topological behavior as it applies to the range of highly distinct systems described above. Perhaps it is clearest to think of it as a way of scaling up systems that contain many components. Disorder in highly complex devices prevents the large number of components (e.g., photonic resonators) from "working together" seamlessly. At its most elemental, topological protection mitigates this: by resisting disorder-induced wave trapping ("Anderson localization"), it allows for larger and larger systems to work in concert. This is the principal reason that this phenomenon is seen as promising for its possibility to allow for higher-yield and more inexpensive micro- and nanofabrication.

That said, as explained above, there are many other possible applications of topological behavior of bosonic and classical waves. Much of the ongoing research is geared towards understanding the effects of phenomena that do not commonly arise in solid-state physics: the effects of gain and loss (non-Hermiticity) and open-system dynamics broadly; the effect of bosonic-type interactions and nonlinearity; and the implications of the ultimate designability of wavelength-scale topological devices (as distinct from solid-state systems). We expect the next several years to bring about new fundamental theories about these properties as well as experimental milestones towards the utilization of topological physics across technological domains.

Table 3 Topological Bosonic/Classical Systems

Research Areas	5 years	10 years	20 years
(1) On-chip non-reciprocal photonic topological insulators	Large-band gap (>10nm) non-reciprocal topological photonic crystal	Wide-band integrated optical isolators with small footprint, on the length scale of 1-10 micron	Orders-of-magnitude smaller-footprint optical devices due to robust topological slow light
(2) Topological nonlinear optics	Nonlinear theory of topological invariants	Fully integrated nonlinear photonic devices based on magneto-optical chiral edge states	Wide application of topological protection in highly nonlinear photonic devices, such as integrated frequency combs and entangled photon sources
(3) Topological quantum optics	Optomechanical chiral edge states (possibly exhibiting protected squeezed light)	Topologically protected quantum communication	Topologically robust and bright sources of single and entangled photons
(4) Topological non-Hermiticity and lasing	Full classification of non-Hermitian topological systems, including invariants that correspond to measurable physical quantities	Narrow-line protected lasing via BICs	Highly defect-tolerant semiconductor topological lasers for telecommunications applications
(5) Strongly interacting optical topological systems	Realization of novel fractional quantum Hall phases with light	Topological protection of circuit-QED-based qubits	Topological quantum computing with light
(6) New uses of topological protection in technology	Demonstrate suppression of backscattering in nonlinear processes (e.g., stimulated Brillouin scattering)	Topological photonic crystal fiber based on protected higher-order modes	Defect-tolerant self-assembled subwavelength photonic devices
(7) Micro and nanofabricated three-dimensional topological photonics	Advancements in 3D fabrication for topological materials (e.g., Weyl materials) in the optical frequency regime	Fully-protected radiation-free octupole cavities in integrated 3D photonic crystals	Narrow-line and high power lasers based on type-I Weyl points in 3D photonic crystals

Conclusion

This report summarizes workshop discussions about the opportunities, challenges, and research trajectory for the nascent field of topological sciences. The workshop participants were optimistic about the prospects of topological materials, especially because of exciting developments with bosonic and correlated electronic systems. They emphasized the high potential of profound new discoveries when strong interactions are combined with topology. The participants anticipated that the next several years will bring about new fundamental theories about topological properties, as well as experimental milestones towards the utilization of topological physics at higher temperatures and across technological domains.

Bibliography

Aidelsburger, M. et al., 2015. Measuring the Chern number of Hofstadter bands with ultracold bosonic atoms. *Nature Physics,* 11(2), pp. 162-166.

Anon., 2019. *Majorana trilogy completed.* [Online] Available at: https://qutech.nl/majorana-trilogy-completed/[Accessed 2019].

Armitage, N. P., Mele, E. J. & Vishwanath, A., 2018. Weyl and Dirac semimetals in three-dimensional solids. *Reviews of Modern Physics,* 90(1), p. 15001.

Atala, M. et al., 2013. Direct measurement of the Zak phase in topological Bloch bands. *Nature Physics,* 9(12), pp. 795-800.

Attaccalite, C. & Grüning, M., 2013. Nonlinear optics from an ab initio approach by means of the dynamical Berry phase: Application to second- and third-harmonic generation in semiconductors. *Physical Review B,* 88(23), p. 235113.

Bahari, B. et al., 2017. Nonreciprocal lasing in topological cavities of arbitrary geometries. *Science,* 358(6363), pp. 636-640.

Balents, L., 2010. Spin liquids in frustrated magnets. *Nature,* 464(7286), pp. 199-208.

Bandres, M. A. et al., 2018. Topological insulator laser: Experiments. *Science,* 359(6381).

Bansil, A., Lin, H. & Das, T., 2016. Colloquium : Topological band theory. *Reviews of Modern Physics,* 88(2), p. 21004.

Barik, S. et al., 2018. A topological quantum optics interface. *Science,* 359(6376), pp. 666-668.

Barkeshli, M. & Qi, X.-L., 2014. Synthetic Topological Qubits in Conventional Bilayer Quantum Hall Systems. *Physical Review X,* 4(4), p. 41035.

Benalcazar, W. A., Bernevig, B. A. & Hughes, T. L., 2017. Quantized electric multipole insulators. *Science,* 357(6346), pp. 61-66.

Bendias, K. et al., 2018. High Mobility HgTe Microstructures for Quantum Spin Hall Studies. *Nano Letters,* 18(8), pp. 4831-4836.

Bergholtz, E. J. & Liu, Z., 2013. Topological Flat Band Models and Fractional Chern Insulators. *International Journal of Modern Physics,* p. 1330017.

Bernevig, B. A., Hughes, T. L. & Zhang, S. C., 2006. Quantum Spin Hall Effect and Topological Phase Transition in HgTe Quantum Wells. *Science,* 314(5806), pp. 1757-1761.

Berry, M. V., 1984. Quantal phase factors accompanying adiabatic changes. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 392(1802), pp. 45-57.

Broholm, C., R. J. Cava, S. A. Kivelson, D. G. Nocera, M. R. Norman, and T. Senthil. 2020. Quantum Spin Liquids. *Science* 367 (6475).

Cao, Y. et al., 2018. Unconventional superconductivity in magic-angle graphene superlattices. *Nature,* 556(7699), pp. 43-50.

Celi, A. et al., 2014. Synthetic Gauge Fields in Synthetic Dimensions. *Phys. Rev. Lett.,* Jan, 112(4), p. 043001.

Cerjan, A. et al., 2019. Experimental realization of a Weyl exceptional ring. *Nature Photonics,* 13(9), pp. 623-628.

Chang, C. Z. et al., 2013. Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator. *Science,* 340(6129), pp. 167-170.

Chen, G. et al., 2019. Tunable Correlated Chern Insulator and Ferromagnetism in Trilayer Graphene/Boron Nitride Moiré Superlattice. *arXiv preprint arXiv:1905.06535.*

Chong, Y., 2013. Optical devices: Photonic insulators with a twist. *Nature,* 496(7444), pp. 173-174.

Clark, L. W. et al., 2019. Observation of Laughlin states made of light. *arXiv preprint arXiv:1907.05872.*

Delplace, P., Marston, J. B. & Venaille, A., 2017. Topological origin of equatorial waves. *Science,* 358(6366), pp. 1075-1077.

Deubel, M. et al., 2004. Direct laser writing of three-dimensional photonic-crystal templates for telecommunications. *Nature Materials,* 3(7), pp. 444-447.

Essin, A. M., Moore, J. E. & Vanderbilt, D., 2009. Magnetoelectric polarizability and axion electrodynamics in crystalline insulators. *Physical Review Letters,* 102(14), p. 146805.

Fox, E. J. et al., 2018. Part-per-million quantization and current-induced breakdown of the quantum anomalous Hall effect. *Physical Review B,* 98(7), p. 75145.

Fruchart, M. et al., 2018. Soft self-assembly of Weyl materials for light and sound. *Proceedings of the National Academy of Sciences of the United States of America,* 115(16), p. 201720828.

Fu, L., Kane, C. L. & Mele, E. J., 2007. Topological Insulators in Three Dimensions. *Physical Review Letters,* 98(10), p. 106803.

Gallagher, P. et al., 2019. Quantum-critical conductivity of the Dirac fluid in graphene. *Science,* 364(6436), pp. 158-162.

