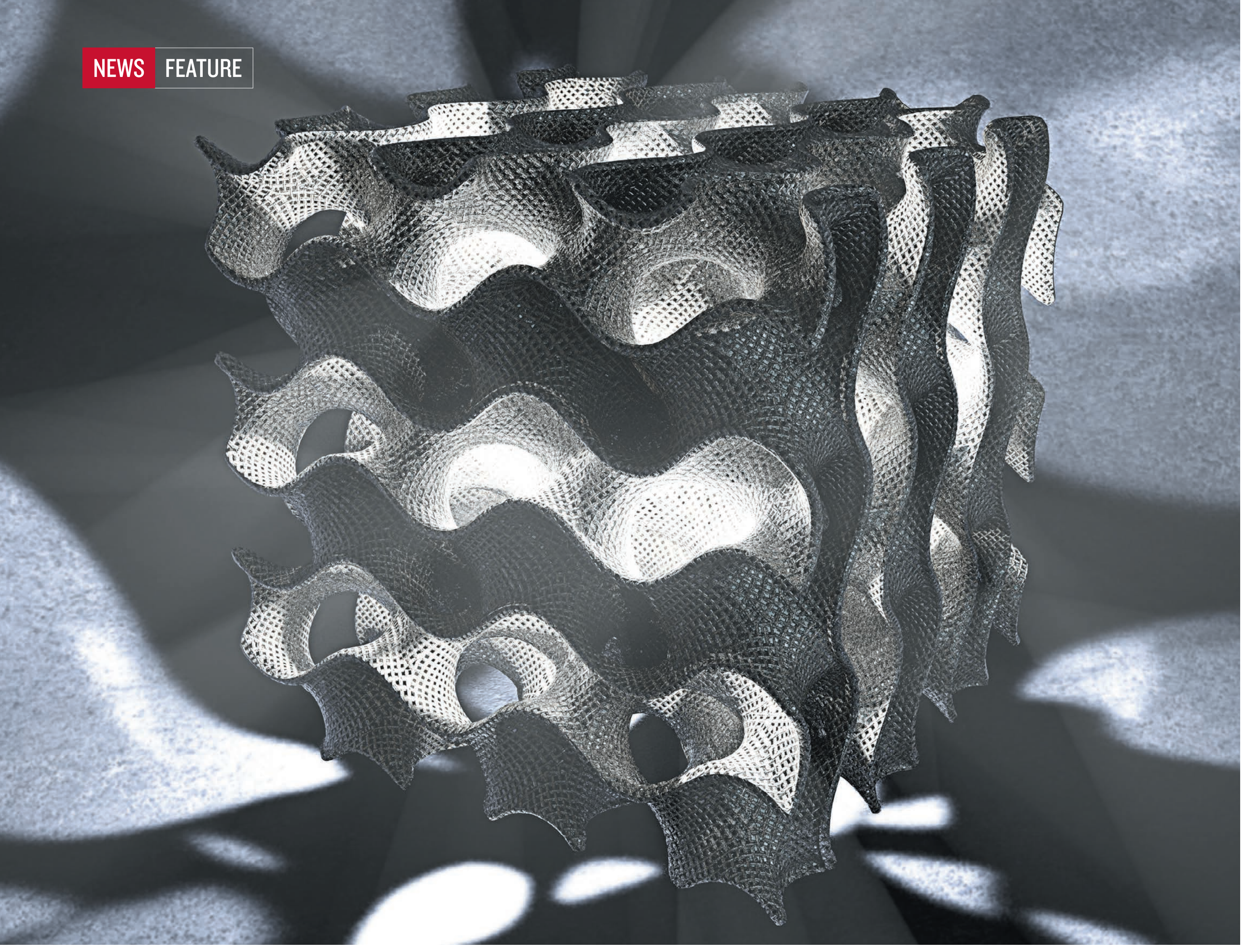

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THE SHAPE OF THINGS TO COME

Strange topological effects might be hiding inside perfectly ordinary materials. Finding them could reveal new particles, deliver superfast transistors and even bolster quantum computing.

BY DAVIDE CASTELVECCHI

Charles Kane never thought he would be cavorting with topologists. "I don't think like a mathematician," admits Kane, a theoretical physicist who has tended to focus on tangible problems about solid materials. He is not alone. Physicists have typically paid little attention to topology — the mathematical study of shapes and their arrangement in space. But now Kane and other physicists are flocking to the field.

In the past decade, they have found that topology provides unique insight into the physics of materials, such as how some insulators can sneakily conduct electricity along a single-atom layer on their surfaces.

