High-Temperature Superconductors

They conduct current without resistance more cheaply than conventional superconductors can and are slowly finding their way to widespread use

by Paul C. W. Chu

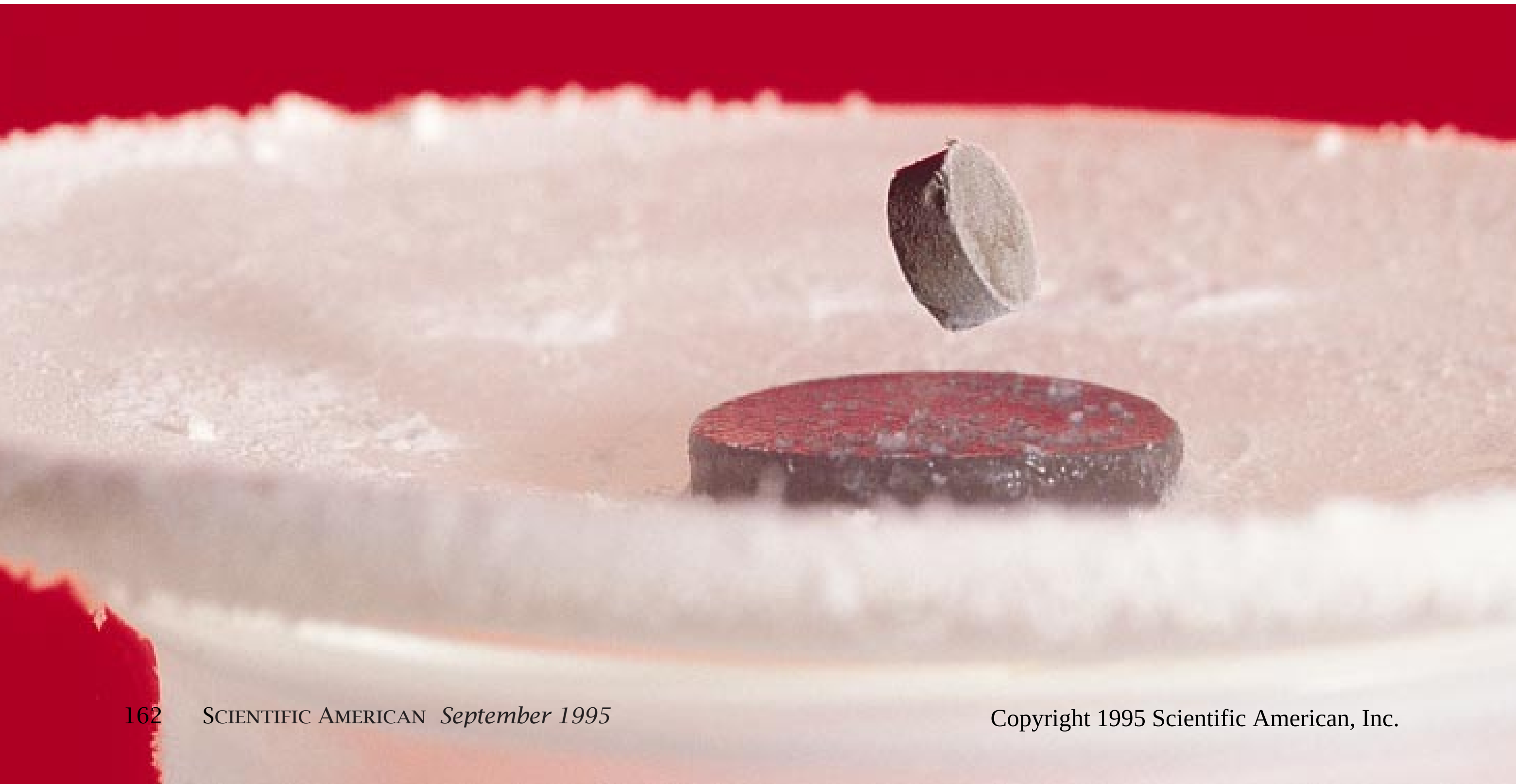
Nature, it would seem, likes to follow the path of least resistance, be it for heat to transfer, water to flow or a car to travel. If we can follow this path when making and using devices, we can save energy and effort, reduce environmental degradation and, in the long run, improve our standard of living. Unfortunately, nature does not readily reveal the path of least resistance. And it may exist only under certain stringent conditions.