Geim, A. K. & Grigorieva, I., 2013. Van der Waals heterostructures. *Nature,* 499(7459), pp. 419-425.

Götz, M. et al., 2018. Precision measurement of the quantized anomalous Hall resistance at zero magnetic field. *Applied Physics Letters,* 112(7), p. 72102.

Guglielmon, J. & Rechtsman, M. C., 2019. Broadband Topological Slow Light through Higher Momentum-Space Winding. *Physical Review Letters,* 122(15), p. 153904.

Hafezi, M. et al., 2013. Imaging topological edge states in silicon photonics. *Nature Photonics,* 7(12), pp. 1001-1005.

Haldane, F. D. M., 1988. Model for a quantum Hall effect without Landau levels: Condensed-matter realization of the "parity anomaly". *Physical Review Letters,* 61(18), pp. 2015-2018.

Haldane, F. D. & Raghu, S., 2008. Possible Realization of Directional Optical Waveguides in Photonic Crystals with Broken Time-Reversal Symmetry. *Physical Review Letters,* 100(1), p. 13904.

Han, J. et al., 2017. Room-Temperature Spin-Orbit Torque Switching Induced by a Topological Insulator. *Physical Review Letters,* 119(7), p. 77702.

Harari, G. et al., 2018. Topological insulator laser: Theory. *Science,* 359(6381).

Hasan, M. Z., and C. L. Kane. 2010. Colloquium: Topological Insulators. *Reviews of Modern Physics, vol. 82*, no. 4, pp. 3045–3067.

He, L. et al., 2019. *Floquet Chern insulators of light.* Nat Commun 10, 4194, pp. 1-6.

Hood, M., 2016. *When is a coffee mug a donut? Topology explains it.* [Online]
Available at: https://www.gmanetwork.com/news/scitech/science/583886/when-is-a-coffee-mug-a-donut-topology-explains-it/story/

Hsieh, D. et al., 2008. A topological Dirac insulator in a quantum spin Hall phase. *Nature,* 452(7190), pp. 970-974.

Hsieh, T. H. et al., 2012. Topological crystalline insulators in the SnTe material class. *Nature Communications,* 3(1), p. 982.

Hsu, C. W. et al., 2016. Bound states in the continuum. *Nature Reviews Materials,* 1(9), pp. 1-13.

Jotzu, G. et al., 2014. Experimental realization of the topological Haldane model with ultracold fermions. *Nature,* 515(7526), pp. 237-240.

Jukić, D. & Buljan, H., 2013. Four-dimensional photonic lattices and discrete tesseract solitons. *Physical Review A,* 87(1).

Kane, C. L. & Lubensky, T. C., 2014. Topological boundary modes in isostatic lattices. *Nature Physics,* 10(1), pp. 39-45.

Kane, C. L. & Mele, E. J., 2005a. Quantum Spin Hall Effect in Graphene. *Physical Review Letters,* 95(22), pp. 226801-226801.

Kane, C. L. & Mele, E. J., 2005b. Z-2 Topological Order and the Quantum Spin Hall Effect. *Physical Review Letters,* 95(14), p. 146802.

Kane, C. L. and Moore, J., 2011 Topological insulators. *Phys. World* 24 (02) 32.

Karzig, T., Bardyn, C.-E., Lindner, N. H. & Refael, G., 2015. Topological Polaritons. *Phys. Rev. X,* Jul.p. 031001.

Khanikaev, A. B. & Shvets, G., 2017. Two-dimensional topological photonics. *Nature Photonics,* 11(12), pp. 763-773.

Kitaev, A. Y., 2001. Unpaired Majorana fermions in quantum wires. *Physics-Uspekhi,* Volume 44, pp. 131-136.

Kitagawa, T. et al., 2012. Observation of topologically protected bound states in photonic quantum walks. *Nature Communications,* 3(1), p. 882.

Klembt, S. et al., 2018. Exciton-polariton topological insulator. *Nature,* 562(7728), p. 1.

Koirala, N. et al., 2015. Record Surface State Mobility and Quantum Hall Effect in Topological Insulator Thin Films via Interface Engineering. *Nano Letters,* 15(12), pp. 8245-8249.

König, M. et al., 2007. Quantum Spin Hall Insulator State in HgTe Quantum Wells. *Science,* 318(5851), pp. 766-770.

Kraus, Y. E. et al., 2012. Topological States and Adiabatic Pumping in Quasicrystals. *Physical Review Letters,* 109(10), p. 106402.

Kushwaha, S. K. et al., 2016. Sn-doped $Bi_{1.1}Sb_{0.9}Te_2S$ bulk crystal topological insulator with excellent properties. *Nature Communications,* 7(1), pp. 11456-11456.

Leykam, D. et al., 2017. Edge Modes, Degeneracies, and Topological Numbers in Non-Hermitian Systems. *Physical Review Letters,* 118(4), p. 40401.

Lindner, N. H. et al., 2014. Lighting up topological insulators: large surface photocurrents from magnetic superlattices. *arXiv:1403.0010 [cond-mat.mes-hall]*

Lu, L. & Joannopoulos, J. D., and Soljacic, M., 2014. Topological photonics. *Nature Photonics,* 8(11), p. 821.

Lu, L. et al., 2015. Experimental observation of Weyl points. *Science,* 349(6248), pp. 622-624.

Lutchyn, R. M., Sau, J. D. & Sarma, S. D., 2010. Majorana Fermions and a Topological Phase Transition in Semiconductor-Superconductor Heterostructures. *Physical Review Letters,* 105(7), p. 77001.

Lu, Y. et al., 2019. Probing the Berry curvature and Fermi arcs of a Weyl circuit. *Physical Review B,* 99(2).

MacDonald, A. H., 2019. Trend: Bilayer Graphene's Wicked, Twisted Road. *Physics,* 12 (12).

Mak, K. F. & Shan, J., 2016. Photonics and optoelectronics of 2D semiconductor transition metal dichalcogenides. *Nature Photonics,* 10(4), pp. 216-226.

Malkova, N. et al., 2009. Observation of optical Shockley-like surface states in photonic superlattices. *Optics Letters,* 34(11), pp. 1633-1635.

Mellnik, A. R. et al., 2014. Spin-transfer torque generated by a topological insulator. *Nature,* 511(7510), pp. 449-451.

Mittal, S., Goldschmidt, E. A. & Hafezi, M., 2018. A topological source of quantum light. *Nature,* 561(7724), p. 1.

Mittal, S. et al., 2019. Photonic quadrupole topological phases. *Nature Photonics,* 13(10), pp. 1-6.

Mogi, M. et al., 2015. Magnetic modulation doping in topological insulators toward higher-temperature quantum anomalous Hall effect. *Applied Physics Letters,* 107(18), p. 182401.

Moore, J. E., 2010. The Birth of Topological Insulators. *Nature,* vol. 464, no. 7286, pp. 194–198.

Morimoto, T. & Nagaosa, N., 2016. Topological nature of nonlinear optical effects in solids. *Science Advances,* 2(5).

Mourik, V. et al., 2012. Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices. *Science,* 336(6084), pp. 1003-1007.

Mousavi, S. H., Khanikaev, A. B. & Wang, Z., 2015. Topologically protected elastic waves in phononic metamaterials. *Nature Communications,* 6(1), pp. 8682-8682.

Mukherjee, S. a. R. M. C., 2019. *Observation of Topological Band Gap Solitons.* [Online]
Available at: arXiv:1907.05872

Murani, A. et al., 2017. Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry. *Nature Communications,* 8(1), p. 15941.

Nalitov, A., Solnyshkov, D. & Malpuech, G., 2015. Polariton Z topological insulator. *Physical Review Letters,* 114(11), p. 116401.

Nash, L. M. et al., 2015. Topological mechanics of gyroscopic metamaterials. *Proceedings of the National Academy of Sciences of the United States of America,* 112(47), pp. 14495-14500.

Noh, J. et al., 2018. Topological protection of photonic mid-gap defect modes. *Nature Photonics,* 12(7), pp. 408-415.

Noh, J. et al., 2017. Experimental observation of optical Weyl points and Fermi arc-like surface states. *Nature Physics,* 13(6), pp. 611-617.

Oreg, Y., Refael, G. & Oppen, F. v., 2010. Helical Liquids and Majorana Bound States in Quantum Wires. *Physical Review Letters,* 105(17), p. 177002.

