Superconductors

Conquering Technology's New Frontier

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To Paul and Mike
who got us started

Preface

In a laboratory in Leiden in 1911, a Dutch scientist observed the remarkable disappearance of all electrical resistance from a thin capillary of mercury metal sitting in a bath of liquid helium. Seventy-six years later, in a laboratory in Huntsville, Alabama, another scientist saw the same thing happen to a greenish ceramic pellet sitting in a much warmer bath of liquid nitrogen. These two events—the original discovery of superconductivity and the recent discovery of high-temperature superconductivity—are linked by a rich history of scientific and technological accomplishments.

Over the years, superconductivity has flourished as a field of scientific endeavor, leading to the awarding of eight Nobel Prizes in physics. In addition, it has emerged as a technology, contributing to advances in medicine, electronics, astronomy, transportation, and experimental science. But in spite of all these things, superconductivity has remained a little-known phenomenon on the periphery of science.

Now, because of the most recent discoveries, superconductivity has become one of the most celebrated areas in all of science. Its applications promise to reshape many aspects of future society. For the first time ever, superconductivity has become a subject that we should all know about.

We have written this book in order to bring the story of superconductivity to an audience beyond students and practitioners of physics and engineering. In some sense, we have three stories to tell. In the first part of the book, we explore the nature of superconductivity, its history, and our theoretical understanding of the phenomenon. In the second part of the book, we survey a wide variety of practical uses for superconductivity throughout society and examine superconductivity's role in today's economy. In the last part of the book, we discuss the recent breakthroughs in superconductivity and evaluate their impact on the future of technology.

We intend this book for readers who have no prior background in physics, electronics, or other pertinent technical fields. We include no mathematics and presume no familiarity with the principles of modern physical science. We therefore introduce whatever relevant scientific background information we require during the course of each chapter. Although we present modern science without mathematical rigor, we have endeavored to provide an accurate and comprehensive explanation of the subject.

Superconductivity is now a rapidly changing field, with new discoveries being made almost all the time. Although this book includes a wealth of up-to-date information, the very latest news on superconductivity will undoubtedly be found in daily newspapers. This book will help to place the newest results in their proper perspective.

During the process of writing *Superconductors,* we have drawn upon the considerable expertise of a number of colleagues from the superconductivity community. Among these are John Clarke, Robert Fagaly, Sadeg Faris, Eric Forsyth, Ken Grey, Eric Gregory, Robert Hazen, Scott Kreilick, Arnold Silver, Michael Superczynski, Joe Thompson, Harold Weinstock, and Dave Woody. We thank them all for their kind assistance.

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We wish to express our gratitude to Anne Kottner at the Niels Bohr Library for locating many of the photographs used throughout the book and to Victor Swayne, whose skillful and vivid illustrations greatly enhance the comprehensibility of the book. Finally, we grate-

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Randy Simon and Andrew Smith

Redondo Beach, California

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CHAPTER 1

In from the Cold

A silvery glint appears on the horizon, catching our eye. Moments later it passes us with scarcely a sound. We have just observed a sleek passenger train traveling 300 miles per hour while floating several inches above its tracks.

A few miles away, an inconspicuous fenced-in area marks the location of the new power company installation. Buried underground are giant coils of special wire carrying huge electrical currents. The currents flow incessantly, keeping electrical energy stored for when it is needed.

In a nearby hospital, doctors are examining a patient who has suffered a mysterious seizure. An unlikely contraption hovers over the patient's head while the doctors gaze intently at a computer screen. They are closely watching abnormal brain activity taking place near a small tumor.

At an industrial park, some engineers are putting their latest achievement through its paces: the heart of a new computer, faster than any machine ever built and small enough to fit in a shoebox. The microscopic electronic switches within the new computer can turn on and off a trillion times every second.

A fanciful depiction of a distant future? Perhaps. Wishful thinking about undiscovered technologies? Definitely not. All these marvels can be achieved with superconductors and we already know how to do it.

What are superconductors and why haven't we already harvested their rewards?

Superconductors are materials—usually metals—that undergo a remarkable transformation at extremely low temperatures. Superconductors have a number of unique characteristics but their most notable property and the origin of their name is their ability to conduct electrical current with absolutely no loss of energy. Nothing else in nature can perform this feat.

Superconductors are hard to find but, paradoxically, they are not at all rare. Nearly a quarter of the natural elements are superconductors. There are also hundreds of compounds and alloys with the property. So why are they hard to find? The answer is that superconductivity only happens at temperatures far below anything we are likely to encounter in our lives.

