Given that user fatigue limits the number of interactions, one must make the most of what little data the user provides. The main approach to this is to automate most design evaluations and only selectively query the user. For parameterized design spaces (*11*), function approximation techniques can be used to assign a goodness score, based on similar designs evaluated by the user. But creating an adequate approximation is difficult, and this approach does not generalize to more open-ended, generative representations (*11*) for encoding designs. Another approach—using mathematical heuristics of aesthetics—has found some success in the interactive evolution of jewelry (*12*). The most promising long-term approach is to continuously learn and refine a model of user preferences (*13*) while simultaneously using this model to perform most evaluations.

The interactive systems described above explicitly present the user with choices to select from. Interactive evolutionary algorithms on the Web can also be invisible to the user. For example, the company SnapAds (www.snapads.com) uses an implicit interactive evolutionary algorithm to evolve banner ads. Variations of an ad are placed on Web pages. On the basis of click-through rates, the ad layout evolves and is optimized over the course of a few days. With this approach, the company has improved click-through rates by as much as 1900% (*14*). The challenge in extending such implicit algorithms to other Web applications will be to convert user interactions into a fitness assignment.

As interactive evolutionary algorithms improve and are adopted by Web site developers, we expect them to become increasingly useful for adding intelligence to interactive Web sites. Web sites with explicit interactive evolutionary algorithms could allow users to custom-design products by interactively browsing through virtual catalogs that evolve as users surf through them. Implicit algorithms could enable search engines to adaptively improve their responses to search queries over time and produce user-customized responses. This intelligent Web of the future will not just be powered by better algorithms, but will emerge from the interactions of millions of online users.

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11. A parameterized representation is like a blueprint in which the parameter values specify dimensions; for example, a table has the parameters of height, width, and depth of the top, plus additional parameters for the dimensions of the legs. A generative representation is a more expressive type of representation and—in contrast to the parameterized representation—allows for the topology of a design to be changed.
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PHYSICS

Edge-State Physics Without Magnetic Fields

A novel class of materials called topological insulators allows spin physics to be probed without the need for magnetic fields.

Markus Büttiker

Solids can be divided into conductors and insulators. A new class of materials, called topological insulators, has been predicted (*1*, *2*) that exhibit surface states that lead to quantized conductance of charge and spin. These surface states are helical edge states, which interconnect spin and momentum of the carriers. Observation of these states should not require application of a magnetic field. On page 294 of this issue, Roth *et al*. (*3*) present compelling experimental evidence for such helical edge states at the surface of a topological insulator—in this case, quantum wells of mercury telluride (HgTe). Related effects are seen in the quantum Hall effect, but only in the presence of high magnetic fields. In the quantum Hall effect, a magnetic field induces cyclotron motion of electrons that is essential for the formation of edge states.

In the band picture of solids, conduction in materials depends on where the chemical potential μ falls. In metals, it lies in the conduction band, but in insulators, it is at a lower energy and falls into the band gap between the valence and conduction bands. Topological insulators (*1*, *2*) are band insulators with particular symmetry properties arising from spin-orbit interactions. According to theory, the surface edge states should reflect the nontrivial topological properties of the band structure, leading to unidirectional carrier motion along the sample boundary. For the system to be time-invariant, the states must come in pairs so that along a horizontal bar of the material, each edge has a set of states allowing propagation to the left, and another allowing propagation to the right (see the figure, panel A).

At equilibrium, when both states of the pairs are equally populated, there is no net charge current. However, carriers moving to the right could all have spins pointing up and carriers moving to the left might all have spins pointing down. This situation would lead to a net circulating spin current that persists at equilibrium. Such a robust effect normally requires an applied magnetic field.

When a potential is applied, a net carrier flow is set up through a non-equilibrium population of edge states. In panel A of the figure, the flow is to the right, and the greater population of states is depicted with a thicker line.

The closest analog to this system is the quantum Hall effect in a two-dimensional electron gas, in which the bulk is insulating but the sample edge has chiral states that describe electron motion along the sample boundaries. The situation is particularly simple in the integer quantum Hall effect, where each edge has an integer number of states, all of which carry charge in the same direction independent of the spin directions

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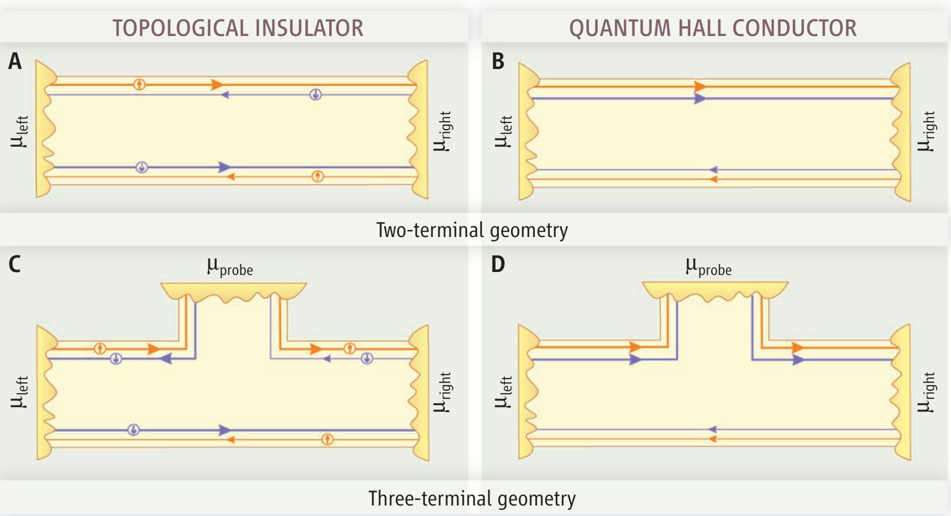