Ozawa, T. et al., 2019. Topological photonics. *Reviews of Modern Physics,* 91(1).

Paiste, D., 2019. *Researchers uncover hidden topological insulator states in bismuth crystals.* [Online]
Available at: https://phys.org/news/2019-08-uncover-hidden-topological-insulator-states.html

Parameswaran, S. A. & Wan, Y., 2017. Viewpoint: Topological insulators turn a corner. *Physics,* 10, 132.

Paulose, J., Chen, B. G.-g. & Vitelli, V., 2015. Topological modes bound to dislocations in mechanical metamaterials. *Nature Physics,* 11(2), pp. 153-156.

Peano, V., Houde, M., Marquardt, F. & Clerk, A. A., 2016. Topological Quantum Fluctuations and Traveling Wave Amplifiers. *Physical Review X,* 6(4), p. 41026.

Pesin, D. & Balents, L., 2010. Mott physics and band topology in materials with strong spin–orbit interaction. *Nature Physics,* 6(5), pp. 376-381.

Peterson, C. W., Benalcazar, W. A., Hughes, T. L. & Bahl, G., 2018. A quantized microwave quadrupole insulator with topologically protected corner states. *Nature,* 555(7696), pp. 346-350.

Philip, T. M. & Gilbert, M. J., 2017. High-performance nanoscale topological energy transduction. *Scientific Reports,* 7(1), pp. 6736-6736.

Pixley, J. H. & Andrei, E. Y., 2019. Ferromagnetism in magic-angle graphene. *Science,* 365(6453), pp. 543-543.

Prodan, E. & Prodan, C., 2009. Topological Phonon Modes and Their Role in Dynamic Instability of Microtubules. *Phys. Rev. Lett.,* Dec.103(24).

Qi, X. L., Hughes, T. L. & Zhang, S. C., 2008. Topological Field Theory of Time-Reversal Invariant Insulators. *Physical Review B,* 78(19), p. 195424.

Qi, X.-L. & Zhang, S.-C., 2010. The quantum spin Hall effect and topological insulators. *Physics Today,* 63(1), pp. 33-38.

Raghu, S. & Haldane, F. D., 2008. Analogs of quantum-Hall-effect edge states in photonic crystals. *Physical Review A,* 78(3), p. 33834.

Rechtsman, M. C. et al., 2013. Photonic Floquet topological insulators. *Nature,* 496(7444), pp. 196-200.

Rees, D. et al., 2019. Observation of Topological Photocurrents in the Chiral Weyl Semimetal RhSi. *arXiv:1902.03230 [cond-mat.mes-hall]*

Regnault, N. & Bernevig, B. A., 2011. Fractional Chern Insulator. *Physical Review X,* 1(2), p. 21014.

Rosen, I. F. E. K. X. P. L. W. K. G.-G. D., 2017. Chiral transport along magnetic domain walls in the quantum anomalous Hall effect. *npj Quant Mater,* Volume 2, p. 69.

Ryu, S., Schnyder, A. P., Furusaki, A. & Ludwig, A. W. W., 2010. Topological insulators and superconductors: tenfold way and dimensional hierarchy. *New Journal of Physics,* 12(6), p. 65010.

Savary, L. & Balents, L., 2017. Quantum spin liquids: a review. *Reports on Progress in Physics,* 80(1), p. 16502.

Serlin, M. et al., 2019. Intrinsic quantized anomalous Hall effect in a moiré heterostructure. *arXiv preprint arXiv:1907.00261.*

Serra-Garcia, M. et al., 2018. Observation of a phononic quadrupole topological insulator. *Nature,* 555(7696), pp. 342-345.

Sharpe, A. L. et al., 2019. Emergent ferromagnetism near three-quarters filling in twisted bilayer graphene. *Science,* 365(6453), pp. 605-608.

Shen, H., Zhen, B. & Fu, L., 2018. Topological Band Theory for Non-Hermitian Hamiltonians. *Physical Review Letters,* 120(14).

Schindler, F., Cook, A. M., Vergniory, M. G., Wang, Z., Parkin, S.P., Bernevig, B. A., and Neupert, T., 2018. "Higher-order topological insulators." *Science Advances* 4(6): eaat0346.

Simon, B., 1983. Holonomy, the quantum adiabatic theorem, and Berry's phase. *Physical Review Letters,* 51(24), pp. 2167-2170.

Sipe, J. E. & Ghahramani, E., 1993. Nonlinear optical response of semiconductors in the independent-particle approximation. *Physical Review B,* 48(16), pp. 11705-11722.

Slobozhanyuk, A. et al., 2017. Three-dimensional all-dielectric photonic topological insulator. *Nature Photonics,* 11(2), pp. 130-136.

Spanton, E. M. et al., 2018. Observation of fractional Chern insulators in a van der Waals heterostructure. *Science,* 360(6384), pp. 62-66.

Stern, A., 2016. Fractional Topological Insulators: A Pedagogical Review. *Annual Review of Condensed Matter Physics,* 7(1), pp. 349-368.

Stern, A. & Lindner, N. H., 2013. Topological Quantum Computation—From Basic Concepts to First Experiments. *Science,* 339(6124), pp. 1179-1184.

Stormer, H. L., 1999. Nobel Lecture: The fractional quantum Hall effect. *Reviews of Modern Physics,* 71(4), pp. 875-889.

Sun, K., Gu, Z., Katsura, H. & Sarma, S. D., 2011. Nearly Flatbands with Nontrivial Topology. *Physical Review Letters,* 106(23), pp. 236803-236803.

Süsstrunk, R. & Huber, S. D., 2015. Observation of phononic helical edge states in a mechanical topological insulator. *Science,* 349(6243), pp. 47-50.

Tang, F., Po, H. C., Vishwanath, A. & Wan, X., 2019. Comprehensive search for topological materials using symmetry indicators. *Nature,* 566(7745), pp. 486-489.

Thouless, D. J., Kohmoto, M., Nightingale, M. P. & den Nijs, M., 1982. Quantized Hall Conductance in a Two-Dimensional Periodic Potential. *Physical Review Letters,* 49(6), pp. 405-408.

Tsui, D., Stormer, H. & Gossard, A., 1982. Two-dimensional magnetotransport in the extreme quantum limit. *Physical Review Letters,* 48(22), pp. 1559-1562.

Vergniory, M. G. et al., 2019. A complete catalogue of high-quality topological materials. *Nature,* 566(7745), pp. 480-485.

Virk, K. S. & Sipe, J. E., 2011. Optical injection and terahertz detection of the macroscopic Berry curvature. *Physical Review Letters,* 107(12), p. 120403.

von Klitzing, K., Dorda, G. & Pepper, M., 1980. New method for high accuracy determination of the fine structure constant based on quantized Hall resistance. *Physical Review Letters,* 45(6), pp. 494-497.

Wang, G. et al., 2019. Bending of Multilayer van der Waals Materials. *Physical Review Letters,* 123(11).

Wang, Z., Chong, Y., Joannopoulos, J. D. & Soljačić, M., 2009. Observation of unidirectional backscattering-immune topological electromagnetic states. *Nature,* 461(7265), pp. 772-775.

Wen, X.-G., 2017. Zoo of quantum-topological phases of matter. *Reviews of Modern Physics,* 89(4), p. 41004.

Wu, L. et al., 2017. Giant anisotropic nonlinear optical response in transition metal monopnictide Weyl semimetals. *Nature Physics,* 13(4), pp. 350-355.

Wu, L. et al., 2016. Quantized Faraday and Kerr rotation and axion electrodynamics of a 3D topological insulator. *Science,* 354(6316), pp. 1124-1127.

Wu, S. et al., 2018. Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal. *Science,* 359(6371), pp. 76-79.

Xiao, M., Chen, W.-J., He, W. & Chan, C. T., 2015. Synthetic gauge flux and Weyl points in acoustic systems. *Nature Physics,* 11(11), pp. 920-924.

Yang, Y. et al., 2019. Realization of a three-dimensional photonic topological insulator. *Nature,* 565(7741), pp. 622-626.

Yang, Z. et al., 2015. Topological Acoustics. *Phys. Rev. Lett.,* 114. 114301.

Yao, S. & Wang, Z., 2018. Edge States and Topological Invariants of Non-Hermitian Systems. *Physical Review Letters,* 121(8), p. 86803.

