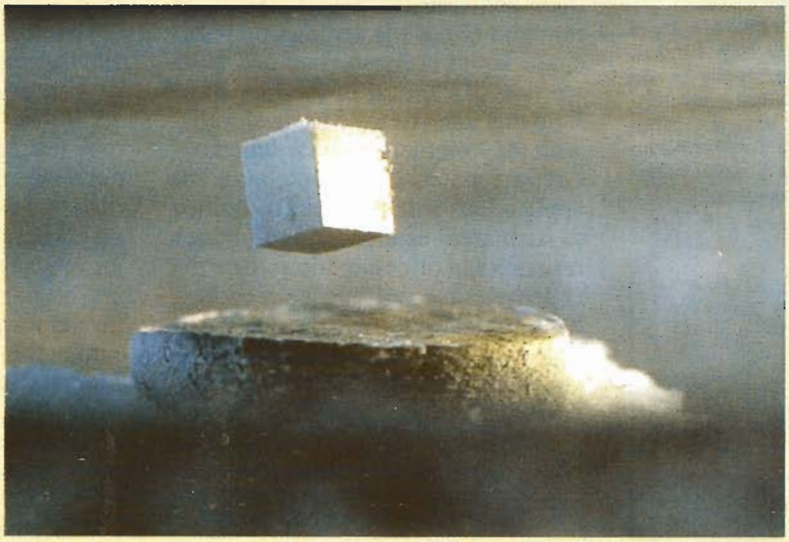
IMAGINE TRAVELING FASTER THAN 300 miles per hour in a train levitating above its tracks on a magnetic field. Imagine transistors operating more than 20 times faster than those of today, yet consuming only one twentieth the power. Imagine an energy-storage device so efficient that you could travel from coast to coast in an electric car—on a single charge.

SUPERCONDUCTIVITY BREAKTHROUGHS



A true revolution in physics has only just begun.

BRIAN C. FENTON, MANAGING EDITOR*

All those dreams won't be fulfilled this year, but thanks to the breakthroughs that have occurred in superconductivity research, they look a lot more probable than they did only a year ago.

The discovery of high-temperature superconductivity in a new class of materials is the most important scientific development in the last fifty years, perhaps even more important than the invention of the transistor, the integrated circuit, or the laser. The interest and excitement it has generated in scientific circles is extraordinary. And the speed at which new discoveries are being made has fired the imagination of the general public as well.

Even high-school students have succeeded in producing superconducting materials and have demonstrated the superconducting properties in magnetic levitation experiments such as that shown in Fig. 1. (You can experiment with superconducting materials too! See Don Lancaster's "Hardware Hacker" elsewhere in this issue for more details on the subject.)

A change of pace

Superconductivity was first discovered in 1911 by Dutch physicist Kamerlingh Onnes. He found that when mercury is cooled to a temperature of 4 Kelvin (that's 4 degrees above absolute zero, or −460°F), it loses all of its resistance to the flow of electricity and becomes a perfect electrical conductor.

For 75 years, research into the phenomenon of superconductivity yielded more than one thousand superconductive substances. The maximum temperature at which a substance becomes superconductive—the *critical temperature* or T_C—did increase linearly with time as new superconductors were discovered. But, although the increase was steady, it was at a very slow pace. As late as April 1986, the record for the highest critical temperature belonged to Niobium-Germanium (NB_3Ge), a substance that was discovered to have a T_C of 23 Kelvin sometime in 1973.

*We would like to thank Gerald Present, Ph.D., Senior Communications Specialist for IBM Corporation for his contributions to this article.