For most people, low temperature means the freezing point of water: 32° Fahrenheit or 0° Celsius. The hardy souls inhabiting the polar climes are even familiar with the one temperature at which the two scales read the same number: −40°. The only lower temperature most of us ever come across is that of dry ice at 108 below zero, Fahrenheit. Yet there are still lower temperatures that can be reached. In fact, there is a lowest temperature in nature. According to present-day physics, nothing in the universe can get any colder than 459 Fahrenheit degrees below zero (−273°C). Scientists refer to this temperature as "absolute zero" and have devised a temperature scale—the Kelvin scale—for which this lowest temperature is simply zero. On this temperature scale, water freezes at 273 Kelvin and boils at 373 Kelvin.

Until quite recently, the only way to make a material superconduct was to reduce its temperature almost all the way to absolute zero. It may safely be said that reaching such temperatures has never been nor will ever be an easy thing to do.

In 1986 and 1987, pandemonium broke out in the scientific world when a new class of superconductors was discovered. They had the same properties as the old superconductors with one crucial exception: they become superconducting at much higher temperatures. How high? Nearly 100 Kelvin. If you do a little arithmetic, you will realize that this is still plenty cold: about −280°F. So why all the fuss?

The answer is primarily economic in nature. Temperatures close to absolute zero are expensive to reach and expensive to maintain. The warmer it gets, the cheaper it gets—that's the rule. It turns out that 77 Kelvin—the temperature of liquid nitrogen—is an affordable and trouble-free temperature in today's technology. If superconductors can operate at such a temperature, then their jobs are waiting. It may sound facetious but in terms of practicality, a 77 K superconductor is truly a high-temperature superconductor.

The discovery of the new superconductors started a mad scramble in the scientific community. A race was on to produce the materials, improve their properties, and exploit them for practical applications. Suddenly superconductivity became a household word, the subject of magazine cover stories and television news reports. The United States Congress and the President called for a national program in superconductivity research. A contagious wave of excitement swept through the physics community. Superconductivity became news but it isn't new at all.

A Dutch physicist named Heike Kamerlingh Onnes lowered the temperature of mercury metal enough so that it became a superconductor back in 1911. He was the first one to do it because only he had the means of reaching such low temperatures. How low? Mercury becomes a superconductor at 4 degrees above absolute zero. The only way to reach such a low temperature is with liquid helium. We know that ordinary steam turns into water if it is cooled below 212°F. In the same way, helium, the gas we use to blow up balloons, becomes a liquid at 4.2 K. It's quite a trick to liquefy helium, but once we've done it, we have a 4-degree fluid. Kamerlingh Onnes became the first person in history to liquefy helium in 1908. Three years later he discovered superconductivity.

Onnes realized almost immediately he was on to something important. He envisioned wire made from superconductors that could be made into huge coils and used as powerful electromagnets requiring no energy to operate. The ensuing decades brought the discovery of new superconductors and new properties of superconductors. Every new discovery presented a new opportunity for useful applications. The only rub was the requirement for temperatures near absolute zero.

So high-temperature superconductivity was an unexpected discovery but an extremely welcome one. Scientists had decades worth of good ideas for using superconductors. They just needed warmer superconductors to make their ideas more practical. It was really no surprise, then, that the 1987 Nobel Prize in physics was awarded to K. Alex Mueller and J. Georg Bednorz of IBM's Zurich laboratory who synthesized and tested the first of the new high-temperature superconductors.

It was also no real surprise that within a few months of the discovery, thousands of scientists around the world were studying the new materials trying to understand how they work and how to improve them. Previously staid, low-key scientific conferences became tumultuous media events with turnaway crowds competing for scarce seats. Universities, government labs, and industrial labs all entered the race for breakthroughs in high-temperature superconductivity.

But for most us, all this uproar about superconductivity is still rather mystifying. We hear things about electrical currents with no loss of energy, we see photos of superconducting magnetically levitated trains, and we read about high-speed superconducting supercomputers. Superconductivity is obviously an important and interesting phenomenon, but just what is it?

To understand anything about *super*conductivity, we have to know something about ordinary conductivity. All ordinary materials resist the flow of electricity to a lesser or greater extent. Electricity or electrical current consists of the movement of electrons through a material. In order to make electrons flow, we need to add energy; we need to push them. Electrons in a metal behave like water in a hose. The water won't flow unless we supply some pressure. The amount of pressure it takes depends on the kind of hose we use.

Similarly, the amount of energy needed to produce a certain electrical current in a material depends on the kind of material we are using. The energy we supply to electrons—the push we give them—is called *voltage*. We get it from a battery or from an outlet in the wall. A 1.5-volt AA battery can supply a certain amount of energy to each electron in a wire. A 6-volt camera battery supplies four times that energy.