Yasuda, K. et al., 2017. Quantized chiral edge conduction on domain walls of a magnetic topological insulator. *Science,* 358(6368), pp. 1311-1314.

Yuan, L., Lin, Q., Xiao, M. & and Fan, S., 2018. Synthetic dimension in photonics. *Optica,* pp. 1396-1405.

Yuen-Zhou, J. et al., 2016. Plexciton Dirac points and topological modes. *Nature Communications,* 7(1), pp. 11783-11783.

Zandonella, C., 2017. *Spotting the spin of the Majorana fermion under the microscope.* [Online]
Available at: https://blogs.princeton.edu/research/2017/10/12/spotting-the-spin-of-the-majorana-fermion-under-the-microscope/
[Accessed 2019].

Zeuner, J. M. et al., 2015. Observation of a Topological Transition in the Bulk of a Non-Hermitian System. *Physical Review Letters,* 115(4), pp. 40402-40402.

Zhang, T. et al., 2019. Catalogue of topological electronic materials. *Nature,* 566(7745), pp. 475-479.

Zhen, B. et al., 2015. Spawning rings of exceptional points out of Dirac cones. *Nature,* 525(7569), pp. 354-358.

Zhou, H. et al., 2018. Observation of bulk Fermi arc and polarization half charge from paired exceptional points. *Science,* 359(6379), pp. 1009-1012.

Zunger, A., 2019. Beware of plausible predictions of fantasy materials. *Nature,* 566(7745), pp. 447-449.

Glossary

2D material – Material composed of one or a few crystalline layers of atoms. Examples are graphene (1 atom thick) and transition metal dichalcogenides (3 atoms thick.)

Angular Resolved Photoemission Spectroscopy (ARPES) – An experimental technique to directly observe the electronic structure of a material.

Backscattering – In physics, the reflection of waves, particles, or signals back towards the direction of origin.

Band structure – An energy level diagram that plots the energy vs. wavevector of a wave (whether it is an electron, photon, or otherwise) as it propagates through a periodic medium.

Band gap – A gap between bulk energy bands in a band structure, where no bulk states reside. Topological edge and surface states reside spectrally therein. For electronic materials, the band gap is the minimum energy required to excite an electron from the valence band to a conduction band.

Chalcogenides – A group of chemical compounds with semiconductor properties, composed of one or more chalcogen elements (e.g. S, Se or Te).

Chern insulators – A 2D topological insulator with chiral (unidirectional) edge states that does not require an applied magnetic field.

Chiral edge states – Edge states that propagate in one direction along an edge, without backscattering.

Decoherence – In quantum computing, decoherence refers to the loss of information from a system into the environment over time.

Degeneracy – In quantum mechanics, degeneracy refers to the existence of more than one state at the same energy level.

Dichalcogenides – A group of chemical compounds with semiconductor properties and formula ME_2, where M = a transition metal and E = S, Se, or Te.

Dirac semimetals – A material (like graphene, for example) within which electrons obey relativistic dynamics governed by the Dirac equation (as opposed to the non-relativistic Schrödinger equation).

Dispersion – The relation between energy and momentum of an excitation.

Dissipationless – A system that does not lose energy.

Edge states – States that are localized to the edge of a 2D material.

Fermi arcs – Surface states that energetically connect between two Weyl points projected into the surface band structure.

Fermi level – The energy level which is occupied by an electron orbital at temperature 0 K. The level of occupancy determines the conductivity of different materials.

Fractional Quantum Hall Effect (FQHE) – Phenomenon in which the Hall conductance of 2D electrons are precisely quantized plateaus at fractional values of e^2/h, where e is the electronic charge and h is Planck's constant. It is a form of topological order.

Hall conductance – The ratio of the electrical current to the induced transverse voltage for a 2D material with a magnetic field applied perpendicular to the surface of the material.

Hamiltonian – A quantum mechanical operator used to describe the total energy of a system. The Hamiltonian sums the kinetic and potential energies for all the particles in the system.

Heterostructure – A 3D structure composed of layers of dissimilar materials with different properties, such as band structure or crystal arrangement.

Higher-order topological materials – Materials in which the topologically protected states are more than one dimension lower than the host lattice (for example, 1D "hinge" states in a 3D material).

Landau levels – In quantum mechanics, the discrete energy level associated with the quantization of charged particles in magnetic fields.

Laughlin states – States associated with the fractional quantum Hall effect that emerge in topological bands as a result of strong interparticle interactions.

Magneto-optical effect – Phenomena resulting from the interaction of electromagnetic radiation (light) with a magnetic field or with matter under the influence of a magnetic field.

Mott insulator – A topological insulator characterized by gapless surface spin-only excitations.

Non-Hermitian systems – Systems that experience gain and loss and therefore can be out of equilibrium or unstable.

Nonlinear dynamical systems – Systems that are governed by equations more complex than the linear, aX+b form. Nonlinear systems often appear chaotic, unpredictable or counterintuitive, and yet their behavior is not random. Nonlinearities can also introduce interactions between particles to a system.

Non-trivial – Topological, as opposed to a "trivial" non-topological state.

Photonic crystal – A periodic crystal structure through which electromagnetic waves (e.g., light) propagate, as governed by Maxwell's equations. In analogy to a semiconductor, photonic crystals have band structures that arise from solving Maxwell's equations using Bloch's theorem. The periodicity of the photonic crystal structure is spaced to tune the wave propagation according to its wavelength.

Quantum Anomalous Quantum Hall Effect (QAHE) – System exhibiting the integer quantum Hall effect in the absence of an external magnetic field, meaning there are no Landau levels.

Quantum Hall Effect (QHE) – A phenomenon observed in 2D materials subjected to low temperatures and strong magnetic fields, in which the Hall conductance undergoes discrete transitions to quantized values, as a function of the magnetic field. There are both integer and fractional forms of this effect.

Quasicrystals – Crystalline materials that have non-crystallographic rotational symmetry (e.g., 5-fold or 8-fold) and no repeating unit cell. They exhibit sharp Bragg spots in their diffraction pattern, corresponding to long-range order.

Rydberg polariton system – A gas of atoms in which light propagates in a coherent superposition of the optical and atomic state (i.e., a polariton). The electronic state of the atom is in a high principal quantum number (i.e., Rydberg) state, giving rise to strong interactions between polaritons.

Scanning Tunneling Microscopy/Spectroscopy (STM/STS) – An instrument used to image surfaces at the atomic scale by scanning a very sharp metal wire tip over a surface.

Semimetal – A material with a gapless band structure with crossings between the valence and conductance bands. Subtopics: Weyl, Dirac.

Soliton – A wave that propagates without changing shape as a result of the interplay between dispersion and nonlinearity.

Spin-orbit coupling – One of the relativistic effects that occur whenever a particle with non-zero spin moves around a region with a finite electric field.

Strongly correlated systems – Systems in which particle interaction produce unusual phenomenon. Examples include high-temperature superconductors, quark–gluon plasmas, organic superconductors and ultracold atoms.

Superlattice – A periodic structure of two or more semiconductors of significantly different band gaps such that multiple quantum wells are formed in the low band gap layers to enable carrier transport by tunneling.

Surface states – States that are localized to the surface of a material.

Symmetry – In physics, a physical or mathematical feature of a physical system that is preserved or remains unchanged under some transformation. For example, a square is unchanged when it is rotated by 90 degrees. Various symmetries (space, time, charge …) underlies the conservation laws of nature.

Symmetry protected topological phase – An insulating gapped phase of matter that cannot be smoothly deformed into the atomic limit without a phase transition if the deformation preserves a particular symmetry. It can be deformed into the atomic limit if the symmetry is broken during the deformation.

Topological crystalline insulator – A topological insulator whose topological properties are connected to the preservation of crystal point group symmetries.

Topological insulator – A material that behaves as an insulator in its interior but is conducting on the surface. The properties of its surface states are dictated by the topological nature of the bulk.

Topological materials – Materials whose properties persist in the face of disruptions to their physical structures.

Topological order – A long-range quantum entangled kind of order described by ground state degeneracy and quantized non-Abelian geometric phases of degenerate ground states.

Topological protection – A phrase used to describe the robustness of topological systems. For example, the electrical properties of topological insulators are not affected by shifts in temperature or physical deformation.