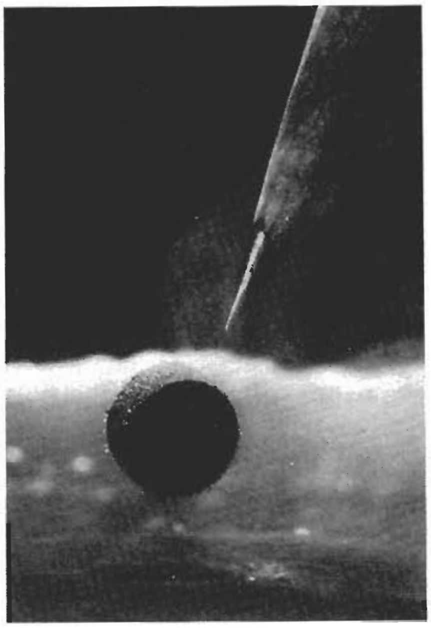


FIG. 1—A SUPERCONDUCTOR FLOATS IN air above a magnet. This experiment, which has come to symbolize the breakthroughs in superconductivity, demonstrates Meissner's effect, whereby magnetic flux does not enter a superconductive material. In effect, the superconductor looks like a "magnetic mirror."

FIG. 2—J. GEORG BEDNORZ AND K. ALEX MUELLER at IBM's Zurich Research Laboratory provided the spark that ignited the excitement of the world scientific community by their discovery of high-temperature superconductivity in a class of oxide materials.

A generally accepted theory, the BCS or *B*ardeen-*C*ooper-*S*chrieffer theory suggested that there was an upper limit to T_C at about 40 K. But two scientists at the IBM Zurich Research Laboratory put an end to that way of thinking. They discovered in early 1986 that a new class of materials exhibits superconductivity at temperatures much higher than anyone had ever seen.

The discovery, by K. Alex Mueller and J. Georg Bednorz, who are shown in Fig. 2, has kicked off a flurry of scientific activity around the world. The critical temperature has jumped sharply and, as shown in Fig. 3, dramatic increases in T_C have been coming at an astounding pace. Headlines in the popular press have proclaimed that superconductivity at room temperatures is not only possible, but around the corner!

Only time will tell whether we will ever reach that milestone. But at this time we have already passed an important point along the way: the liquid nitrogen barrier.

Finding a material that superconducts above the boiling point of liquid nitrogen (77 K) is so important because liquid nitrogen is so cheap—a fraction of the cost of the liquid helium that must be used when working with the lower-temperature superconducting materials. Superconductor applications will no longer be limited to such areas as high-energy physics research and oil exploration where the expense and inconvenience of cooling by liquid helium can be justified. Many common electrical applications could benefit, including electric-power generation, transmission, and storage; high-speed rail transport, computers; and electronic instruments as well.

Superconducting materials

Before the recent discoveries, *intermetallic* compounds (such as niobium-tin, niobium-germanium, etc.) were the best superconductors. But Mueller and Bednorz had become convinced that no further progress would occur in raising the critical temperatures of such compounds. Their insight led them to metallic oxides. The Zurich researchers were very familiar with those oxides and believed they were candidates for higher-temperature superconductors.

For high superconducting-transition temperatures to occur in a material, either the number of electrons available to carry current must be high or the attractive or coupling forces between the electron pairs responsible for superconductivity must be strong. Even though oxides have fewer available electrons than metals (which generally make good superconductors), some metallic oxides were already known to be superconductors, although only at temperatures of up to 13 K. That could only imply, the researchers reasoned, that the materials had particularly strong electron-pairing forces. They thought they could find even stronger pairing forces in oxides of nickel and also copper.

After much work on a number of different systems, they become aware of a class of copper oxides that was reported to behave like a metal in conducting electricity. Those materials had not been studied previously for possible superconductivity, but Mueller and Bednorz believed they were perfect candidates.

In January 1986 they found a strong decrease in electrical resistance when they cooled the material, a ceramic copper oxide containing lanthanum and barium. By April, their best samples showed a transition occurring at 35 K—a very substantial increase over the 23 K reported for niobium-germanium in 1973. They immediately reported their results and the race was on—a new chapter in physics had begun.

The impact of the IBM discovery on the world physics community was astounding—by January 1987 several other research teams had prepared their own versions of the IBM compound and reported similar results and even higher transition temperatures.