Some of these topological effects were uncovered in the 1980s, but only in the past few years have researchers begun to realize that they could be much more prevalent and bizarre than anyone expected. Topological materials have been "sitting in plain sight, and people didn't think to look for them", says Kane, who is at the University of Pennsylvania in Philadelphia.

Now, topological physics is truly exploding: it seems increasingly rare to see a paper on solid-state physics that doesn't have the word topology in the title. And experimentalists are about to get even busier. A study on page 298 of this week's *Nature* unveils an atlas of materials that might host topological effects[1], giving physicists many more places to go looking for bizarre states of matter such as Weyl fermions or quantum-spin liquids.

Scientists hope that topological materials could eventually find applications in faster, more efficient computer chips, or even in fanciful quantum computers. And the materials are already being used as virtual laboratories to test predictions about exotic and undiscovered elementary particles and the laws of physics. Many researchers say that the real reward of topological physics will be a deeper understanding of the nature of matter itself. "Emergent phenomena in topological physics are probably all around us — even in a piece of rock," says Zahid Hasan, a physicist at Princeton University in New Jersey.

Some of the most fundamental properties of subatomic particles are, at their heart, topological. Take the spin of the electron, for example, which can point up or down. Flip an electron from up to down, and then up again, and you might think that this 360° rotation would return the particle to its original state. But that's not the case.

In the strange world of quantum physics, an electron can also be represented as a wavefunction that encodes information about the particle, such as the probability of finding it in a particular spin state. Counter-intuitively, a 360° rotation actually shifts the phase of the wavefunction, so that the wave's crests become troughs and vice versa. It takes another full 360° turn to finally bring the electron and its wavefunction back to their starting states.

This is exactly what happens in one of mathematicians' favourite topological oddities: the Möbius strip, formed by giving a ribbon a single twist and then gluing its ends together. If an ant crawled one full loop of the ribbon, it would find itself on the opposite side from where it started. It must make another full circuit before it can return to its initial position.

The ant's situation is not just an analogy for what happens to the electron's wavefunction — it actually occurs within an abstract geometric space made of quantum waves. It's as if each electron contains a tiny Möbius strip that carries a little bit of interesting topology. All kinds of particles that share this property, including quarks and neutrinos, are known as fermions; those that do not, such as photons, are bosons.

Most physicists study quantum concepts such as spin without worrying about their topological meaning. But in the 1980s, theorists such as David Thouless of the University of Washington in Seattle began to suspect that topology might be responsible for a surprising phenomenon called the quantum Hall effect, which had just been discovered. This effect sees the electrical resistance in a single-atom-thick layer of a crystal jump in discrete steps when the material is placed in magnetic fields of different intensities. Crucially, the resistance remains unchanged by fluctuations in temperature, or by impurities in the crystal. Such robustness was unheard of, says Hasan, and it is one of the key attributes of topological states that physicists are now eager to exploit.

> ***"Emergent phenomena in topological physics are probably all around us — even in a piece of rock."***

PHYSICS WITH A TWIST

In 1982, Thouless and his colleagues[2] unravelled the topology behind the quantum Hall effect, which ultimately helped to win Thouless a share of last year's Nobel Prize in Physics. Like the electron's spin, this topology occurs in an abstract space. But in this case, the underlying shape is not a Möbius strip, but the surface of a doughnut. As the magnetic field ramps up and down, vortices can form and disappear on the surface, like the wind pattern around the eye of a hurricane (see 'All wound up').

Vortices have a property known as a winding number, which describes how many times they loop around a central point. Winding numbers are topological invariants — they do not change as the shape is deformed. And the total sum of the winding numbers of vortices that wink in and out of existence as a magnetic field is applied around the doughnut always stays the same. That sum is called the Chern number, named after the Chinese-American mathematician Shiing-Shen Chern. It had been known to topologists since the 1940s.

The most astounding discovery was yet to come. Until the mid-2000s, the quantum Hall effect and other topological effects had been seen only in the presence of strong magnetic fields. But Kane and his colleagues[3], and separately another team[4], realized that some insulators made from heavy elements could provide their own magnetic fields through internal interactions between electrons and atomic nuclei. This gave electrons on the surface of the material robust, 'topologically protected' states, which allowed them to flow with next to no resistance. By 2008, Hasan's group had demonstrated the effect in crystals of bismuth antimonide[5], which were dubbed topological insulators. "That was the beginning of the fun," he says.

The discovery shook the physics world, says Edward Witten, a theoretician at the Institute for Advanced Study in Princeton and the only physicist ever to have won a Fields Medal, the most coveted award in mathematics. Far from being exotic exceptions, topological states now seemed to offer a vast array of possibilities for discovering unknown effects in nature, he says. "The paradigm has changed."