Topologically non-trivial – In mathematics, a donut shape, which cannot be converted to a simple ball no matter how it is stretched or twisted. In physics, this describes any material described by a topological invariant that cannot be stretched out to isolated atoms without closing its bulk band gap.

Topology – A branch of mathematics that describes phenomena that do not change under deformation.

Weyl semimetals – 3D materials where valence and conduction bands cross in single points, the Weyl points. When the Fermi energy is near these nodes, the electrons effectively behave as relativistic Weyl fermions with a linear energy dispersion and a given chirality.

Weyl points – Point degeneracies in a 3D band structure at which two bands touch. Weyl points are quantized, monopole sources of dispersion for a given energy band.

Acronyms

0D – zero–dimensional

1D – one–dimensional

2D – two–dimensional

3D – three–dimensional

AFM – atomic force microscope

ARPES – angle–resolved photoelectron spectroscopy

CVD – chemical vapor deposition

DFT – density functional theory

h–BN – hexagonal boron nitride

MBE – molecular beam epitaxy

MX2 – metal atoms (M) and chalcogen atoms (X)

QAH – quantum anomalous Hall

QSHE – quantum spin hall effect

SOC – spin–orbit coupling

STEM – scanning transmission electron microscopy

STM – scanning tunneling microscopy

TB – tight–binding

TEM – transmission electron microscopy

THz – terahertz

TMDs – transition metal dichalcogenides

UHV – ultrahigh vacuum

vdW – van der Waals

Appendix I – Workshop Attendees

Co-Chairs

David Goldhaber-Gordon	Stanford University
Nadya Mason	University of Illinois at Urbana-Champaign
Mikael C. Rechtsman	Pennsylvania State University

Academic/Industry Participants

Peter Armitage	Johns Hopkins University
Gaurav Bahl	University of Illinois at Urbana-Champaign
Miguel Bandres	University of Central Florida
Fiona Burnell	University of Minnesota
Cui-Zu Chang	Pennsylvania State University
Joe Checkelsky	Massachusetts Institute of Technology
Claudia Felser	Max Planck Institute
Kin Chung Fong	Raytheon/BBN
Matthew Gilbert	University of Illinois at Urbana-Champaign
Mohammad Hafezi	University of Maryland
WIlliam Irvine	University of Chicago
Michal Lipson	Columbia University
Stuart Parkin	Max Planck Institute
Gil Refael	California Institute of Technology
Kirill Shtengel	University of California at Riverside
Jon Simon	University of Chicago
Susanne Stemmer	UC Santa Barbara
Feng Wang	UC Berkeley
Andrea Young	UC Santa Barbara
Bo Zhen	University of Pennsylvania
Jun Zhu	Pennsylvania State University

DoD Participants

Patrick Folkes	Army Research Laboratory
Michelle Johannes	Navy Research Laboratory
Berry Jonker	Navy Research Laboratory

Government Observers

Jean Luc Cambrier	Air Force Office of Scientific Research
Shamik Das	MITRE
Jason Day	OUSD(R&E)
George De Coster	Army Research Laboratory
Ken Goretta	Air Force Office of Scientific Research
Jiwei Lu	University of Virginia
Antti Makinen	Office of Naval Research
Bindu Nair	OUSD(R&E)
Gernot Pomrenke	Air Force Office of Scientific Research
David Stout	OUSD(R&E)
Marc Ulrich	Army Research Office

Appendix II – Workshop Participant Biographies

N. Peter Armitage, Professor
Johns Hopkins University
https://physics-astronomy.jhu.edu/directory/n-peter-armitage/
npa@pha.jhu.edu
N. Peter Armitage is a Professor in the Physics and Astronomy Department at Johns Hopkins University. He received his B.S. in Physics from Rutgers University in 1994 and his Ph.D. from Stanford University in 2002. He is a physicist whose research centers on material systems which exhibit coherent quantum effects at low temperatures, like superconductors and "quantum" magnetism. Dr. Armitage's principal scientific interest is understanding how is it that large ensembles of strongly interacting, but fundamentally simple particles like electrons in solids act collectively to exhibit complex emergent quantum phenomena. He is exploiting (and developing) recent technical breakthroughs using very low frequency microwave and THz range radiation to probe these systems at their natural frequency scales. The material systems of interest require novel measurement techniques as their relevant frequencies typically fall between the range of usual optical and electronic methods.

Gaurav Bahl, Associate Professor
University of Illinois at Urbana-Champaign
http://bahl.mechse.illinois.edu/
bahl@illinois.edu
Gaurav Bahl is an Associate Professor of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign. He received his Ph.D. and MS degrees in Electrical Engineering from Stanford University in 2010 and 2008. Dr. Bahl has pioneered the development of optomechanical excitation and cooling using Brillouin scattering in microresonators. Most recently, his group has been investigating nonreciprocal interactions, and high-order, nonlinear, and non-Hermitian topological insulators in microwave, optical, and mechanical systems. He is a recipient of the AFOSR Young Investigator Award in 2015, the ONR Director of Research Early Career Grant in 2016 and was elevated to Senior Member of the IEEE in 2016.

Miguel Bandres, Assistant Professor
University of Central Florida
http://www.mabandres.com/
bandres@creol.ucf.edu
Miguel A. Bandres is an Assistant Professor at the College of Optics and Photonics (CREOL) at the University of Central Florida. He received his Ph.D. degree from the California Institute of Technology (Caltech) in Physics. He was a Postdoctoral Research Fellow at the Technion – Israel Institute of Technology, in Professor Moti Segev's group. He is the recipient of the Marie Curie Fellowship, the SPIE John Kiel Scholarship, the SPIE Laser Technology Scholarship, and the Premio Nacional de la Juventud, which is the highest public recognition awarded by the Mexican government to outstanding young professionals.

Dr. Bandres' research focuses on finding and observing new fundamental phenomena that allow us to control light in nontrivial ways, such as photonic topological insulators, artificial gauge fields in optics, and non-Hermitian photonics; and studying how these phenomena can be applied to improve or realize new photonic systems such lasers, waveguides and imaging systems. His most recent accomplishment is the prediction and experimental observation of the first non-magnetic topological insulator laser.

Fiona Burnell, Assistant Professor
University of Minnesota
https://www.physics.umn.edu/people/burnell.html
fburnell@umn.edu
Fiona Burnell is Assistant Professor in the School of Physics and Astronomy at the University of Minnesota. Dr. Burnell's research focuses on theoretical aspects of topological phases of matter, with a particular emphasis on systems where strong interactions play an important role. She has worked on a variety of topics, from experimentally relevant properties of spin liquid materials to the classification of interacting topological phases of matter. Dr. Burnell earned her Ph.D. at Princeton University, and was a post-doctoral research fellow at All Souls College in Oxford University prior to joining the faculty at the University of Minnesota in 2013.

Cui-Zu Chang, Assistant Professor
The Pennsylvania State University
https://sites.psu.edu/changresearch/
cxc955@psu.edu
Cui-Zu Chang is Assistant Professor in the Physics Department at the Pennsylvania State University. He received his B.S. in Physics in 2007 from Shandong University, China, and his Ph.D. in Physics in 2013 from Tsinghua University, China. He then moved to MIT, where he was doing his postdoc until moving to the Pennsylvania State University in 2017.

Joseph Checkelsky, Associate Professor
MIT
http://web.mit.edu/physics/people/faculty/checkelsky_joseph.html
checkelsky@mit.edu
Joseph Checkelsky is an Associate Professor of Physics at Massachusetts Institute of Technology. Dr. Checkelsky's research focuses on the study of exotic electronic states of matter through the synthesis, measurement, and control of solid-state materials. Of particular interest are studies of correlated behavior in topologically non-trivial materials, the role of geometrical phases in electronic systems, and novel types of geometric frustration. These studies aim to uncover new physical phenomena that expand the boundaries of understanding of quantum mechanical condensed matter systems and also to open doorways to new technologies by realizing emergent electronic and magnetic functionalities.

Claudia Felser, Director
Max Planck Institute for Chemical Physics of Solids
https://www.cpfs.mpg.de/felser
felser@cpfs.mpg.de
Claudia Felser is the Director of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany. Dr. Felser studied chemistry and physics at the University of Cologne (Germany, completing there both her diploma in solid state chemistry (1989) and her doctorate in physical chemistry (1994). After postdoctoral fellowships at the Max Planck Institute in Stuttgart (Germany) and the CNRS in Nantes (France), she joined the University of Mainz (Germany) in 1996 becoming a full professor there in 2003. Her research foci are the design and discovery of novel inorganic compounds, in particular, Heusler compounds for multiple applications and new topological quantum materials.

