Solid State Physics: The Mechanism Behind High-Temperature Superconductors

> *"Every body continues in its state of rest or uniform motion*
> *in a straight line, except insofar as it doesn't."*
> —Sir Arthur Stanley (1882–1944)

Solid-state physics deals with the properties of solids, from the atomic level upwards. It is closely linked to materials science (which also explores the chemical and engineering aspects of materials) and to electronic device technology (which has had a profound influence on our way of life). This chapter discusses the unsolved problem of solid-state physics as the mechanism behind high-temperature superconductors (HTS) and some of the technological revolutions that have relied on HTS for the basic discoveries and inventions. But in order to lay the foundation for an in-depth discussion of HTS, a general discussion of superconductor basics and history must be conducted first.

Superconductors

The phenomenon of superconductivity was discovered by Onnes in 1911, when he reduced the temperature of solid mercury below 4.3 kelvin and found that its resistance vanished. (See sidebar, "Superconductor History.") Since then, about half of the common chemical elements have been found to exhibit superconductivity (see sidebar, "Superconductivity: What Is It?") if cooled below a critical temperature (Tc). The values of Tc vary from 0.0003 K (for rhodium) to 9.5 K (for niobium).

Superconductor History

Superconductors are composed of materials that have no resistance to the flow of electricity. They are one of the last great frontiers of scientific discovery. Not only have the limits of superconductivity not yet been reached, but the theories that explain superconductor behavior seem to be constantly under review.

In 1911, superconductivity was first observed in mercury by Dutch physicist Heike Kamerlingh Onnes of Leiden University. When he cooled mercury to the temperature of liquid helium, 4 kelvin (–452° F, –269° C), its resistance suddenly disappeared. The kelvin scale represents an "absolute" scale of temperature. Thus, it was necessary for Onnes to come within 4 degrees of the coldest temperature that is theoretically attainable to witness the phenomenon of superconductivity. Later, in 1913, he won a Nobel prize in physics for his research in this area.

In 1933, the next great milestone in understanding how matter behaves at extreme cold temperatures occurred. Walter Meissner and Robert Ochsenfeld discovered that a superconducting material will repel a magnetic field. A magnet moving by a conductor induces currents in the conductor. This is the principle upon which the electric generator operates. But in a superconductor, the induced currents exactly mirror the field that would have otherwise penetrated the superconducting material—thus causing the magnet to be repulsed. This phenomenon is known as diamagnetism and is today often referred to as the "Meissner effect." The Meissner effect is so strong that a magnet can actually be levitated over superconductive material.

Other superconducting metals, alloys, and compounds were discovered in subsequent decades. For instance, in 1941, niobium-nitride was found to superconduct at 16K. Then, in 1953, vanadium-silicon displayed superconductive properties at 17.5K. And in 1962, scientists at Westinghouse developed the first commercial superconducting wire (an alloy of niobium and titanium). In the 1960s (at the Rutherford-Appleton Laboratory in the UK), high-energy, particle-accelerator electromagnets made of copper-clad niobium-titanium were then developed. In 1987, they were first employed in a superconducting accelerator at the U.S. Fermilab Tevatron.

The first widely accepted theoretical understanding of superconductivity was advanced in 1957 by American physicists John Bardeen, Leon Cooper, and John Schrieffer. Their *theories of superconductivity* became known as the BCS theory (derived from the first letter of each man's last name). This won them a Nobel prize in 1972. For elements and simple alloys, the mathematically complex BCS theory explained superconductivity at temperatures close to absolute zero. However, the BCS theory has subsequently become inadequate to fully explain how superconductivity is occurring at higher temperatures (and with different superconductor systems).

Another significant theoretical advancement came in 1962 when Brian D. Josephson (a graduate student at Cambridge University) predicted that electrical current would flow between two superconducting materials (even when they are separated by a non-superconductor or insulator). His prediction was later confirmed and won him a share of the 1973 Nobel Prize in Physics. This tunneling phenomenon is today known as the "Josephson effect." It has been applied to electronic devices such as the superconducting quantum interference device (SQUID)—an instrument capable of detecting even the weakest magnetic fields.

In the field of superconductivity, the 1980s were a decade of unrivaled discovery. In 1964, Bill Little of Stanford University had suggested the possibility of organic (carbon-based) superconductors. The first of these theoretical superconductors was successfully synthesized in 1980 by Danish researcher Klaus Bechgaard of the University of Copenhagen, and three French team members. It had to be cooled to an incredibly cold 1.2K transition temperature and subjected to high pressure to superconduct. But its mere existence proved the possibility of "designer" molecules. These are molecules that are fashioned to perform in a predictable way.

Next, in 1986, a true breakthrough discovery was made in the field of superconductivity. Alex Muller and Georg Bednorz (researchers at the IBM Research Laboratory in Ruschlikon Switzerland) created a brittle ceramic compound that superconducted at the highest temperature then known: 30K. What made this discovery so remarkable was that ceramics are normally insulators. They don't conduct electricity well at all, so researchers had not considered them as possible high-temperature superconductor candidates. The lanthanum, barium, copper, and oxygen compound that Muller and Bednorz synthesized behaved in a not-as-yet-understood way. The discovery of this first of the superconducting copper-oxides (cuprates) won the two men a Nobel Prize the following year. Due to a small amount of lead having to be added as a calibration standard (making the discovery even more noteworthy), it was later found that tiny amounts of this material were actually superconducting at 58K.

Muller and Bednorz' discovery triggered a flurry of activity in the field of superconductivity. In a quest for higher and higher Tc's, researchers around the world began "cooking" up ceramics of every imaginable combination. A research team at the University of Alabama-Huntsville then substituted yttrium for lanthanum in the Muller and Bednorz molecule in January of 1987. They achieved an incredible 92K Tc. For the first time, a material (today referred to as yttrium barium copper oxygen [YBCO]) had been found that would superconduct at temperatures warmer than liquid nitrogen (a commonly available coolant). Using exotic (and often toxic) elements in the base perovskite ceramic, additional milestones have since been achieved. Now, the current class (or "system") of ceramic superconductors with the highest transition temperatures are the mercuric-cuprates. The first synthesis of one of these compounds was achieved in 1993 by Prof. Dr. Ulker Onbasli at the University of Colorado and by the team of A. Schilling, M. Cantoni, J. D. Guo, and H. R. Ott of Zurich, Switzerland. The world record Tc of 138K is now held by a thallium-doped mercuric-cuprate comprised of the elements mercury, thallium, barium, calcium, copper, and oxygen. Then, in February of 1994, the Tc of this ceramic superconductor was confirmed by Dr. Ron Goldfarb at the National Institute of Standards and Technology–Colorado. Its Tc can be coaxed up even higher (approximately 25 to 30 degrees more at 300,000 atmospheres) under extreme pressure.