One of the biggest surprises was that these states could often be explained by theories that had been invented to solve completely different problems, such as reconciling gravity with quantum physics. Concepts such as Witten's topological quantum-field theories, which had subsequently led to breakthroughs in pure mathematics, were now coming back to physics in unexpected places. "It was a marvellous circle of ideas," says mathematician Michael Atiyah, another Fields medallist, who is now at the University of Cambridge, UK, and who also worked on these theories.

SHEER WEIRDNESS

Another major source of excitement is that in a topological material, electrons and other particles can sometimes form states in which they collectively behave as if they were one elementary particle. These 'quasiparticle' states may have properties that are not present in any known elementary particle (see page 324)[6]. They could even mimic particles that physicists have yet to discover.

Some of the most hotly anticipated quasiparticles were found two years ago. Known as Weyl fermions, or fermions without mass, they were conjectured in the 1920s by the mathematician Hermann Weyl. All of the fermions that have been discovered in the menagerie of conventional particles have some mass. But Hasan calculated that topological effects inside crystals of tantalum arsenide should create massless quasiparticles that act like Weyl fermions. For a quasiparticle, being massless means that it moves at the same speed whatever its energy. In 2015, Hasan's team confirmed[7] that experimentally, as did a group led by Hongming Weng at the Chinese Academy of Sciences in Beijing[8]. Researchers hope that these sorts of material might one day be used in applications such as superfast transistors. Electrons moving through a crystal usually scatter when they hit an impurity, which slows their progress, but the topological effects in Hasan's tantalum arsenide crystals allow electrons to travel unimpeded.

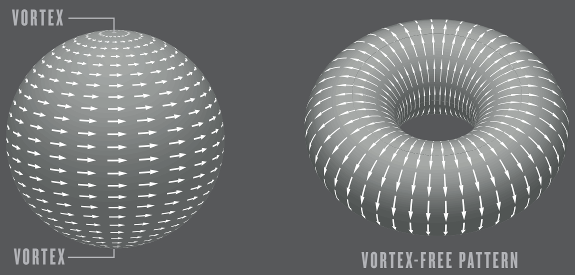
Meanwhile, Marin Soljačić, a physicist at the Massachusetts Institute of Technology in Cambridge, and his colleagues had observed something very similar to Weyl fermions, but in electromagnetic waves rather than in a solid crystal[9]. First, they built a gyroid structure — a mesmerizing 3D pattern that looks like a system of interlocking spiral staircases — by carefully drilling holes through a stack of plastic slabs. Then they fired microwaves at the gyroid, and saw that the photons — which are massless bosons — were behaving like the Weyl fermion quasiparticles in Hasan's material. One of the most exciting prospects for this booming area of topological photonics would be to use crystals to create optical fibres that allow light to go in only one direction. This would prevent light from bouncing back off imperfections and would dramatically increase the efficiency of long-distance transmissions.

On the sheer weirdness scale, perhaps the only quasiparticles that top Soljačić's boson–fermions are curious things called anyons. Ordinarily, individual particles can be either fermions or bosons. But anyons — quasiparticles that live in 2D, atom-thin materials — break that rule. Researchers can observe this transgression when two identical particles swap places. In bosons, the swap has no effect on the collective wavefunction; for fermions, it shifts their wavefunctions' phases by 180°, similar to what happens when a single electron does a 360° turn. But for anyons, the phase of the wavefunction changes by an angle that depends on the type of anyon. What's more, theory suggests that in some cases, swapping the anyons back again does not restore their original wavefunction.

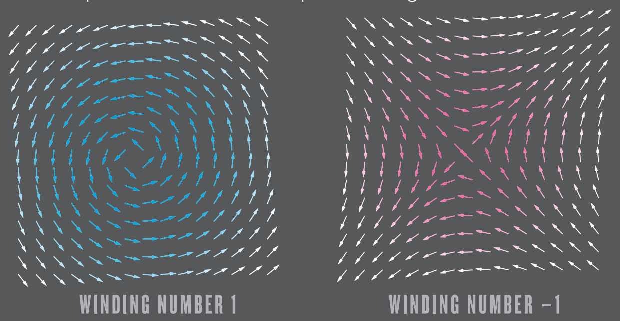
So if researchers could create several of these anyons next to each other and shuffle them around, their quantum states would 'remember' how they had been shuffled. Physicists can visualize this process by adding the anyon's 2D spatial motions to a third dimension, representing time. The result is a tracery of lines that tangle together into beautiful braids. In principle, such braided states could be used to encode quantum bits, or qubits, the units of information in quantum computers. Their topology