Dr. Felser was honored as a Distinguished Lecturer of the IEEE Magnetics Society in 2011 and in 2017 she received an ERC Advanced grant. In 2019, she was awarded the APS James C. McGroddy Prize for New Materials together with Bernevig, Dai and in 2014 the Alexander M. Cruickshank Lecturer Award of the Gordon Research Conference, and received a SUR-grant Award from IBM. In 2014 she received the Tsungmin Tu Research Prize from the Ministry of Science and Technology of Taiwan, the highest academic honor granted to foreign researchers in Taiwan. She is a Fellow of the American Physical Society and the Institute of Physics, London and since 2018 a member of the Leopoldina, the German National Academy of Sciences.

Patrick Folkes, Physicist
Army Research Laboratory
https://www.researchgate.net/scientific-contributions/20330482_P_A_Folkes
patrick.a.folkes.civ@mail.mil
Patrick Folkes is a Physicist at the Army Research Laboratory. Dr. Folkes obtained his Ph.D. from Columbia University in 1981. He was employed at Bell Laboratories during 1981—1987 and at the Army Research Laboratory from 1987—present. He is currently engaged in research on topological materials and topologically enabled devices at Army Research Laboratory.

Kin Chung Fong, Scientist
Raytheon BBN Technologies
Harvard University
http://www.people.fas.harvard.edu/~fong/
fongkc@gmail.com
Kin Chung Fong is a Scientist at Raytheon BBN Technologies and Associate of Physics at Harvard University. Dr. Fong earned his Ph.D. under the supervision of Prof. Chris Hammel at Ohio State University. After his postdoc at Caltech, Dr. Fong joined BBN Technologies in 2013. His research now focuses on studying the fundamental physics of strongly interacting Dirac and Weyl fermions in condensed matter systems with their connections to holographic principle and developing the Josephson junction single photon detector for quantum information science, radio astronomy, and the search of dark matter axions.

Matthew Gilbert, Associate Professor
University of Illinois
https://ece.illinois.edu/directory/profile/matthewg
matthewg@illinois.edu
Matthew Gilbert is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. His research focuses of the development of post-CMOS technology, quantum transport theory in condensed matter systems particularly those systems under extreme conditions of strong confinement or large magnetic fields, many-body theory of strongly correlated systems, and topological condensed matter systems including insulators, metals and superconductors. His current research focuses on understanding the role of topological materials in the design of post-CMOS device technologies and functionalities.

David Goldhaber-Gordon, Professor
Stanford University
https://ggg.stanford.edu/
goldhaber-gordon@stanford.edu
David Goldhaber-Gordon is Professor of Physics at Stanford University. Dr. Goldhaber-Gordon earned his AB in Physics and AM in History of Science from Harvard in 1994, and his Ph.D. in Physics from the Massachusetts Institute of Technology in 1999, as a Hertz Fellow. During his Ph.D., David made the first demonstration of the Kondo effect in a semiconductor nanostructure. Following his Ph.D., he spent two years as a Junior Fellow in the Harvard Society of Fellows, then joined the faculty at Stanford University in 2001, where he cofounded and led the NSF-sponsored Center for Probing the Nanoscale. Dr. Goldhaber-Gordon's research group studies and manipulates how electrons organize themselves and flow on the nanoscale. In this regime, quantum effects and electron interactions are important, confounding intuitions gleaned from larger-scale electronics. Dr. Goldhaber-Gordon also explores how nanostructured materials can change our thinking on electronic devices and energy conversion technology.

Dr. Goldhaber-Gordon has received numerous awards and distinctions. Notable examples: In 2002, he received the inaugural George E. Valley Prize of the American Physical Society, and the University of Illinois's McMillan Award in condensed matter physics, the premier recognition for an early-career condensed matter physicist. He then received the 2006 Award for Initiatives in Research from the National Academy of Sciences (one awarded per year), and a Packard Fellowship.

Mohammad Hafezi, Associate Professor
University of Maryland
https://groups.jqi.umd.edu/hafezi/
hafezi@umd.edu
Mohammad Hafezi is an Associate Professor with a joint appointment in the Physics and Electrical and Computer Engineering Departments at the University of Maryland. Dr. Hafezi studied for two years at Sharif University before completing his undergraduate degree in Physics from École Polytechnique. He received his Ph.D. in Physics from Harvard University in 2009. He was a senior research associate at the Joint Quantum Institute before joining the ECE faculty. His research interest is quantum optics, topological physics, condensed materials, and quantum information sciences.

William T.M. Irvine, Associate Professor
University of Chicago
https://jfi.uchicago.edu/~william/
wtmirvine@uchicago.edu
William T. M. Irvine is Professor of Physics at the University of Chicago. Dr. Irvine's research interests are in the fields of experimental soft condensed matter and theoretical and experimental "knotted fields." He is specifically interested in the strong role played by geometry and advanced optical techniques. He recently investigated some intricate and stable topological structures that can exist in light fields whose evolution is governed entirely by the geometric structure of the field.

He is coauthor of several publications, including "Pleated Crystals on Curved Surfaces," "Interstitial Fractionalization in Curved Space" (in preparation), "Topological Tweezers (submitted for publication), and "Lock and Key Colloids through Polymerization-Induced Buckling of Monodisperse Silicon Oil Droplets" (submitted for publication). He was awarded the Northern Telecom Prize (experimental) and Tyndall Prize (theory) from Imperial College.

Michelle Johannes, Research Physicist
Naval Research Laboratory
Michelle.johannes@nrl.navy.mil
Dr. Johannes is a Research Physicist and Head of the Center for Computational Materials Science at the Naval Research Laboratory. She is a computational materials physicist with expertise in electronic structure properties of materials. Her interests lie mainly in materials for energy and span the fields of superconductivity, battery electrodes, magnetic materials, fuel cell catalysts and topological materials. Dr. Johannes received her bachelor's degree in physics from Mount Holyoke College in 1993 and her Ph.D. in computational physics from the University of California at Davis in 2003. She worked as a National Research Council postdoctoral fellow at NRL and then was hired as a staff member in 2005.

Berend (Berry) Jonker, Senior Scientist
Naval Research Laboratory
berry.jonker@nrl.navy.mil
Berend (Berry) T. Jonker is a Senior Scientist and Head of the Magnetoelectronic Materials & Devices section in the Materials Science & Technology Divison at the Naval Research Laboratory, Washington, DC. His current research focuses on semiconductor spintronics, including electrical spin injection and transport in semiconductors, and the fabrication and development of prototype spintronic devices. His work also addresses the epitaxial growth and study of ferromagnetic semiconductors, a class of materials which combine

both ferromagnetic and semiconducting properties with the potential for new device functionality. Berry obtained his Ph.D. in solid state physics / surface science from the University of Maryland in 1983 in the area of thin film quantum size effects. He has co-authored approximately 180 refereed publications and presented 85 invited talks. Berry is a Fellow of the American Physical Society and of the AVS Science & Technology Society, and an Adjunct Professor at the State University of New York, Buffalo. He has served as co-organizer for the APS Focus Topics Magnetic Nanostructures & Heterostructures (1999) and Spin-Dependent Phenomena in Semiconductors (2004), and as program or conference chair for several magnetism and spin-related conferences, including SpinTech II (Belgium, 2003). He has recently served on the AIP Steering Committee for Magnetic Materials, and as a committee member for Emerging Research Devices & Materials for the 2005 and 2009 International Technology Roadmap for Semiconductors.

Michal Lipson, Professor
Columbia University
http://cni.columbia.edu/cni
ml3745@columbia.edu
Michal Lipson is the Eugene Higgins Professor of Electrical Engineering and Professor of Applied Physics at Columbia University. She earned B.S., M.S., and Ph.D. degrees in Physics in the Technion in 1998. Following a Postdoctoral position in MIT in the Material Science department from 1998 to 2001, she joined the School of Electrical and Computer Engineering at Cornell University and was name the Given Foundation Professor of Engineering at the School of Electrical and Computer Engineering in 2012. In 2015 she joined Columbia University.