Paul C.W. Chu, a leading superconductivity researcher from the University of Houston, found that by pressurizing a superconducting oxide, he could raise the critical temperature to 70 K. He theorized that the pressure helped increase the critical temperature by bringing the layers of copper and oxygen and lanthanum and barium closer together. He found another way to bring the layers closer: He replaced the barium with strontium, which is a similar element but has a "smaller atom." That raised the critical temperature even more. When Chu replaced lanthanum with the element yttrium, the composition of the substance was altered drastically—and the critical temperature shot up to 95 K. He announced his results on January 29, 1987, and started a revolution within a revolution. The liquid-nitrogen barrier had been broken.

By the time of the March, 1987 meeting of the American Physical Society in New York, thousands of scientists and engineers throughout the world were trying to understand more about the new class of oxide superconductors, to find variations that had still higher transition temperatures, and to explore possible applications.

Shortly after that, IBM researchers made the first thin films of the new higher-temperature superconducting material, which led to the development of the first superconducting devices to operate in the liquid-nitrogen range. The device, called a SQUID or *S*uperconducting *QU*antum *I*nterference *D*evice, is an extremely sensitive magnetic-field detector.

It's not easy

Despite all the truly fantastic discoveries and developments, there are still problems to overcome. But researchers seem intent on overcoming all of them.

For example, one of the major problems with the new superconductors was their low *critical current*—the current above which a material loses its superconductive properties. But researchers changed things in record time. IBM researchers reported that the materials were inherently capable of carrying 100,000 amperes-per-square-centimeter at liquid-nitrogen temperatures—more than 100 times more current than previously believed. Shortly after, Japan's NTT Ibaragi Telecommunication Laboratory reported producing a superconductor able to conduct 1.8 million amperes-per-square-centimeter!

Being able to *consistantly* produce materials with such high critical currents is still a problem. The first isolated single crystals were grown by IBM scientists, who were able to show that the superconducting properties of the materials are stronger in certain special directions of the single-crystal specimens. The current can vary by as much as a factor of 30 depending on its direction in the crystal. That property, called *anisotropy*, might partially explain why typical samples of the new material, which are generally composed of a multitude of tiny crystals oriented in random directions, show low values of critical current.

Another problem with the new superconductive materials is that they are very brittle. It will take much more research to find a way to turn the materials into a type of flexible wire.

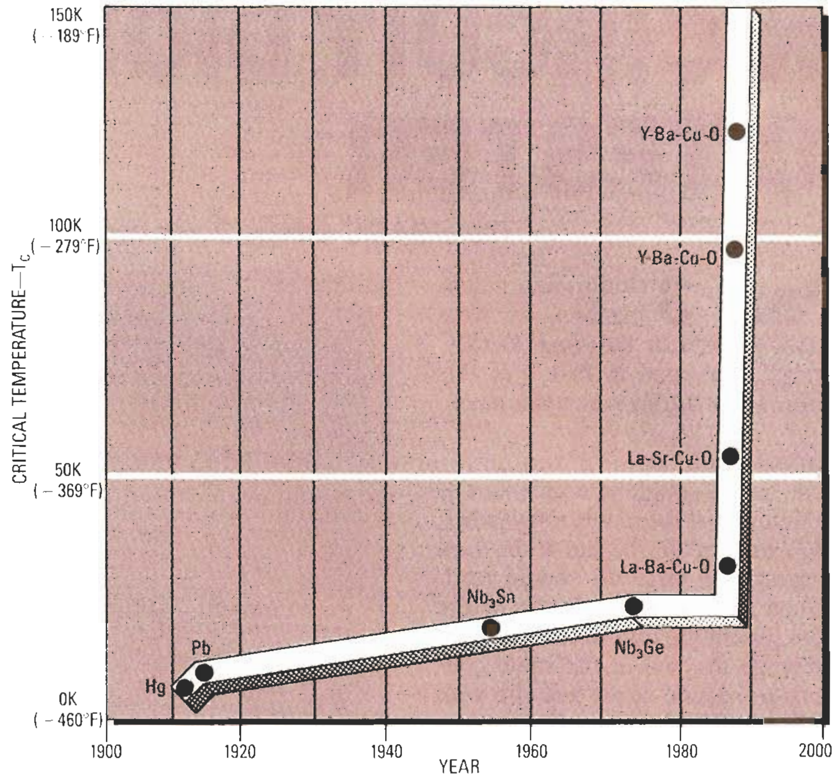


FIG. 3—AFTER 75 YEARS OF SLOWLY INCREASING as new superconducting materials were found, critical temperatures jumped dramatically with the discoveries of Mueller and Bednorz. While it's not certain that room-temperature superconductivity will ever be achieved, we're certainly heading in the right direction!