The first company to capitalize on high-temperature superconductors was Illinois Superconductor (today known as ISCO International). Formed in 1989, this amalgam of government, private-industry, and academic interests introduced a depth sensor for medical equipment that was able to operate at liquid nitrogen temperatures (< 77K).

While no significant advancements in superconductor Tc's have been achieved in recent years, other discoveries of equal importance have been made. In 1997, researchers discovered that at a temperature very near absolute zero, an alloy of gold and indium was both a superconductor and a natural magnet. Conventional wisdom held that a material with such properties could not exist! Since then, over a half-dozen such compounds have been found.

Recent years have also seen the discovery of the first high-temperature superconductor that does not contain any copper (in 2000), and the first all-metal perovskite superconductor (in 2001). Startling (and serendipitous) discoveries like these are forcing scientists to continually re-examine longstanding theories on superconductivity and to consider heretofore unimagined combinations of elements.

Superconductivity: What Is It?

Superconductivity is a phenomenon observed in several metals and ceramic materials. These materials have no electrical resistance when they are cooled to temperatures ranging from near absolute zero (–459 degrees Fahrenheit, 0 kelvin, –273 degrees Celsius) to liquid nitrogen temperatures (–321°F, 77K, –196°C). The Tc is the temperature at which electrical resistance is zero, and it varies with the individual material. Critical temperatures are achieved by cooling materials with either liquid helium or liquid nitrogen for practical purposes.

These materials can carry large amounts of electrical current for long periods of time without losing energy as heat because they have no electrical resistance (meaning electrons can travel through them freely). With no measurable loss, superconducting loops of wire have been shown to carry electrical currents for several years. This property has implications for electrical power transmission, for electrical-storage devices, and for transmission lines if they can be made of superconducting ceramics.

Another property of a superconductor is that once the transition from the normal state to the superconducting state occurs, external magnetic fields can't penetrate it. This effect is called the Meissner effect and has implications for making high-speed, magnetically levitated trains. It also has implications for making powerful, small, superconducting magnets for magnetic resonance imaging or MRI.

How do electrons travel through superconductors with no resistance? "At the beginning of the twentieth century," explains physicist Dr. Steven Weinberg (University of Texas at Austin), "several leading physicists, including Lorentz and Abraham, were trying to work out a theory of the electron. This was partly in order to understand why all attempts to detect effects of Earth's motion through the ether had failed. We now know that they were working on the wrong problem. At that time, no one could have developed a successful theory of the electron, because quantum mechanics had not yet been discovered. It took the genius of Albert Einstein in 1905 to realize that the right problem on which to work was the effect of motion on measurements of space and time. This led him to the special theory of relativity." [3] Let's look at this more closely.

The atomic structure of most metals is a lattice structure, much like a window screen in which the intersection of each set of perpendicular wires is an atom. Metals hold on to their electrons quite loosely, so these particles can move freely within the lattice. This is why metals conduct heat and electricity very well. As electrons move through a typical metal in the normal state, they collide with atoms and lose energy in the form of heat. In a superconductor, the electrons travel in pairs and move quickly between the atoms with less energy loss.

As a negatively charged electron moves through the space between two rows of positively charged atoms (like the wires in a window screen), it pulls inward on the atoms. This distortion attracts a second electron to move in behind it. This second electron encounters less resistance, much like a passenger car following a truck on the freeway encounters less air resistance. The two electrons form a weak attraction, travel together in a pair and encounter less resistance overall. In a superconductor, electron pairs are constantly forming, breaking, and reforming, but the overall effect is that electrons flow with little or no resistance. The low temperature makes it easier for the electrons to pair up.

One final property of superconductors is that when two of them are joined by a thin insulating layer, it is easier for the electron pairs to pass from one superconductor to another without resistance (the Josephson effect). This effect has implications for superfast electrical switches that can be used to make small, high-speed computers.

The future of superconductivity research is to find materials that can become superconductors at room temperature. Once this happens, the whole world of electronics, power, and transportation will be revolutionized.

Careful measurements show that the resistivity of a superconductor really is zero. For example, a persistent current circulating in a superconducting loop of wire showed no decrease after several years. Joule heating would dissipate electrical power as heat and reduce the current flow if the resistance were non-zero. Quantum mechanics provides an explanation for this remarkable behavior: Below Tc, the electrons in a superconductor form Cooper pairs (with opposite spin) which are not scattered by atoms within a solid. In fact, the motion of all Cooper pairs is correlated. They form a single quantum-mechanical state. The thermal energy of the solid disrupts each Cooper pair, and normal conduction (with resistance) resumes if the superconductor is warmed to a temperature exceeding Tc.

Without consuming electrical power, superconductors are useful because the persistent current can generate a constant magnetic field. Unfortunately, the magnetic field tends to destroy the superconductivity. There is a critical field (Bc) above which the superconductivity vanishes. The value of Bc depends on the temperature (T). Its value is at a maximum at T = 0K, and decreases to zero at T = Tc. Therefore, the windings of superconducting magnets must be cooled to a temperature considerably below Tc in order to generate a useful large magnetic field. Alloys containing niobium have been developed that have Tc as high as 23K. They also support magnetic fields of more than 20 Tesla at T = 4.2K (the boiling point of liquid helium). Helium is used as the refrigerant in large magnets, such as those used for MRI scanning.