ALL WOUND UP

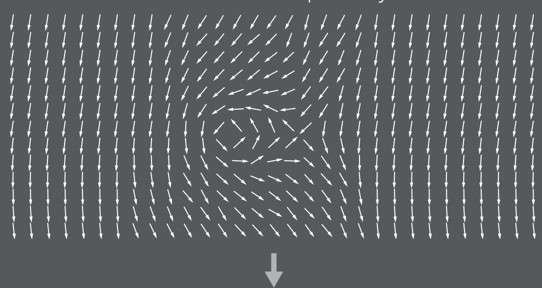
Many physical phenomena, such as air or water currents, can be represented as patterns of arrows on a surface, and their behaviour partly depends on the topology of that surface. Just as combing a hairy ball inevitably produces 'cowlicks' at each pole, a sphere will always host some swirls, or vortices, in the patterns. But that is not always the case for a doughnut.



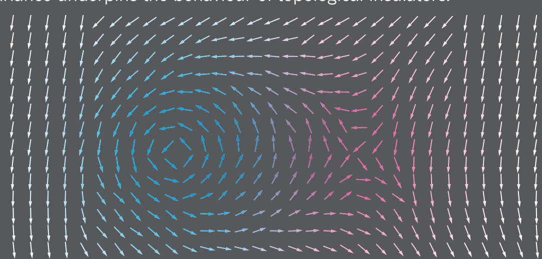
Each vortex has a 'winding number' that captures how many times it loops around a point. This number can be positive or negative.



A pair of vortices can form in an area that previously had none.



The vortices separate, showing their opposite winding numbers. The number of vortices can change, but the sum of their winding numbers cannot. This invariance underpins the behaviour of topological insulators.



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would protect the qubits from external noise, something that has plagued every other technology for storing quantum information.

In 2005, Microsoft made a big investment in quantum braids when it put mathematician Michael Freedman in charge of its efforts on quantum computing. Freedman had bagged a Fields Medal in 1986 for cracking the topology of 4D spheres, and went on to develop some of the key ideas about braiding qubits in the 1990s. Initially, Freedman's team focused mostly on the theory side. But late last year, Microsoft hired several star experimentalists from academia. One of them was physicist Leo Kouwenhoven of the Delft University of Technology in the Netherlands, who in 2012 was the first to confirm experimentally that particles such as anyons remember how they are swapped[10]. He is now setting up a new Microsoft lab at the Delft campus, which aims to demonstrate that anyons can encode qubits and do simple quantum computations. The approach is at least two decades behind other forms of quantum computing, but Freedman thinks that the robustness of topological qubits will ultimately win the day. "If you're going to build a new technology, you have to get the foundation right," he says. Hasan is attempting similar experiments, but thinks that topological quantum computers are at least four decades away. "My projection is that topological phases of matter will remain in university labs for many years," he says.

A TOPOLOGICAL ATLAS

There might be a way to speed up the work, however. Experimentalists looking for new topological insulators have conventionally relied on a laborious process that involves calculating the possible energies of electrons in each material to predict its properties.

A team led by theoretical physicist Andrei Bernevig of Princeton University has now found a shortcut. The researchers created an atlas of topological matter by looking at all 230 different symmetries that can exist in a material's crystal structure. Then they systematically predicted which of these symmetries could, in principle, accommodate topological states, without having to first calculate all their energy levels. They think that between 10% and 30% of all materials could display topological effects, potentially amounting to tens of thousands of compounds[1]. Until now, only a few hundred of these topological materials had been identified. "It turns out that what we know so far is just a small part of a multitude of topological materials that can exist, and there's a lot more," Bernevig says.

The team included three specialists in the mathematics of crystals at the University of the Basque Country in Bilbao, Spain, and researchers will soon be able to consult the Bilbao Crystallographic Server to find out whether a particular crystalline material is potentially topological. Wei Li, a physicist at Tsinghua University in Beijing, says that Bernevig's method is "definitely a more efficient way" to search for new topological insulators. "I believe there will be a lot of new materials coming out," he says.

"Knowing that a material has some topological state of matter, however, does not mean immediately predicting its properties," cautions co-author Claudia Felser, a materials scientist at the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany. These properties will still have to be calculated and measured for each material, she says.

Most of the topological materials studied so far — including those in Bernevig's atlas — have been relatively easy to understand, because the electrons inside them feel very little of each other's electrostatic repulsion. The next big challenge for theorists is to understand 'strongly interacting' topological materials, in which the electrons push hard against one another. If theorists can crack that, Hasan says, "you'll find a whole zoo of new physics phenomena that we cannot even imagine".

It is this interplay between maths and physics that lies at the heart of the field, says Kane: "What drives me is the intersection of something which is both incredibly beautiful, and also comes to life in the real world." ■

Davide Castelvecchi *writes for* Nature *from London.*

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