A case in point is the path of zero resistance—superconductivity, the ability to conduct electricity without resistance. Superconductivity was first discovered in 1911, when Dutch physicist Heike Kamerlingh Onnes chilled mercury with liquid helium to four degrees above absolute zero, or four kelvins (a room temperature of 25 degrees Celsius equals 298 kelvins). At that temperature, Onnes observed, mercury would suddenly transmit electricity without loss. Other metals and alloys have since been found to superconduct if cooled to low enough temperatures, most of them to below about 23 kelvins. Such frigid readings—colder than the surface of Pluto—can be reached only with rare gases such as liquefied helium or state-of-the-art refrigeration systems. Despite these conditions, the phenomenon has spawned several technologies—magnetic resonance imaging (MRI) machines, particle accelerators and geological sensors for oil prospecting, among others.

Superconductivity is poised to make an even greater impact on society in the next century, however, thanks to a discovery in the late 1980s. K. Alexander Müller and J. Georg Bednorz of the IBM Research Laboratory in Zurich observed that a ceramiclike substance known as lanthanum barium copper oxide began superconducting at a then record high of 35 kelvins. More dramatic news followed shortly thereafter: in early 1987 Maw-Kuen Wu, then at the University of Alabama at Huntsville, and I, together with our co-workers, demonstrated superconductivity at 93 kelvins in yttrium barium copper oxide, or YBCO for short. At that temperature, YBCO would become superconducting in a bath of liquid nitrogen, which, unlike liquid helium, is abundant and cheap.

That work sparked a flurry of activity as researchers sought other superconducting cuprates, as these copper oxide compounds are called. Indeed, physicists have discovered more than 100 superconductors with critical temperatures that exceed those of the best conventional superconductors. (This fact prompted some theorists to plead, "Stop discovering more new ones before we understand what we have!")

The novel materials raised many questions, perhaps foremost among them: Can superconductors follow in the footsteps of their cousins, the semiconductors, and dramatically change our lives for the better? A qualified "yes" is

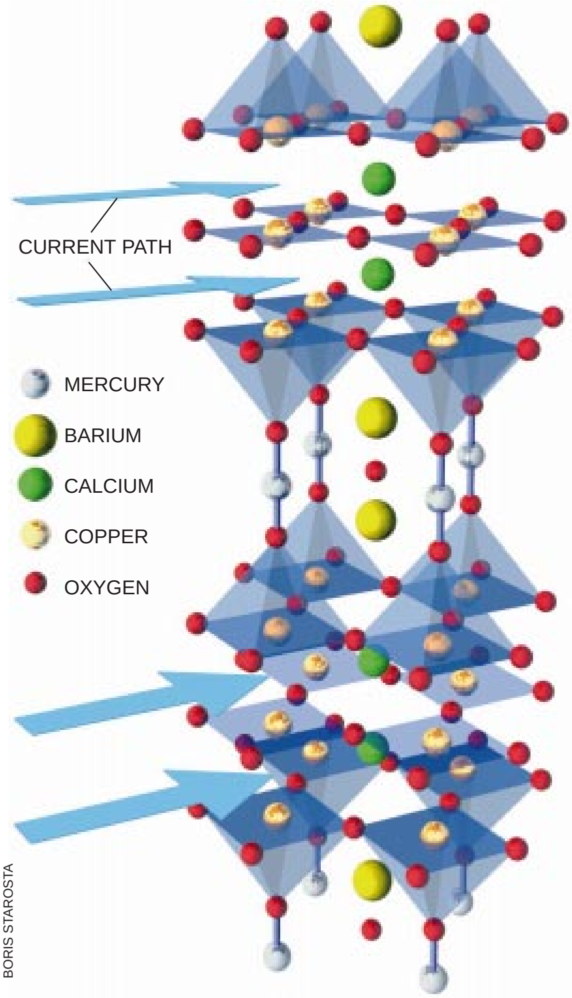


not overly optimistic, because superconductors can touch every aspect of our existence that involves electricity. Superconducting trains, nearly perfect, large energy storage systems and ultrafast computers are not realistic goals at the moment, but plenty of other applications are, in principle, possible soon: efficient generation, transmission and storage of electricity; detection of electromagnetic signals too small to be sensed by conventional means; protection of electrical grids from power surges, sags and outages; and the development of faster and more compact cellular communications technology.

A Troublesome Material

Although they may sound rather mundane, these potential uses are in a way almost too good to be true, considering the myriad hurdles that became apparent shortly after the discovery of the cuprates. One of the biggest was that cuprates carried only a limited amount of electricity without resistance, a problem stemming from the positioning of the layers that made up the materials. If the layers did not line up properly, electrons would bump into the boundary in the misaligned region and slow down. Magnetic fields further exacerbated the situation, as they could easily penetrate this misaligned region and disrupt the free flow of current. In fact, even a perfectly aligned material can fall victim to this intrusion if the magnetic field is extremely strong.