However, liquid helium is expensive (about $10/liter), whereas liquid nitrogen (boiling point 77K) is cheap and easier to handle. This situation created an incentive to develop superconductors with a higher Tc. As previously explained, the first major progress in this direction came in 1986. This is when two scientists at the IBM Zurich laboratories created a superconductor containing lanthanum, barium, copper, and oxygen, with a Tc being greater than 30K. In 1987, scientists at the University of Texas replaced lanthanum with the element yttrium to give a superconductor (Y Ba2 Cu3 07, generally known as YBCO) a Tc equaling 93K. That same year, a superconducting compound containing bismuth, strontium, calcium, copper, and oxygen (known as BSCCO) was found to form a phase having a Tc equaling 110K. Related compounds have been discovered with a Tc of up to 133K. Collectively, these materials are known as high-temperature superconductors**.**

High-Temperature Superconductors

Few technologies ever enjoy the sort of rock-star celebrity that superconductors received in the late 1980s. Headlines the world over trumpeted the discovery of HTS, and the media and scientists alike gushed over the marvels that we could soon expect from this promising young technology. (See sidebar, “Why Are They Called HTS?”) Levitating 300-mph trains, ultra-fast computers, and cheaper, cleaner electricity were to be just the beginning of its long and illustrious career.

Why Are They Called HTS?

As previously explained, the first superconductors discovered in 1911 were simple metals like mercury and lead. They were ordinary conductors at room temperature, but they became superconductors when the temperature dropped to only a few degrees (3K) above absolute zero. These superconductors were too cold for many practical applications. Ever since, researchers have been trying to figure out how to make substances superconduct at room temperature. High temperature superconductors operate at 100K to 150K. That's very cold compared to the air around you, but much warmer than the original superconductors of 1911. Hence, scientists call them high-temperature superconductors.

Today you might ask: what ever happened to the high-temperature hype? It was the hottest potato of its time, but it all fizzled out.

The problem was learning to make wire out of it. These superconductors are made of ceramics—the same kind of material in coffee mugs. Ceramics are hard and brittle. Finding an industrial way to make long, flexible wires out of them was going to be difficult.

Indeed, the first attempts were disappointing. The so-called "first-generation" HTS wire was relatively expensive: five to ten times the cost of copper wire. Furthermore, the amount of current it could carry often fell far short of its potential: only two or three times that of copper, versus a potential of more than 100 times.

But now, thanks to years of research involving experiments flown on the space shuttle, this is about to change. The NASA-funded Texas Center for Superconductivity and Advanced Materials (TcSAM) at the University of Houston is teaming with Houston-based Metal Oxide Technologies, Inc. (MetOx) to produce the "smash hit" that scientists have been seeking since the 1980s. Of course, this would be a "second-generation" HTS wire that realizes the full 100-fold improvement in current capacity over copper, yet costs about the same as copper to produce. The once-famous superconductors may be about to step back into the limelight.

An Awaiting Audience

The special "talent" of superconductors is that they have zero resistance to electric current. Absolutely none. In theory, a loop of HTS wire could carry a circling current forever without even needing a power source to keep it going.

In normal conductors, such as copper wire, the atoms of the wire impede the free flow of electrons, sapping the current's energy and squandering it as heat. Today, about 6 to 7% of the electricity generated in the United States gets lost along the way to consumers, partly due to the resistance of transmission lines, according to U.S. Energy Information Agency documents as shown in Table 9.1.[2] Replacing these lines with superconducting wire would boost utilities' efficiencies, and would go a long way toward curbing the nation's greenhouse gas emissions.

Of course, with the Bush Administration's present energy policy and a Congress that is heavily influenced by special interest groups from coal-burning electric power plants (utilities) and oil companies, it is rather doubtful at this time that these lines will ever be replaced with superconducting wire to boost utilities' efficiencies to produce clean cheap energy and help curb greenhouse gas emissions. But one can hope! Nevertheless, please see Chapter 19, "Electrical Energy: Free Energy—The Quantum Mechanical Vacuum," for a very detailed discussion on free energy.

On a hopeful note, the fledgling "maglev" train industry would also welcome the availability of higher-quality, cheaper HTS wire. Economic realities stalled the initial adoption of maglev transit systems, but maglev development is still strong in Japan, China, Germany, and the United States.

NASA is looking at how superconductors could be used for space. For example, the gyros that keep satellites oriented

Table 9.1 Electricity Overview, 1949–2002 (billion kilowatt hours)

	Net Generation											
	Electric Power Sector [a]											
Year	Electric Utilities	Independent Power Producers	Total	Commercial Sector[b]	Industrial Sector[c]	Total	Imports[d]	Exports[d]	Losses and Unaccounted for[e]	Retail Sales[f]	Direct Use[g]	Total
1949	291	NA	291	NA	5	[R] 296	2	(s)	43	255	NA	255
1950	329	NA	329	NA	5	[R] 334	2	(s)	44	291	NA	291
1951	371	NA	371	NA	5	[R] 375	2	(s)	47	330	NA	330
1952	399	NA	399	NA	5	[R] 404	3	(s)	50	356	NA	356
1953	443	NA	443	NA	4	[R] 447	2	(s)	53	396	NA	396
1954	472	NA	472	NA	5	[R] 476	3	(s)	54	424	NA	424
1955	547	NA	547	NA	3	[R] 550	5	(s)	58	497	NA	497
1956	601	NA	601	NA	3	[R] 604	5	1	62	546	NA	546
1957	632	NA	632	NA	3	[R] 635	5	1	62	576	NA	576
1958	645	NA	645	NA	3	[R] 648	4	1	64	588	NA	588
1959	710	NA	710	NA	3	[R] 713	4	1	70	647	NA	647
1960	756	NA	756	NA	4	[R] 759	5	1	76	688	NA	688
1961	794	NA	794	NA	3	[R] 797	3	1	77	722	NA	722

1962	855	NA	855	NA	3	R 858	2	2	81	778	NA	778
1963	917	NA	917	NA	3	R 920	2	2	88	833	NA	833
1964	984	NA	984	NA	3	R 987	6	4	93	896	NA	896
1965	1,055	NA	1,055	NA	3	R 1,058	4	4	104	954	NA	954
1966	1,144	NA	1,144	NA	3	R 1,148	4	3	113	1,035	NA	1,035
1967	1,214	NA	1,214	NA	3	R 1,218	4	4	118	1,099	NA	1,099
1968	1,329	NA	1,329	NA	3	R 1,333	4	4	129	1,203	NA	1,203
1969	1,442	NA	1,442	NA	3	R 1,445	5	4	133	1,314	NA	1,314
1970	1,532	NA	1,532	NA	3	R 1,535	6	4	145	1,392	NA	1,392
1971	1,613	NA	1,613	NA	3	R 1,616	7	4	150	1,470	NA	1,470
1972	1,750	NA	1,750	NA	3	R 1,753	10	3	166	1,595	NA	1,595
1973	1,861	NA	1,861	NA	3	R 1,864	17	3	165	1,713	NA	1,713
1974	1,867	NA	1,867	NA	3	R 1,870	15	3	177	1,706	NA	1,706
1975	1,918	NA	1,918	NA	3	R 1,921	11	5	180	1,747	NA	1,747
1976	2,038	NA	2,038	NA	3	R 2,041	11	2	194	1,855	NA	1,855
1977	2,124	NA	2,124	NA	3	R 2,127	20	3	197	1,948	NA	1,948
1978	2,206	NA	2,206	NA	3	R 2,209	21	1	211	2,018	NA	2,018

R = Revised; P = Preliminary; E = Estimate; NA = Not available; (s) = Less than 0.5 billion kilowatt hours.