Lipson pioneered critical building blocks in the field of silicon photonics, which today is recognized as one of the most promising directions for solving the major bottlenecks in microelectronics. In 2004, she showed the ability to tailor the electro-optic properties of silicon (Almeida, et al., Nature 2004 with more than 1400 citations and Xu et al Nature 2005 with more than 2200 citations) which represent critical advances that led to the explosion of silicon photonics research and development. The number of publications related to silicon photonic devices and systems is now more than 50,000 a year. A large fraction of these publications is based on Lipson's original papers published since 2001. Today more than one thousand papers published yearly involve devices and circuits based on Lipson's original modulators, as well as on other silicon photonics devices demonstrated by her group including slot waveguides (Almeida et al, Optics Letters 2004 with more than 1600 citations) and inverse tapers (Almeida et al, Optics Letters, 2003 with more than 900 citations). The growth of the field of silicon photonics has also been evident in industry with an increasing number of companies developing silicon photonics products (IBM and Intel, HP Aurrion, Melannox, Apic, Luxtera, etc).

Nadya Mason, Professor
University of Illinois at Urbana-Champaign
https://physics.illinois.edu/people/directory/profile/nadya
nadya@illinois.edu
Nadya Mason is a Professor of Physics at the University of Illinois at Urbana-Champaign. She earned her Ph.D. in physics from Stanford University and engaged in postdoctoral research as a Junior Fellow at Harvard University. A condensed matter experimentalist, Dr. Mason focuses on quantum electron behavior in materials such as graphene, nano-structured superconductors, and topological systems. Her research is relevant to the fundamental physics of small systems and applications involving nanoscale electronic elements. Dr. Mason was a recipient of the 2009 Denise Denton Emerging Leader Award, the 2012 Maria Goeppert Mayer Award of the American Physical Society (APS), and was named an APS Fellow in 2018 and an Illinois University Scholar in 2019. She is a former General Councilor of the APS and Chair of the APS Committee on Minorities, and currently serves as Director of the Illinois Materials Research Science and Engineering Center (I-MRSEC).

Stuart Parkin, Director
MPI of Microstructure Physics
https://www.mpi-halle.mpg.de/NISE/director
stuart.parkin@mpi-halle.mpg.de
Stuart Parkin is the Managing Director of the Max Planck Institute for Microstructure Physics, Halle, Germany, and an Alexander von Humboldt Professor, Martin Luther University, Halle-Wittenberg. His research interests include spintronic materials and devices for advanced sensor, memory, and logic applications, oxide thin-film heterostructures, topological metals, exotic superconductors, and cognitive devices. Parkin's discoveries in spintronics enabled a more than 10,000-fold increase in the storage capacity of magnetic disk drives. For this work, that thereby enabled the "big data" world of today, Parkin was awarded the Millennium Technology Award from the Technology Academy Finland in 2014 (worth 1,000,000 Euro). Most recently, Parkin proposed and demonstrated a novel memory device, "Racetrack Memory", that is an innately 3D solid-state device with the storage capacity of a disk drive but with much higher performance.

Mikael C. Rechtsman, Assistant Professor
The Pennsylvania State University
https://www.phys.psu.edu/people/mcr22
mcrworld@psu.edu
Mikael C. Rechtsman is an Assistant Professor at the Pennsylvania State University working in the areas of experimental and theoretical nonlinear, quantum, and topological photonics. At the Laboratory for emergent phenomena and technology in the optical sciences (leptos), Mikael C. Rechtsman's research group focuses their research efforts on complex, nonlinear and quantum optics at the interface between emergent fundamental physics and optical device applications. Dr. Rechtsman is a recipient of the Sloan, Packard, and Kaufman fellowships, the ONR Young Investigator Award and the ICO Prize of the International Commission for Optics.

Gil Refael, Professor
California Institute of Technology
http://gilrefael.org/
refael@caltech.edu
Gil Refael, is the Taylor W. Lawrence Professor of Theoretical Physics at the California Institute of Technology. Dr. Refael is best known for his works on realizing Majorana fermions in solid state systems, and on quantum dynamics and control. Dr. Refael's group has introduced the concepts of Floquet Topological insulators, and topological polaritons, and additionally worked on disordered magnets, superconductors and superfluids. Currently, he focuses on implementing concepts from topological physics to quantum control, as well as the microscopic origins of many-body localization. Dr. Refael is a recipient of a Sloan Fellowship, a Packard Fellowship, a Cottrell prize, and the Humboldt Foundation's Bessel Prize. Dr. Refael graduated from Harvard University in 2003, where he worked under the guidance of Daniel Fisher and Eugene Demler.

Kirill Shtengel, Associate Professor
University of California, Riverside
https://physics.aps.org/authors/kirill_shtengel
kirills@hotmail.com
Kirill Shtengel is an Associate Professor of Physics at the University of California, Riverside. He received his Ph.D. from UCLA in 1999 for his work in statistical mechanics. Following postdoctoral appointments at UC Irvine, Microsoft Research, and Caltech, in 2005 he joined UC Riverside as a faculty member. His research interests include topological phases of matter and their potential applications for quantum information processing. He is a Fellow of the American Physical Society.

Jonathan Simon, Professor
University of Chicago
simonlab.uchicago.edu
simonjon@uchicago.edu
Jon Simon is an Associate Professor of Physics and The James Franck Institute, IME Fellow at the University of Chicago. Dr. Simon's research focuses on quantum materials made of light, quantum optics, control and dynamical systems, and cats of the classical variety (Siamese especially). Dr. Simon studies quantum many-body physics by engineering synthetic materials from ultra-cold atoms. Dr. Simon has co-authored numerous publications, including "Quantum Simulation of Antiferromagnetic Spin Chains in an Optical Lattice" and "Orbital Excitation Blockade and Algorithmic Cooling of Quantum Gases."

Dr. Simon earned his Ph.D. in physics from Harvard University in 2010 and a B.S. in physics from the California Institute of Technology in 2004. He is the recipient of the Martin and Beate Block Award from the Aspen Center for Physics and the American Academy of Arts and Sciences (AAAS) Newcomb Cleveland Prize.

Susanne Stemmer, Professor
University of California, Santa Barbara
https://materials.ucsb.edu/people/faculty/susanne-stemmer
stemmer@mrl.ucsb.edu
Susanne Stemmer is Professor of Materials at the University of California, Santa Barbara. She did her doctoral work at the Max-Planck Institute for Metals Research in Stuttgart (Germany) and received her degree from the University of Stuttgart in 1995. Her research interests are in the development of scanning transmission electron microscopy techniques, molecular beam epitaxy, functional and strongly correlated oxide heterostructures, and topological materials. She has authored or co-authored more than 240 publications. Honors include election to Fellow of the American Ceramic Society, Fellow of the American Physical Society, Fellow of the Materials Research Society, Fellow of the Microscopy Society of America, and a Vannevar Bush Faculty Fellowship of the Department of Defense.

Feng Wang, Professor
University of California, Berkeley
https://physics.berkeley.edu/people/faculty/feng-wang
fengwang76@berkeley.edu
Feng Wang is a Professor in the Physics Department of University of California, Berkeley. Dr. Wang received his Ph.D. of physics from Columbia University in 2004. In 2005, he went to University of California, Berkeley as a Miller research fellow. Later he joined the physics department at University of California, Berkeley as an Assistant Professor in 2007. He was awarded the Sloan fellowship in 2008, the IUPAP C10 young scientist prize in 2009, the PECASE award and the Packard fellowship for science and engineering in 2010.

Andrea Young, Assistant Professor
University of California, Santa Barbara
https://www.afylab.com/
af.young@gmail.com
Andrea Young is an Assistant Professor at the University of California, Santa Barbara. Dr. Young earned a Ph.D. at Columbia University in 2012, under supervisor Philip Kim. Dr. Young was a Pappardo Postdoctoral fellow at MIT 2012-2014, Visiting Scientist Weizmann Institute 2014-2015 before moving to the University of California, Santa Barbara in 2015. Dr. Young's research combines nanofabrication and electronic measurement techniques in order to investigate the properties of electronic states in quantum materials. Currently, he is interested in the interplay between symmetry, topology, and correlations in low dimensional systems, both in equilibrium ground states and with strong electromagnetic drive.