Researchers found one way around these hindrances: lay down micron-thin layers of the material on well-organized substrates. The process had the effect of lining up the superconducting layers more accurately. Although thin films do not carry tremendous amounts of current, many organizations have begun marketing instruments based on them. Du Pont, the Massachusetts Institute of Technology's Lincoln Laboratory, Conductus, Illinois Superconductor, and Superconductor Technologies Incorporated (STI) are all making devices that operate in the microwave frequencies for military instruments and cellular telephone systems. The superconducting films provide greater signal strength and process signals more efficiently in a smaller package than can ordinary conductors. Conductus and IBM are also making magnetic-field sensors known as superconducting quantum interference devices, or SQUIDs [see "SQUIDs," by John Clarke; SCIENTIFIC AMERICAN, August 1994]. These devices perform as well at the liquid nitrogen temperature of 77 kelvins as do conventional SQUIDs operating at 4.2 kelvins. Conductus currently sells models for educational and research purposes.



BORIS STAROSTA

HIGHWAYS FOR ELECTRONS are located between planes of copper and oxygen atoms, as shown in this representation of a mercury barium calcium copper oxide, which loses its electrical resistance at 134 kelvins—among the highest of the high-temperature superconductors.

While some investigators traveled the thin-film route, others tackled the intractable problem of limited current capacity and intrusive magnetic fields head-on, in the hopes of having wires and motors and other "bulk" applications. They devised many ways to surmount the obstacles. For instance, careful processing that aligned the layers of the cuprates boosted the current capacity. Investigators also sought to introduce structural defects into selected parts of the superconductor, which would act to "pin down" magnetic fields and limit their disruptive tendency.

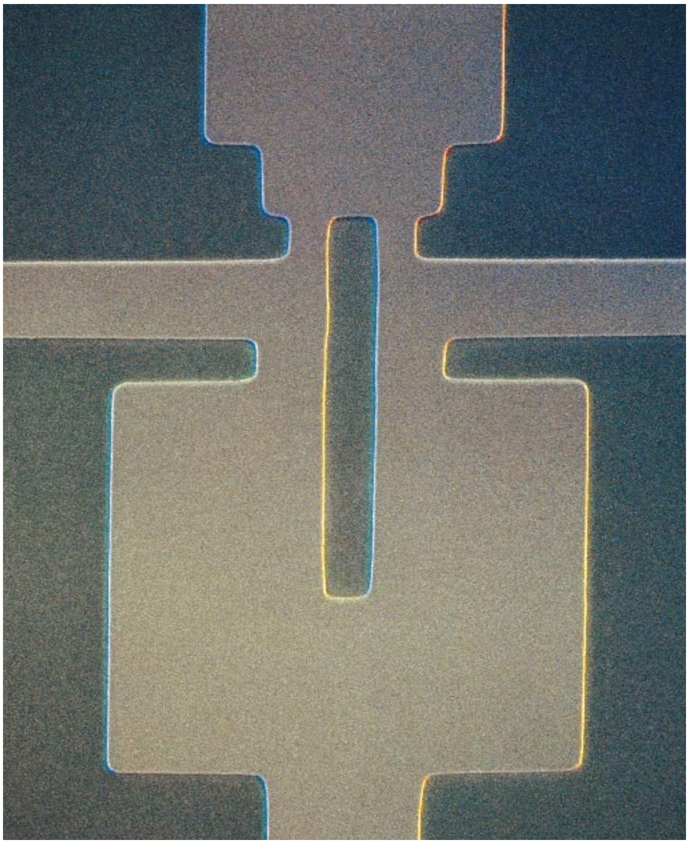
Such modifications have produced remarkable results. The maximum current density YBCO can carry is now one million amperes per square centimeter at 77 kelvins, dropping only to 400,000 amperes when a magnetic field of nine teslas is applied. Both values are much higher than initial results, when YBCO could carry only 10 amperes per square centimeter and lost all conductivity in only a 0.01-tesla field. In many respects, the current capacity now obtainable is comparable to those of conventional superconductors. When cooled to identical temperatures and placed in high fields, the cuprates in some ways outperform their low-temperature cousins.

Still, bulk applications faced another hurdle. The cuprates are essentially ceramics, which are brittle and difficult to form into wires. Through new processing techniques and materials selection, researchers have managed to coax flexible wires out of the breakable substance. They pack a precursor powder into a silver tube that is rolled and

KEPT IN SUSPENSE: a magnet floats above a superconductor cooled with liquid nitrogen, which repels all external magnetic fields.