But researchers at AT&T Bell Laboratories are developing coils by filling copper tubing with powdered superconductors. And IBM scientists have shown how plasma spraying, a common industrial technique, can be used to coat even large and complex shapes with superconducting material.

Applications

The potential applications for high-temperature superconductors are far-reaching. Even if critical temperatures do not increase over what they are today, the new superconductors will change our world.

For example, fusion power could become economically competitive years down the road because the superconducting electromagnets required to contain the fusion reaction will cost much less to produce and maintain than the magnets used in today's test reactors.

The tremendously expensive MRI (*M*agnetic *R*esonance *I*maging) machines that are currently giving medical doctors detailed internal views of the human body will also become much more affordable because they will be cooled by liquid nitrogen. The images will also become many times more detailed as the magnets became more powerful.

Supercomputers will become smaller, faster, and therefore will be more powerful.

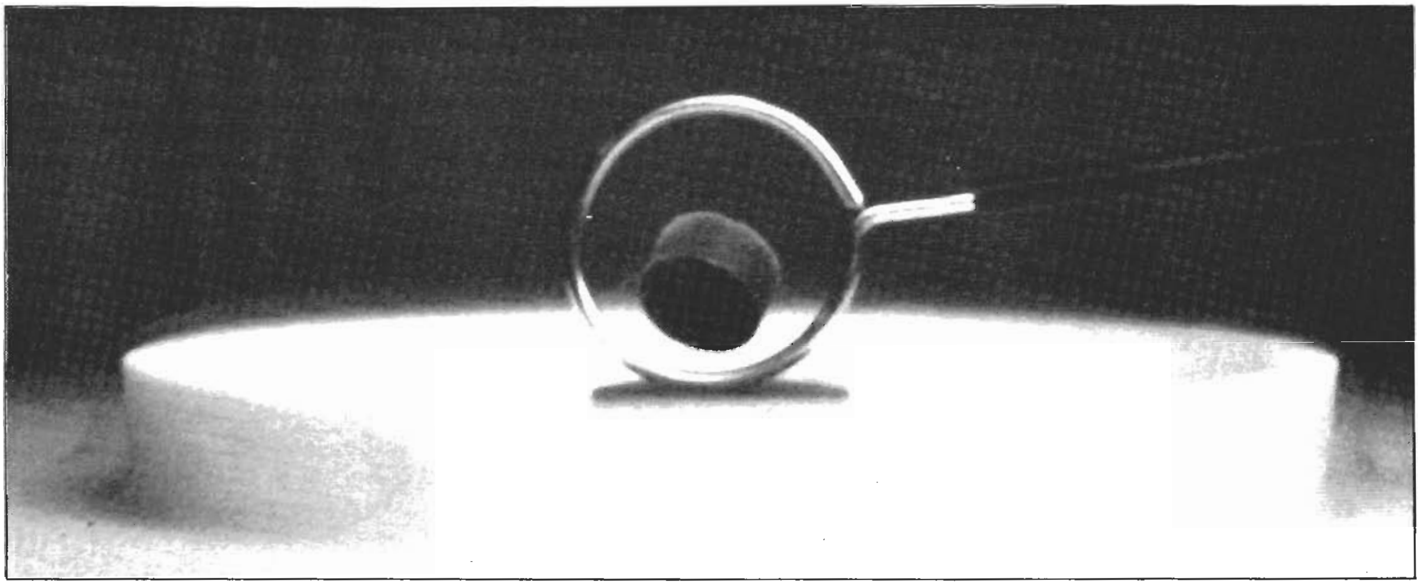
But just imagine what would happen if room-temperature superconducting materials could be developed. In short, the world as we know it would change dramatically. Trains levitating on a magnetic cushion as they travelled quietly and pollution-free at speeds better than 300 miles per hour would become a reality. Power-generating plants could be located far from population centers, as lossless power transmission would become a reality. Power plants would even become good neighbors as they generated safe, pollution-free power using fusion or magneto-hydromagnetic technology.