Bo Zhen, Assistant Professor
University of Pennsylvania
https://www.physics.upenn.edu/people/standing-faculty/bo-zhen
bozhen@sas.upenn.edu
Bo Zhen is an Assistant Professor of Physics at the University of Pennsylvania. He received B.S. degree from Tsinghua University in 2008, and Ph.D. from MIT in 2014. His research focuses on topological photonics, specifically in non-Hermitian systems and in driven nonlinear system. His recent honors and awards include AFOSR YIP, Kaufman New Investigator, and Army-ECASE (previously known as PECASE).

Jun Zhu, Professor
Pennsylvania State University
https://www.phys.psu.edu/people/jxz26
jxz26@psu.edu
Jun Zhu is Professor of Physics at the Pennsylvania State University. Dr. Zhu earned her Ph.D. from Columbia University in 2003. She was a postdoc fellow in Cornell University from 2003-2005 before joining the Pennsylvania State University in 2006. Dr. Zhu's research interest focuses on the understanding of new physics and device functionalities arising from reduced dimensionality, many-body interactions and the control of new electronic degrees of freedom in nanoscale materials and devices. Her recent research projects explore the electronic properties of van der Waals materials and interferences, with a particular emphasis on valleytronic, topological, and quantum Hall phenomena.

Appendix III – Workshop Agenda and Prospectus

DAY 1 – TUESDAY, July 30, 2019

Time	Title
8:00–8:15	**Check-in and Continental Breakfast**
8:15–8:20	**Welcome and Introductions and Expectations** David Goldhaber-Gordon
8:20–8:45	**Workshop framing talk** David Goldhaber-Gordon and Mikael C. Rechtsman
8:45–9:00	**Breakout Instructions and Morning Break**
9:00–9:45	**Working Group I: Challenges and Opportunities in Topological Sciences** *What are the promising research directions? What are the fundamental questions that Topological Science is poised to address?* *Group A – Topological bosonic metamaterials/photonics* *Group B – Solid-state topological electronic devices* *Group C – Strongly correlated topological systems*
9:45–10:45	**Rotations**
10:45–11:15	**Working Group follow-up**
11:15–11:30	**BREAK** Transition to main conference room and leads draft outbriefing summary
11:30–12:30	**Working Group 1: Outbriefing**
12:30–1:30	**LUNCH (provided for participants)**
1:30–3:45	**Working Group II: Technical Capabilities and Challenges** *What are the potential capabilities? What are the roadblocks for success?* *Group A – Topological bosonic metamaterials/photonics* *Group B – Solid-state topological electronic devices* *Group C – Strongly correlated topological systems*
3:45–4:00	**BREAK** Transition to main room and leads draft outbriefing summary
4:00–4:45	**Report Out from Breakout II**
4:45–5:00	**Summary of Day** Mikael C. Rechtsman
5:00	**MEETING ADJOURNED FOR THE DAY**

DAY 2—Wednesday, July 17TH, 2019

Time	Title
8:00–8:15	**Check-in and Continental Breakfast**
8:15–8:30	**Welcome and Day 1 Recap** TBD
8:30–9:30	**'White Space' Discussion I** Small group discussion of topics which did not fit into the framework of day 1, but need to be discussed, including far-out potential applications or research areas. TBD
9:30–10:30	**'White Space' Discussion II** Large group discussion of particularly far-out (or long-term), high-risk, high-impact ideas. TBD
10:30–10:45	**BREAK**
10:45–11:45	**Discussion of Key Ideas/Components for Report** TBD
11:45–12:00	**Closing Remarks**
12:00	**DEPARTURE**

Future Directions Workshop on Topological Sciences

Basic Research Office, Office of the Under Secretary of Defense (R&E)

30–31 July 2019
Basic Research Innovative Collaboration Center
4100 N. Fairfax Road, Suite 450 Arlington, VA 22203

Co-Chairs: David Goldhaber-Gordon (Stanford), Nadya Mason, (UIUC), Mikael C. Rechtsman (Penn State)

Topological sciences research has exploded over the past ten years. For example, the number of sessions at the annual American Physical Society grew from one session in 2008 to over 80 sessions, with over 800 presentations, in 2018. Publications on the topic have similarly risen, from roughly 200 a year in 2008 to around 1600 in 2017. Excitement for this field is driven by the rapid pace of prediction and discovery of interesting and functional behavior from exotic new materials, like 3D topological insulators, quantum anomalous Hall systems, Weyl semimetals, and spin liquids, that promise to transform what had been thought possible in condensed matter physics, photonics, electronics, quantum science, and more. Further, the exploration of topological materials has inspired design of engineered metamaterials with analogous properties for photons or other bosonic excitations—as opposed to for electrons.

Topological properties are defined by their robustness to distortion, as in the famous characterization of a topologist as someone who cannot tell the difference between a donut and a coffee cup, because each's shape has a single hole. In the context of materials, a topological property is one that is robust to physical distortion such as strain or disorder. Such robustness, and the unusual properties that are so stabilized, appear highly attractive for technological applications. To date, thousands of materials—a quarter of those in a broad database of inorganic crystals—have been computationally determined to have topological properties. In fact, we've moved from finding topological materials to designing such materials, opening up even more possibilities. We have only begun to scratch the surface of the possible applications for topological materials. The most widely proposed application is topological quantum computing based on the potential that Majorana fermions should be present in some topological materials. Such Majorana fermions, which emerge from a combination of topological band structure, superconductivity, and sometimes magnetism, could be the basis for a scalable solid-state platform stable against decoherence. Topological magnetic materials may provide opportunities for energy efficiency and energy conversion, ranging from information processing expending several orders of magnitude less energy than the theoretical minimum of CMOS, to micro-Volt energy harvesting from a local environment, to dissipationless conductors for computing or power transmission. Spin-based topological electronic devices could use topological surface or edge currents to manipulate magnetic states to store information, act as novel sensors, or enable compact nonreciprocal electromagnetic devices. Topological photonic devices could enable small-footprint and wide-band operation of on-chip optical isolators and high-power single-mode lasers. Topological mechanics could allow for materials that distribute external forces on the surfaces of objects while protecting the interior.

Much work remains to be done in identifying materials with useful topological properties, exploring the full phase space of functionality based on topological properties, demonstrating these topological effects and determining how they may be exploited. In addition, there are sure to be useful properties of topological insulators, semimetals, and metamaterials that have not yet been discovered.

To explore the promise and challenges of topological materials research, the Basic Research Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), is sponsoring a Future Directions workshop on July 30-31, 2019 in Arlington, VA. This workshop will gather global leaders in topological sciences research from across academia, industry and government to discuss recent advances in topological sciences, the challenges and opportunities for progress, and the trajectory for research over the next 10-20 years.

Rather than a standard conference format, the workshop is structured around small-group breakout sessions and whole-group discussions for scientists and engineers from academia, national laboratories, and industry to express their perspectives and outlooks over three areas of rapid progress in topological sciences:

1. Topological bosonic metamaterials/photonics

In recent years, topological protection has been demonstrated in photonic devices, optical lattices of ultracold atoms, elastic/phononic/mechanical devices, exciton-polariton condensates, and even geophysical flows. These systems offer entirely complementary applications to those in electronic solid-state materials/devices, including the possibility of on-chip optical isolation, robust lasing in semiconductors, and quantum simulation of exotic phases of matter. By 2019 it has become clear that topological protection is a general wave phenomenon that is applicable and exploitable in many domains of physics, electrical engineering and materials science in ways that were not conceived of 10 years ago.

2. Solid-state topological electronic devices

The unique properties of topological materials—such as dissipationless conduction, spin-momentum locking, and magnetoelectric effects—may pave the way for the next generation of solid-state electronic devices, for computing and beyond. The challenge remains to identify both the most distinctive phenomena and also key applications and materials where topological properties can be exploited in practical devices.

3. Strongly correlated topological systems

Except for quantum hall effects, most topological electronic phenomena discovered to date have been understandable in terms of single-particle band structure. This has allowed powerful theoretical guidance, notably prediction of the family of chalcogenide-based topological insulators. Recently several classes of topological materials and heterostructures have emerged in which correlations play a key role, opening new possibilities for realizing phenomena from integer and fractional Chern insulators at zero magnetic field to topological superconductivity, and new horizons for theory.

The discussion and ensuing distributed report are expected to provide a signpost for this rapidly emerging field of study and valuable long-term guidance to the federal funding community, as well as the broader S&T community in the federal laboratories, domestic industrial base, and academia.