The amount of voltage we apply to a conductor determines how much electrical current will flow. The more we push on the electrons, the faster they move. We measure current in units called *amperes* (amps for short). One ampere of current corresponds to more than 10,000,000,000,000,000,000 (usually written as 10^{19}) electrons passing by every second, about the amount of current that flows in an ordinary 100-watt light bulb.

The actual amount of current we get for a given voltage depends on the nature of the material we are using. The more the material resists the flow of electricity, the more we have to push to keep current flowing. We call the measure of this property the resistance of the material. If we apply 1 volt across a material and we get 1 amp of current to flow, then by definition the material has a resistance of

1 *ohm.* If only half as much current flows, then the material has a resistance of 2 ohms, since it resists the flow of electricity more strongly.

Resistances of common materials vary wildly. A chunk of copper—the metal used in most common wire—might have a resistance of only a few millionths of an ohm. A piece of glass, on the other hand, can easily have a resistance in millions of millions of millions (that's quintillions!) of ohms. Almost nothing in nature has as much diversity as the resistance of materials. But all ordinary materials have one thing in common: they have *some* electrical resistance. It takes at least some amount of energy to permit current to flow.

Ordinary materials require voltage to sustain current because they burn up energy in the form of heat. Electrical resistance is a form of friction like the heat generated by tires skidding on pavement. A car stops moving when it loses its energy of motion to heat in its brakes and tires. Similarly, electrons lose their motion in a metal by heating up the metal. We call this loss of energy *Joule heating.*

Superconductors are extraordinary because they alone are immune from the effects of Joule heating. It takes no energy at all to make current flow in a superconductor, and no energy is lost to friction to sustain the current either. Its electrical resistance is precisely zero.

This property is truly sensational, but two questions immediately come to mind: how do we know that the resistance is really zero, and why should the difference between zero ohms in a superconductor and a millionth of an ohm in copper matter to anyone?

The first question almost sounds silly. Zero is zero, after all. But zero really is not an easy number to measure. All instruments have their limits and zero is below the resolution of any measuring device. A human hair would weigh nothing on a bathroom scale, not because it is weightless, but because its weight cannot be detected by the scale. Nevertheless, not even the most careful experiments using the most sensitive instruments have ever found any electrical resistance in a superconductor. These experiments have shown that if there was any resistance at all in a superconductor, it would be at least a trillion times smaller than the resistance of copper. Furthermore, scientists have established a theory that explains superconductivity, and according to the theory, the resistance of a superconductor truly is zero.

So we'll accept that superconductors have no resistance whatsoever. Still, who needs them? Why shouldn't we be satisfied with a few millionths of an ohm in copper? The answer is an issue of energy and scale. Joule heating gets worse and worse for higher resistance materials; double the resistance and we double the heat loss. It gets worse much faster as the amount of current flowing increases. If we double the current in a wire, we quadruple the amount of energy lost to Joule heating.

But copper has such a low resistance. How much energy is lost from a millionth of an ohm? This is where scale comes in. A 1-inch cube of copper has a resistance of a millionth of an ohm. Take the cube and stretch it some to make a block 2 inches long and half an inch wide. What is its resistance now? Four times greater. Why is that? We've done two bad things for the resistance: we've made the conductor longer—so the electrons have more opportunities to lose energy to friction—and we've made it narrower, so their path is more constricted. You can't flow as much water through a narrow pipe as you can through a wide pipe. Electricity obeys the same rules. This produces the problem of scale. Even the resistance of copper causes significant energy losses if we need either very long wires or very narrow wires. The wire that connects a power plant with a distant city is a very long wire indeed. The hair's-width conductors in a complex microcircuit are very narrow wires. Joule heating makes trouble for us with the best ordinary conductors.

Superconductors are a natural solution to the whole problem. They will be most welcome in any application where we need a lot of wire. Ordinary wire used to transmit electricity from power plants to cities wastes 5 to 10 percent of the electrical energy because of resistance. Superconductors would waste nothing at all. Electrical generators made with superconducting wire would be smaller, lighter, and more efficient. When space and weight are at a premium, as on a ship, the benefits could be enormous.

Kamerlingh Onnes' dream of giant superconducting electromagnets has already come true. Current flowing in a coil creates a temporary magnet, called an electromagnet. If the coil is big enough or the current is big enough, such a magnet can be far more powerful than any permanent magnet (like the ones stuck to our refrigerator door). We can build powerful electromagnets with superconducting wire in a fraction of the space needed with ordinary wire. Even coils made from small diameter superconducting wire can handle large currents without burning out from Joule heating. Such superconducting magnets are used today in hospitals around the world for the important new technique of magnetic resonance imaging, in magnet-