Table 9.1 Electricity Overview, 1949–2002 (billion kilowatt hours) (continued)

	Net Generation											
	Electric Power Sector [a]											
Year	Electric Utilities	Independent Power Producers	Total	Commercial Sector[b]	Industrial Sector[c]	Total	Imports[d]	Exports[d]	Losses and Unaccounted for[e]	Retail Sales[f]	Direct Use[g]	Total
1979	2,247	NA	2,247	NA	3	^{R} 2,251	23	2	200	2,071	NA	2,071
1980	2,286	NA	2,286	NA	3	^{R} 2,290	25	4	216	2,094	NA	2,094
1981	2,295	NA	2,295	NA	3	^{R} 2,298	36	3	184	2,147	NA	2,147
1982	2,241	NA	2,241	NA	3	^{R} 2,244	33	4	187	2,086	NA	2,086
1983	2,310	NA	2,310	NA	3	^{R} 2,313	39	3	198	2,151	NA	2,151
1984	2,416	NA	2,416	NA	3	^{R} 2,419	42	3	173	2,286	NA	2,286
1985	2,470	NA	2,470	NA	3	^{R} 2,473	46	5	190	2,324	NA	2,324
1986	2,487	NA	2,487	NA	3	^{R} 2,490	41	5	158	2,369	NA	2,369
1987	2,572	NA	2,572	NA	3	^{R} 2,575	52	6	164	2,457	NA	2,457
1988	2,704	NA	2,704	NA	3	^{R} 2,707	39	7	161	2,578	NA	2,578
1989	2,784	^{P} 62	^{P} 2,847	^{P} 4	^{P} 115	^{RP} 2,966	26	15	^{R} 222	2,647	^{RP} 108	^{R} 2,755
1990	2,808	^{P} 88	^{P} 2,896	^{P} 6	^{P} 122	^{RP} 3,024	18	16	^{R} 199	2,713	^{RP} 115	^{R} 2,827
1991	2,825	^{P} 108	^{P} 2,934	^{P} 6	^{P} 132	^{RP} 3,072	22	2	^{R} 211	2,762	^{RP} 118	^{R} 2,880

1992	2,797	^{P} 137	^{P} 2,934	^{P} 6	^{P} 143	^{RP} 3,084	28	3	224	2,763	^{P} 122	^{R} 2,886
1993	2,883	^{P} 161	^{P} 3,044	^{P} 7	^{P} 146	^{P} 3,197	31	4	236	2,861	^{RP} 128	^{R} 2,989
1994	2,911	^{P} 178	^{P} 3,089	^{P} 8	^{P} 151	^{RP} 3,248	47	2	^{R} 224	2,935	^{RP} 134	^{R} 3,069
1995	2,995	^{P} 200	^{P} 3,194	^{P} 8	^{P} 151	^{RP} 3,353	43	4	235	3,013	^{RP} 144	^{R} 3,157
1996	3,077	^{P} 207	^{P} 3,284	^{P} 9	^{P} 151	^{RP} 3,444	43	3	237	3,101	^{RP} 146	^{R} 3,247
1997	3,123	^{P} 207	^{P} 3,329	^{P} 9	^{P} 154	^{RP} 3,492	43	9	^{R} 232	3,146	^{RP} 148	^{R} 3,294
1998	3,212	^{P} 245	^{P} 3,457	^{P} 9	^{P} 154	^{RP} 3,620	40	13	^{R} 221	3,264	^{RP} 161	^{R} 3,425
1999	3,174	^{P} 356	^{P} 3,530	^{P} 9	^{P} 156	^{RP} 3,695	43	14	^{R} 229	3,312	^{RP} 183	^{R} 3,495
2000	^{R} 3,015	^{P} 622	^{P} 3,638	^{P} 8	^{P} 157	^{RP} 3,802	^{R} 49	15	^{R} 231	^{R} 3,421	^{RP} 183	^{R} 3,605
2001	2,630	^{E} 932	^{P} 3,562	^{E} 7	^{E} 150	^{E} 3,719	38	18	138	3,397	^{E} 205	3,602
2002	2,821	^{E} 1,022	^{P} 3,451	^{E} 6	^{E} 143	^{E} 3,608	27	21	116	3,286	^{E} 316	3,599

[a] The electric power sector (electric utilities and independent power producers) comprises electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public—i.e., NAICS 22 plants. Due to the restructuring of the electric power sector, the sale of generation assets is resulting in a reclassification of plants from electric utilities to independent power producers.

[b] Commercial combined-heat-and-power (CHP) and commercial electricity-only plants. See Appendix G for commercial sector NAICS codes.

[c] Industrial combined-heat-and-power (CHP) and industrial electricity-only plants. Through 1988, includes industrial hydroelectric power only. See Appendix G for industrial sector NAICS codes.

[d] Electricity transmitted across U.S. borders with Canada and Mexico.

[e] Energy losses that occur between the point of generation and delivery to the customer, and data collection frame differences and nonsampling error. See Note 1 at end of section.

[f] Electricity retail sales to ultimate customers reported by electric utilities and other energy service providers.

[g] Commercial and industrial facility use of onsite net electricity generation; and electricity sales among adjacent or co-located facilities for which revenue information is not available.

Note: Totals may not equal sum of components due to independent rounding.

could use frictionless bearings made from superconducting magnets, improving the satellites' precision. Also, the electric motors aboard spacecraft could be a mere 1/4 to 1/6 the size of non-superconducting motors, saving precious volume and weight in the spacecraft's design.