Tremendous progress in superconductivity has been made in a very short time. And you can be sure that there are many other applications of superconductors yet to be discovered. Until 1986, it was generally believed that room-temperature superconductivity would never occur. Now we're asking not *if* that event will happen, but *when*. **R-E**

A Superconductor Kit

Watch a superconductor in action right before your eyes.

BILL MARKWICK



Not long ago, the superconductor existed only in major laboratories. The drop to zero of electrical resistance had only been observed at temperatures colder than 23°K (23 degrees above absolute zero), a temperature that could only be maintained with liquid helium. However, it was predicted that materials research would turn up a substance that would exhibit superconductivity at much higher and more manageable temperatures. In 1986, IBM's Zurich Research Laboratory announced a ceramic oxide which exhibited a Tc (temperature of superconductivity) of 35°K. In early 1987, the University of Houston produced a material made from yttrium, barium and copper oxide with a Tc of 93°K. This allowed superconductivity using liquid nitrogen with a boiling point of 77°K.

Today, CS Technologies, a company in Kanata, Ontario, is selling a superconductor kit that can demonstrate the effect to anyone with access to a flask of liquid nitrogen, which is not that difficult to locate from science labs, gas product companies or welding suppliers. The kit consists of a ceramic disk of the superconductor (yttrium oxide, barium carbonate and copper oxide), an insulated stand, a magnet, a small hoop and a pair of tweezers.

We took the kit over to Marc Garneau Collegiate in Don Mills, where the science department could demonstrate the kit to some of the students. A cryogenic flask of liquid nitrogen was kindly donated by the Ontario Science Centre, and we donned safety glasses and gloves as a precaution against spills. It may be warmer than helium, but it can instantly turn your fingers to Popsicles...

The superconductor pellet is placed on the stand and the tiny magnet placed on top of it. When a little liquid nitrogen is poured over them, the magnet suddenly jumps about 5mm into the air and hovers there, twisting this way and that in the air currents. The hoop can be used to demonstrate to scoffers that they're actually looking at genuine levitation. Occasionally the magnet might slip out of range, or even freeze from condensed water vapour; the tweezers are for setting it in place without getting too close to the liquid nitrogen.

The reason the levitation occurs is that the magnet is inducing an equal magnetic field in the resistance-less superconductor. The equal fields repel; should the magnetic move in relation to the superconductor, the magnetic fields alter together, keeping the magnet in balance. You can even set it spinning in the air, with a very slow decay rate.

The potential for this new technology is enormous. The loss is power transmission would be greatly reduced, though it's unlikely the cost of replacing the existing grid would be justified. Semiconductor junctions could become faster by several orders of magnitude, and electric motors could be much smaller and more efficient for the same power.

CS Technologies will soon be introducing the world's first commercially available superconducting motor. This experimental motor places 24 electromagnets around the circumference of a rotating 8.5" aluminum plate. As these iron-cored electromagnets pass close to the two superconducting disks placed below the plate, they induce mirror magnetic fields in the superconductors that repel the electromagnets, resulting in rotation of the aluminum plate at about 50RPM.

You can order a semiconductor disk (part 87001) for $30, the entire kit (part 87002) for $50, and a fabrication kit is available for about $200, which includes the chemicals, crucible and die required for making your own. Facilities required, such as a 1000°C kiln and a large vise, should be available in most school labs. Please note that prices do not include taxes or shipping.

For more information, contact: *CS Technologies, 21 Sumner St., Kanata, Ontario K2L 2P3, (613) 836-4617.* ■