Different at the edges. Both topological insulators (**A** and **C**) and quantum Hall conductors (**B** and **D**) have edge states that connect adjacent contacts. For the topological insulator in (A), the edge states are in pairs that allow spin transport (red, spin up; blue, spin down). In all these examples, the higher chemical potential for the left contact (μ_{left}) leads to transport to the right. In the presence of transport, thick lines show greater occupancy of the states, versus the thin lines showing the unoccupied channels. The topological insulator has states with high occupancy on both sides of the sample, whereas in the quantum Hall conductor, states with higher occupation occur only on one side (B). Adding a probe with chemical potential (μ_{probe}) has no effect for the quantum Hall conductor in (D), but for the topological insulator, a current flows back from the probe to the left contact, cutting the overall conductance by half a conductance quantum (C).

but determined by the applied magnetic field (see the figure, panel B). This system has the same conductance as the topological insulator, but the two edge states that transport current in the integer quantum Hall effect are on the same (upper) side of the sample. In contrast, in the topological insulator, there is one edge state on each side of the sample (see the figure, panel A).

Molenkamp and co-workers provided experimental evidence for topological insulators (*4*) by measuring a conductance consistent with the theoretically predicted number of edge states. However, it remained to be shown that the observed conductance measurements arose from edge states. Roth *et al*. now show changes in conductance caused by a voltage probe. The theoretical predictions are based on a simple application of the scattering theory of multiprobe conductance (*5*) to topological insulators with multiple contacts.

The main effect can be understood by considering the conductance of a three-probe conductor, with one contact playing the role of a voltage probe (*1*). At such a contact, the net current vanishes. Electrons that leave the conductor are replaced by electrons from the contact reservoir. In the quantum Hall effect sample, two edge states from the left source contact enter the voltage probe, and two edge states leave the probe to the right drain contact (see the figure, panel D). The potential of the probe is equal to that of the source contact, and the voltage probe has no effect on the overall conductance.

The situation is very different for a topological insulator (see the figure, panel C). Here, only one edge state is directed from the source contact to the voltage probe. Two other edge states lead away from the probe—one to the source contact and one to the sink contact. To maintain zero current, it is sufficient to tune the chemical potential at the probe halfway between the potentials of the source and sink contact. Now, half the current is directed back to the source contact (a channel that was not populated in the two-terminal geometry in panel A). The voltage probe reduces the overall conductance by half a conductance quantum. Roth *et al.* observed this effect in several different multiprobe geometries.

In the topological insulator, a voltage probe that maintains zero charge current provides momentum relaxation, because it forces half the carriers back against their direction of incidence. Such a probe maintains zero net charge current into the contact. However, the spin current into the probe is nonzero and net spin up in the case depicted. Simultaneously, a spin current is induced into both the source and drain electrodes.

Conceptually, we could ask for a probe that nullifies both the charge and the spin current. It would require separate potentials for spin-up and spin-down carriers. It would, in analogy to the quantum Hall effect, have no effect on conductance. The spin-up potential would be equal to the source contact and the spin-down potential equal to the sink contact. Only one edge state would be filled along both the upper and lower edges. Experiments that relied on unequally populated edge states (*5*) were used almost 20 years ago to prove the physical reality of edge states in the quantum Hall effect (*6*–*8*).

Much of the physics of topological insulators is still under active investigation. Weak disorder has no effect, but strong disorder has been found theoretically to lead to a new phase (*9*) termed a "topological Anderson insulating state." The material used by Roth *et al.* is not the only topological insulator being explored. Martin *et al.* have proposed (*10*) that applying gates to bilayer graphene should generate edge states that are wide relative to the underlying lattice constants of graphene. Topological states may also exist at the interface of ferromagnets and superconductors deposited on top of a topological insulator (*11*, *12*). Such heterostructures could be used to generate qubits (the working states of quantum computers) that are largely immune to the limiting effects of decoherence.

Edge states can be used to direct electrons from one place to another, in a manner similar to directing beams of photons with optics. Such capabilities are of interest in quantum information and quantum processing. The first steps in this direction will be the realization in topological insulators of basic building blocks such as quantum point contacts, Mach-Zehnder interferometers, and the demonstration of two-particle effects (*13*, *14*) without the use of a magnetic field.

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