Should any country ever establish a base on the moon, superconductors would be a natural choice for ultra-efficient power generation and transmission, since ambient temperatures plummet to 100K (–173°C, –280°F) during the long lunar night—just the right temperature for HTS to operate. And, during the months-long journey to Mars, a "table top" MRI machine (see Figure 9.1) [1] made possible by HTS wire would be a powerful diagnosis tool to help ensure the health of the crew. Worldwide, the current market for HTS wire is estimated to be $40 billion, according to industry analysts, and it is expected to grow rapidly.

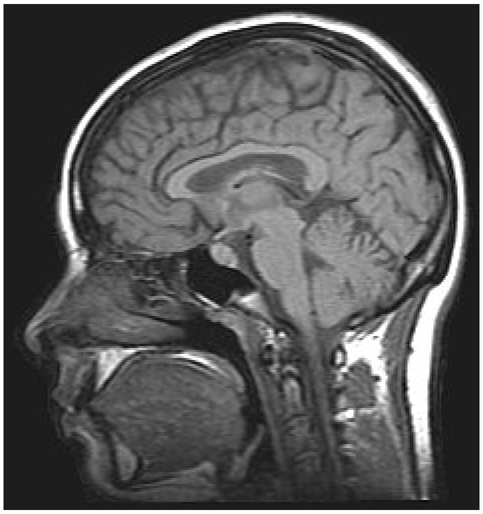

Figure 9.1 MRI scans, a powerful tool for medical diagnosis, use superconducting electromagnets to generate detailed images of body tissues. Most of today's MRI machines require expensive liquid helium to cool their low-temperature superconducting wire.

Behind the Scenes

The University of Houston has licensed this new wire-making technology to MetOx, a company founded in 1997. MetOx plans to begin full-scale production of this high-quality HTS wire in 2004.

Basically, the wire is made by growing a thin film of the superconductor only a few microns thick (thousandths of a millimeter) onto a flexible foundation. This well-known production method was improved upon in part through "Wake Shield" experiments flown on the space shuttle to learn about growing thin films in the hard vacuum of space, as shown in Figure 9.2.[1] Researchers learned how to grow higher-quality oxide thin films from the shuttle experiments and used that in the lab to improve the quality of their superconducting films.

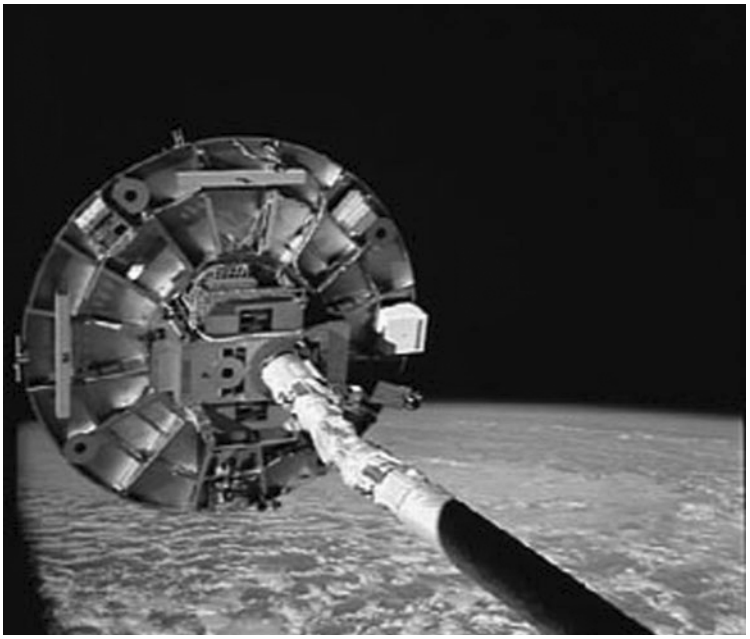

Figure 9.2 The Wake Shield Facility being held out in space by the shuttle's robot arm. Image courtesy NASA.

Not surprisingly, the NASA group at Texas Center for Superconductivity at the University of Houston (TCSUH), can't reveal exactly how they make their HTS wire. The technologies springing from these NASA/industry research partnerships must be patented to achieve NASA's goal of using space to benefit American businesses.

But shouldn't this technology be shared with everyone? How many times have government and industry made excuses for why they can't reveal the inner workings of a new technological breakthrough under the guise of protecting U.S. businesses? The answer of course is many, many times, and there is nothing wrong with that as long as the new technology is made available immediately, not 40 or 45 years later like the video phone that was introduced at the World's Fair in 1960.

It makes one wonder whether these energy-saving technologies are a threat to big business—the threat being that they would have to re-tool (spending billions right away) their industrial operations in order to appease an awaiting public. The history of American big business has a track record of just the opposite in this area. Can you say "complacency"?

U.S. business has always operated on obtaining short-term profits, and making very, very long-term investments. This is why research and development departments within these companies have always received little funding, for fear that they might actually revolutionize that particular industry, which would cost trillions of dollars.

By the way, where are those flying cars that they promised us? Overall, it makes one wonder, and keeps conspiracy theories alive and well. Wait until you read Chapter 19 on free energy!

Nevertheless, in the years to come, it is hoped that the quality of HTS wire will translate into improvements in dozens of industries from power generation to medical care. Keep an eye on this one: The glamorous career of superconductors has only just begun.

Other HST Applications

Finally, with the preceding applications in mind, let's take a detailed look at some of the other high-temperature superconductor applications:

- Superconductors to sustain Internet growth
- E-bomb
- Electrical power transmission for electrical storage devices
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Superconductors to Sustain Internet Growth

Irvine Sensors Corporation (Costa Mesa, CA) recently received an approximate $2 million research and development contract to demonstrate a superconducting digital router for high-speed communications. With the communications industry's ever-increasing need for speed, Irvine Sensors (under the contract) plans to exploit TRW's superconducting high-speed switching technology to develop a "super switch" that could evolve along with HTS technology. The initial demonstration goal of the R&D contract is a 256 × 256 switch that can operate at a minimum of 10 gigabits per second per channel and that can reconfigure in less than a nanosecond. This capability will be extended to a 4,096 × 4,096 switch with at least 40 gigabits per second per channel, if the full goals of the contract are met. Irvine Sensors is in the process of organizing a consortium of potential industry users to assist in defining potential product requirements and benchmarking the planned switch's performance. In order to support the ever-increasing need for faster and faster data transmission rates, conventional technology cannot handle the scalability requirements needed. TRW's superconducting technology addresses the power issues typically associated with high speed switches, while Irvine Sensors' chip-stacking enables the necessary electronics to be compressed into a space comparable to the size of an incoming fiberoptics data cable.