TEXAS CENTER FOR SUPERCONDUCTIVITY, UNIVERSITY OF HOUSTON pressed into wires. Subsequent baking converts the powder into a bismuth-based cuprate. Short samples can carry 200,000 amperes per square centimeter at 4.2 kelvins (about 200 times the amount copper can usually handle) and 35,000 amperes at 77 kelvins. American Superconductor can now routinely spin out kilometer-long lengths of wire. By using ion beams, physicists at Los Alamos National Laboratory recently produced samples of flexible YBCO tape that can resist magnetic fields much better than bismuth wires do.

Several devices demonstrating the feasibility of bulk applications have been constructed. Intermagnetics General and the Texas Center for Superconductivity at the University of Houston have built different types of cuprate magnets that can generate up to two teslas, about five times the field provided by the best permanent magnet. Reliance Electric will use American Superconductor's wire to produce a five-horsepower motor. These and other institutions have also crafted flywheels to store energy and fault-current limiters to shunt electrical surges from equipment. Although some of these devices have analogues among ordinary conductors, as superconducting devices they should perform with greater efficiency and capacity.



DAVID SCHARF

SQUID, or superconducting quantum interference device, serves as a highly sensitive detector of magnetic fields. This one, only 30 microns across, contains two Josephson junctions (*not visible*) lying just above the horizontal strip that runs across the image.

Prototypes to Market?

Predicting the future is always a bit hazardous, even more so in the absence of an adequate present. Nevertheless, I will venture a few prognostications about the impact of high-temperature superconductivity on our lives in the next 10 to 30 years, based on the developments of the past nine years.

Many of the demonstration devices now being built will become ubiquitous, as manufacturing and processing become more refined and performance improves. SQUIDs, which can detect the weak magnetic signals from the heart and brain, will become a common tool for the noninvasive diagnosis of diseases. Tests have shown that these sensors can pinpoint the areas of the brain responsible for focal epilepsy. SQUIDs will also become standard issue in nondestructive testing of infrastructure such as oil pipes and bridges, because fatigued metal produces a unique magnetic signature. The advantages of liquid nitrogen should render these detectors more widely used in all areas of scientific investigation.

MRI devices will probably become smaller and more efficient. More sensitive superconducting amplifiers and coil detectors will mean that the magnetic field required for imaging can be weaker, which would result in a smaller and cheaper machine. The greater sensitivity will lead to faster signal processing, hence greatly lowering the present cost of operating the machine.

Less visible but important economically, high-temperature superconductors will work their way into microwave communications systems, acting as filters and antennas. They will prove indispensable in boosting the capacity of cellular telephone base stations by a factor of three to 10. They will also be common equipment in military aircraft to filter out extraneous radar signals that could confuse the onboard computers.

Highly populated areas may see old underground power cables replaced with superconducting lines to meet the increasing demand for electricity. Such transmission lines may also reduce electric rates—about 15 percent of the bill stems from loss caused by electrical resistance. Power stations will rely on the materials for current limiters, providing more stable voltages for a computer-dependent society.

Energy storage is also a strong possibility. Superconducting magnetic energy storage (SMES) devices may become widespread. Essentially, a superconducting coil would be charged and then wound into a circle. The current will theoretically flow without loss. When the electricity is needed, the coil is snapped back into the main grid, providing a boost of electricity. Prototype SMES devices, using low-temperature superconductors, are now being tested. Advanced flywheels, which would be supported by frictionless superconducting bearings and would spin continuously until tapped for their energy, would serve a similar purpose.

The cuprates may also prove economically feasible in equipment for space exploration. Away from the direct rays of the sun, the temperatures in space are below that needed to sustain superconductivity for many of these materials. With that realization in mind, the National Aeronautics and Space Administration has funded the development of prototype sensing and electromechanical devices for spaceship use.

Some researchers are exploring even more remote applications, specifically in computer technology. One is to make Josephson junction circuits. A Josephson junction, crafted by sandwiching a thin insulating barrier between two superconducting layers, can be made to turn on and off rapidly with low power. The junctions could replace the circuits in computers and in theory boost the speed of computation by up to 50 times. Technical obstacles, however, have prevented significant progress toward an all-superconducting computer. A hybrid system may be viable. The key problems here are making reliable superconducting circuits and designing appropriate interfaces between superconductors and semiconductors, not to mention fighting off the competition from the ever improving field of semiconductors.