Recent studies estimate that data traffic on the Internet alone is now doubling every four months. Competing Silicon Germanium and Gallium Arsenide technologies are already having a hard time keeping up and are very size- and power-intensive. Stacked superconducting electronics may be a means to overcome these limitations and enable continued rapid growth of Internet and telecommunications traffic.

E-bomb

The next Pearl Harbor will not announce itself with a searing flash of nuclear light or with the plaintive wails of those dying of Ebola or its genetically engineered twin. You will hear a sharp crack in the distance. By the time you mistakenly identify this sound as an innocent clap of thunder, the civilized world will have become unhinged, for the "E-bomb," or electromagnetic pulse weapon, has come of age.

A fictional and dramatic preview of the E-bomb's potential damage was shown in Fox's *Dark Angel* TV show (cancelled): The year is 2020. The scene is Seattle, shortly after terrorists have set off an electromagnetic pulse bomb in the atmosphere that knocks out all satellites, toppling the economy and plunging the world into a 1930s-style depression in which politicians are for hire, cops are crooked, and the future looks drearier than Seattle in March.

The reality show followed in March of 2003, when the U.S. invaded Iraq. One of the first news reports went something like this: "The U.S. Air Force has hit Iraqi TV with an experimental electromagnetic pulse device called the E-Bomb in an attempt to knock it off the air and shut down Saddam Hussein's propaganda machine. Iraqi satellite TV, which broadcasts

24 hours a day outside Iraq, went off the air around 4:30 a.m. local time."

E-bombs can unleash in a flash as much electrical power (3 billion watts or more) as the Hoover Dam generates in 36 hours. And, although the Pentagon prefers not to use experimental weapons on the battlefield, the world intervenes from time to time.

America has remained at the forefront of electromagnetic pulse (EMP) device weapons development. It's believed that current efforts are based on using high-temperature superconductors to create intense magnetic fields, although much of this work is classified. It's an astoundingly simple weapon. It consists of an explosives-packed tube placed inside a slightly larger copper coil. The instant before the chemical explosive is detonated, the coil is energized by a bank of capacitors, creating a magnetic field. The explosive charge detonates from the rear forward. As the tube flares outward, it touches the edge of the coil, thereby creating a moving short circuit. The propagating short has the effect of compressing the magnetic field while reducing the inductance of the stator coil. The result is that two stage flux compression generators (FCGs) will produce a ramping current pulse, which breaks before the final disintegration of the device. Published results suggest ramp times of thousands of microseconds and peak currents of tens of millions of amps. The pulse that emerges makes a lightning bolt seem like a flashbulb by comparison.

Ultimately, the Army hopes to use E-bomb technology to explode artillery shells in midflight. The Navy wants to use the E-bomb's high-power microwave pulses to neutralize antiship missiles. And the Air Force plans to equip its bombers, strike fighters, cruise missiles, and unmanned aerial vehicles with E-bomb capabilities. When fielded, these will be among the most technologically sophisticated weapons the U.S. military establishment has ever built.

There is, however, another part to the E-bomb story, one that military planners are reluctant to discuss. While American versions of these weapons are based on advanced technologies, terrorists could use a less expensive, low-tech approach to create the same destructive power. Any nation with even a 1940s technology base could make them. The threat of E-bomb proliferation is very real. Scientists estimate that a basic weapon could be built for around $300.

Electrical Power Transmission for Electrical Storage Devices

Every appliance, from your toaster to your laptop computer, relies on a single aspect of subatomic physics: the negative charge of the electron. Charge is what makes electrical current flow through a maze of wires to do useful things, such as activating a heating element or encoding data. But another property of the electron, called spin, could greatly expand the particle's usefulness. Moving far beyond today's electronics, the emerging technologies of superconducting and spintronics may soon make it possible to store movies on a PalmPilot or build a radical new kind of computer.

The principle behind this trickery is deceptively simple. Ignoring for a moment the weirdness of the quantum world, the electron can be thought of as a tiny rotating bar magnet with two possible orientations: spin-up or spin-down. Engineers can distinguish between spin-up and spin-down electrons by the corresponding orientation of their magnetic fields, north-up or north-down. Conversely, a properly applied magnetic field can flip electrons from one state to the other. In this way, spin can be measured and manipulated to represent the zeros and ones of digital programming, analogous to the "current on" and "current off" states in a conventional silicon chip.

The first spin-related technology was the compass, a broadly defined piece of metal in which electron spins are mostly pointing in the same direction to generate a magnetic field. This field, in turn, attempts to align itself with Earth's magnetic pole. Physicists have used spin forever. Magnetism arises from the fact that electrons carry spin. But exploiting the magnetic properties of the electron doesn't really qualify as spintronics, according to physicists, until you start deliberately flipping the particle's spin back and forth and moving it from one material to another.

About a decade ago, when materials scientists set out to find ways to cram more data onto computer hard drives, the first major breakthroughs in full-fledged spintronics came at IBM's Almaden Research Center. A hard drive uses an electrical charge to place tiny patches of magnetic field in the recording material; it then reads back the encoded data by measuring which way the field points at different locations.

In 1988, the IBM project latched on to the work of two European scientific teams who had discovered a spin-related effect known as giant magnetoresistance. Starting with a magnetic material whose spins were all locked in one direction, the researchers had added a thin layer of metal and topped it off with another material in which the spins can flip. Current flowed easily from the top to the bottom of this composite if the spins were the same in both layers, but the current faced higher resistance if the spins were opposed. In theory, such a setup allowed a much more sensitive way to read back the data on a magnetic disk, but giant magnetoresistance seemed to occur only in expensive, pure crystals exposed to intense magnetic fields.

The Almaden team in 1991 found it could achieve the same effect in cheaper materials that responded to much weaker fields. The researchers eventually built a magnetic read head composed of one of these spintronic sandwiches. Transmitting digital data, magnetized patches on the spinning hard disk flip the spin state in the read head back and forth. A spintronic read head can detect much weaker magnetic fields than older devices can, so each bit of data can be much smaller. It's the world's most sensitive detector of magnetic fields at room temperature. Spintronics is why today's hard drives hold up to 100 gigabytes or more, compared to less than 1 gigabyte in 1997.

Now, researchers at Honeywell, Motorola, and the Naval Research Laboratory are trying to create spin-based computer memory. Based on the same principles, this is called magnetic random access memory, or M-RAM. A prototype design contains a series of tiny magnetic sandwiches placed on a silicon chip between crisscrossing arrays of wires. Electric current through the wires flips the spin, which stays put until it is changed again. Measuring the electrical resistance of a particular sandwich tells whether it represents a 1 or a 0.

Random access memory (information that is available only while the device is turned on) is refreshed 60 times a second by a surge of electricity in conventional desktop computers. M-RAM, in contrast, has almost no electrical demands. NASA is intrigued, because M-RAM could make it possible to build longer-lived spacecraft that perform more elaborate functions without requiring additional power. In more down-to-earth applications, M-RAM might lead to instant-on computers and cell phones with so much built-in memory that they could store entire conversations. You could do all sorts of things that you can't do today, like have video on your PDA. It is expected that IBM will be selling M-RAM by 2005.

Further ahead, spintronics could realize a long-sought, radical kind of data crunching known as quantum computing. According to the laws of quantum mechanics, an electron can be in both spin-up and spin-down states at the same time. That mixed state could form the base of a computer built around not binary bits, but the quantum bit, or qubit. It's not just a 1 or a 0, but any combination of a 1 and a 0. It's one of the first truly revolutionary concepts for computing that's come along in a long time. Feed a problem into a quantum computer, and instead of trying all possible results one at a time, it could calculate them all simultaneously. Barring any unforeseen breakthroughs, however, it will be at least 50 years before anybody builds a quantum computer. A discussion of how to build a quantum computer concludes this chapter.

The benefits of spintronics may spill over to other areas of electronics long before then. In 2002, scientists at the University of California at Santa Barbara and Pennsylvania State University demonstrated that they could drag a cloud of electrons from one semiconductor material to another without disrupting the spin state of the cloud. This achievement points the way toward spin-mediated versions of transistors, the on–off switches that form the building blocks of just about every device powered by a battery or plugged into a wall outlet.

Spintronics transistors might lead to faster, smaller, less-power-hungry versions of existing devices: New science enables new technologies. And the most exciting ones will be things you haven't even imagined yet.

High-Speed Quantum Computers

Sitting in a classroom building at Caltech, behold the world's most feeble computer network. It connects a grand total of two processors, crosses all of a basement corridor, and transmits a whopping single bit of information. Or it would if it were working, which it isn't. So, is it possible to build a High-Speed Quantum Computer?

"Generally large (complex) physical systems behave as classical objects," explains Physicist Dr. Mikhail Lukin (Harvard University). "In other words there is no chance to control its quantum mechanical properties. One of the challenges is to learn how to control quantum mechanical behavior of the complex systems. In other words, we would like to find out how to control quantum properties of large systems both in principle and in practice. And, that is the largest system that can be controlled this way." [4]

Given the pathetic specs, it might seem just a little surprising to hear that Caltech's network is widely considered to be one of the most challenging projects in all of computer science. That's because the one bit of data Caltech's network is designed to transmit won't be an ordinary one or zero of the sort that everyday networks traffic in. It will be a mixture of the two—a so-called quantum bit, or "qubit."

Physicists at Caltech are trying to build the world's first quantum computer network via superconducting technology. In a sense, they're getting a little ahead of themselves, since no one has yet come close to building a practical quantum computer—a computer, that is, that makes calculations on data in the weird multiple-reality state that is the hallmark of quantum mechanics. Still, the benefits of this stunningly radical approach to processing, promises to be so great that the young field of quantum computing has been steadily attracting researchers, not only from computer science, but also from physics, math, and chemistry. Just a few years ago most computer scientists doubted that a quantum computer could ever be built. Now, the tide of opinion seems to be turning, and the past year or two have seen some important advances. (See sidebar, "Lighting Up Quantum Computers.") For example, physicists at MIT have actually built a simple quantum computer. It can't do much. What it does is pick out one name from a list of four—but it does it faster than a conventional computer.

Lighting Up Quantum Computers

In 2003, according to physicists, they brought light to a complete halt for a fraction of a second and then sent it on its way, an achievement that could someday help scientists develop powerful new quantum computers. The research differs from work published in 2001 that was hailed at the time as having brought light to standstill. In that work, light pulses were technically "stored" briefly when individual particles of light, or photons, were taken up by atoms in a gas.

Harvard University researchers have now topped that feat by truly holding light and its energy in its tracks—if only for a few hundred-thousandths of a second. They have succeeded in holding a light pulse still without taking all the energy away from it.

Harnessing light particles to store and process data could aid the still-distant goal of building quantum computers, as well as methods for communicating information over long distances without risk of eavesdropping. The research may also have applications for improving conventional fiberoptic communications and data processing techniques that use light as an information carrier. The present research is just another step toward efforts to control light, but additional work is needed to determine if it can aid these applications.

According to Dr. Matthew Bigelow (University of Rochester), "The new research is an important scientific first. The new study is very clever. This is something that may ultimately spur the development of superior light-based quantum computers." [5]

So what's the big deal about quantum computing? Imagine you were in a large office building and you had to retrieve a briefcase left on a desk picked at random in one of hundreds of offices. In the same way that you'd have to walk through the building, opening doors one at a time to find the briefcase, an ordinary computer has to make its way serially through long strings of ones and zeros until it arrives at an answer. Of course, you could speed up the briefcase hunt by organizing a team, coordinating a floor-by-floor search, and then getting them all back together again to compare results. Likewise, ordinary computers can do this sort of thing by breaking up a task and running the components in parallel on several processors. That sort of extra coordinating and communicating, however, exacts a huge toll in overhead.

But what if instead of having to search by yourself or put together and manage a team, you could instantly create as many copies of yourself as there were rooms in the building? Could all the versions of yourself simultaneously peek in all the offices and then (best of all) every copy of yourself disappear except for the one that found the briefcase?