Superconducting Secrets

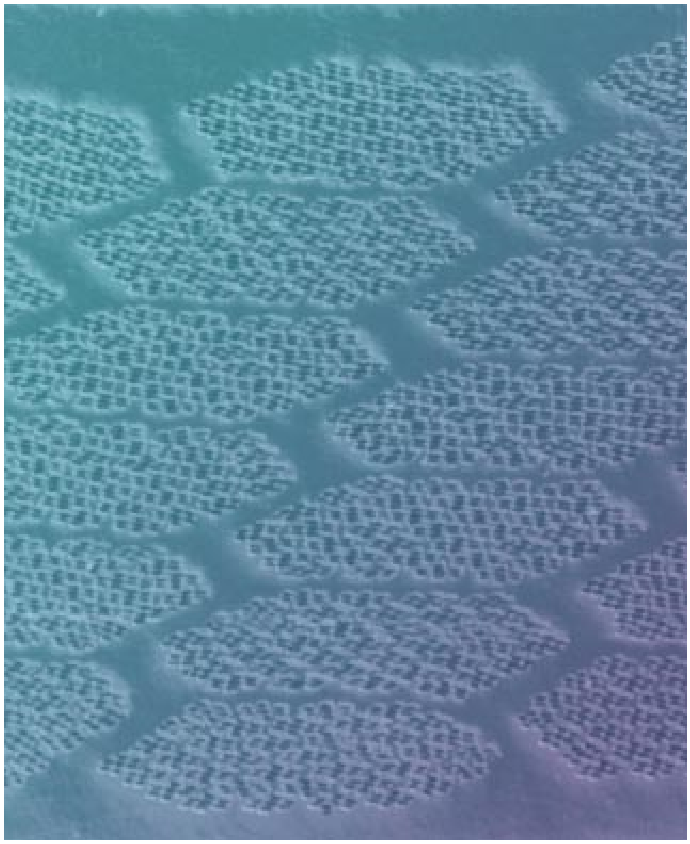
Even greater technological change may rely on advances in basic research of the superconductors. The complexity of the material has made the mechanism behind high-temperature superconductivity impervious to probing. The traditional theory of superconductivity states that vibrations of the solid cause electrons, which ordinarily repel one another, to form pairs. These pairs can then race along without resistance.

This conception, however, appears inadequate for cuprates. The high transition temperature means that the solid would have to shake so much that the lattice structure of the compound would not be stable enough for electron pairs to form. Something else must be matching up the electrons. One clue lies in the normal (that is, nonsuperconducting) state. Here the materials show unusual electric and magnetic properties that defy prevailing wisdom. Many experiments are being conducted to narrow the field of theories. I suspect that many mechanisms are acting together to produce superconductivity in cuprates and that they will be elucidated within the next 10 years.

Once the materials are understood, even higher transition temperatures may be reached. The confirmed mark for a substance under normal conditions is 134 kelvins, first observed in 1993 by Andreas Schilling and his colleagues at the Swiss Federal Institute of Technology in Zurich in mercury barium calcium copper oxide. By squeezing the compound, Dave Mao of Geophysical Lab and I, along with our co-workers, raised the critical temperature to 164 kelvins. Such a temperature, equal to –109 degrees Celsius, is attainable with technology used in household air-conditioning.

In fact, a room-temperature superconductor may be found; most theories do not exclude the possibility. Sporadic but irreproducible results have appeared suggesting superconductivity as high as 250 kelvins (–23 degrees C). A room-temperature superconductor would surely initiate another industrial revolution. Although the pace of improvement has made workers optimistic, the existence of a technology alone does not guarantee it a major position in a market-oriented society. The cost-benefit factor dictates the outcome. Hence, the challenge is to reduce the price to process the material, fabricate the device and implement the technology.

During the past nine years, scientists have made the normal abnormal by discovering high-temperature superconductors. Then they have made the abnormal normal by unraveling some mysteries of the phenomenon. Now they are trying to make the normal practical by demonstrating the technical feasibility of the effect. Although unforeseen applications are certain to arise—no one predicted that MRI technology would emerge from superconductors—the high-temperature wonderland will most likely consist of subtle yet economically profound changes, a conversion of esoteric technology into instruments we can rely on every day.


AMERICAN SUPERCONDUCTOR

SUPERCONDUCTING WIRE cut laterally reveals filaments four microns thick that are packed into hexagonal patterns. This design, used by American Superconductor, helps to make the brittle ceramic bendable and strong.

The Author

PAUL C. W. CHU, who directs the Texas Center for Superconductivity at the University of Houston, earned his doctorate from the University of California, San Diego. He has served as a consultant to several organizations and received numerous awards, including the National Medal of Science. Besides studying superconductivity, he also researches magnetism and dielectric materials.

Further Reading

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