This is an example of how a quantum computer could work. Quantum computers would exploit the fact that under certain conditions the denizens of the atomic-scale world can exist in multiple realities—atoms and subatomic particles can be simultaneously here and there, fast and slow, pointing up and down. How? Not even physicists agree on that one, but countless experiments over the past seven decades have verified the bizarre phenomenon. By thinking of each of these different atomic states as representing different numbers or other types of data, a group of atoms with all their various combinations of potential states could be used to explore simultaneously all possible answers to a problem. And, with some clever jiggling, the combination representing the correct answer could be made to stand out.

Conventional computer chips are getting so jammed with ever tinier components that they may soon hit their physical limits in power and speed. Some researchers are hoping that quantum computers might break through those barriers. But, although a number of research teams are struggling mightily, even the most optimistic among them don't expect to do more than demonstrate some almost uselessly simple devices within the next three years or so.

Even then, the quantum future is not guaranteed. Any computer (quantum or otherwise) can't do much good unless it can be programmed to perform a practical task. And many researchers have been wondering whether quantum computers will be able to tackle real-world computing problems—or at least run them significantly faster than conventional computers can.

Most applications actually won't lend themselves to quantum computing. That's because the typical computer task, like calculating the orbit of a satellite or rotating a graphic image, requires computer logic that proceeds in serial fashion, each step depending on the results of the preceding one. Quantum computing can't speed up that sort of task. There isn't much advantage in having multiple selves, for example, if instead of looking for a briefcase in a single room you had to assemble a wristwatch out of parts scattered throughout all the rooms. Whether one person was to do the job or a thousand copies of that person, someone would still have to walk into each room, grab a component of the watch, and then add each piece, one at a time, in the correct order, to the wristwatch-in-progress. The desired result (in this case a completed wristwatch) requires that every searcher does part of the job. No one's contribution can be discarded.

In contrast, a suitable task for a quantum computer would be a problem in which one of the many possible combinations of quantum states can find and represent the answer all by itself. The other combinations, all chugging along toward wrong answers, must "collapse," as physicists put it, into the right answer. It's this selective collapsing that poses the challenge. After all, a large enough quantum computer could always be programmed to have its multiple-state atoms represent all possible answers. But what good would that do if there's no way of indicating which of the panoply of results is the right one?

To winnow out the desired result, physicists have come up with a general strategy. The approach is based on the ability of atoms to behave like waves rather than particles. Like two identical but opposite ocean waves colliding, atoms in multiple states can cancel each other out or reinforce each other, depending on how they're aligned.

Unfortunately, for a decade after the late physicist Richard Feynman first suggested the possibility of quantum computation in the early 1980s, no one could figure out a way to apply the phenomenon to a practical task. All that time, physicists were convinced that quantum computers would be good for only one thing: making calculations about quantum mechanics. It was as if, when computer chips were first developed, their designers had announced that the only thing the chips could be used for was learning more about the electrical properties of silicon.

Then, in 1994, AT&T researcher Peter Shor discovered the first practical chore a quantum computer might tackle. One of the more vexing problems in mathematics is the task of finding the prime-number factors of very large numbers.

NOTE

Prime numbers, such as 1, 3, 5, 7, and so forth, cannot themselves be broken into smaller whole-number factors.

Shor found that this problem could be reduced to the simpler one of determining when a certain complicated mathematical sequence starts repeating itself. Identifying a repeated sequence, Shor realized, was something a quantum computer could do. Roughly speaking, by encoding all the elements of the sequence onto the qubits, the states of the qubits that represent identical (and thus repeated) segments can be lined up to strengthen one another. After a while, these reinforced qubits wash everything else out, providing the answer. In theory, a quantum computer with 5,000 or so qubits could solve in about 30 seconds a prime-number problem that would take a conventional supercomputer 10 billion years.

It just so happens there is now an important application for this seemingly esoteric task. Computer data are protected from prying eyes by scrambling the characters of code that represent the data. The mathematical "key" to unscrambling the data is in the form of a very large number (typically 250 digits long) and its prime factors. Such encryption is considered unbreakable, because no conventional computer can figure out the prime factors of such large numbers in a reasonable amount of time.

But, in theory at least, a quantum computer could blow right through these prime-number encryption schemes. A quantum computer hacker would thus have clear access not only to credit card numbers and other personal information that routinely flies around computer networks (including the Internet), but also to government and military secrets. This explains why certain government agencies, operating on the assumption that it's better to lead than to follow, have been throwing millions of dollars at quantum computer research.

Quantum computer success wouldn't necessarily mean all of a physicist's data would become unsafe. Even if computer scientists were able to defy all predictions and build a working device in the near future, cryptographers would turn to schemes that aren't based on prime numbers. One such scheme already exists. It involves coding the data in the form of the shortest distance between two secret points in an abstract, multidimensional space. No one has yet shown that a quantum computer could solve this problem.

It seems that a quantum computer giveth as well as taketh away with regard to data security. That's because a quantum computer could (theoretically) be used to encrypt data in a multiple-state form that could be read properly only by other quantum computers specifically prepared by the sender to read data from the first one. According to physicists, you'd probably need only about a ten-qubit quantum computer to be useful for an encryption application.

Not only is it unlikely that quantum computers will destroy the integrity of the Internet, but they could also end up being a huge boon to it. In 1997, Bell Labs researcher Lov Grover discovered a way to apply quantum computers to a task that many of us engage in every day: searching out information hidden away somewhere in a vast repository of data. Finding information in a database is like the finding-the-briefcase problem. If different combinations of qubit states could each take a look at a different small segment of the database, then one of the combinations of states would come across the desired information.

Grover also figured out how to cause the combination of qubit states with the right answer to stand out. Again, speaking very roughly, the scheme depends on the fact that the qubit states representing "empty rooms" (that is, qubits that haven't found the desired data) are more similar to one another than they are to the qubit states with the answer, just as empty rooms more resemble one another than they do the room that holds the briefcase. Because of their similarity, the wrong qubit states can be combined in such a way as to cancel one another out. Eventually, the one set of qubit states representing the right answer remains.

The speedup offered by this sort of quantum search wouldn't be as dramatic because the difference between the "right" and "wrong" qubit states is more subtle than with the prime-number problem, thus slowing the cancellation process. For example, to search among 100 million addresses, a conventional computer would have to make about 50 million attempts before finding what it was looking for. A quantum computer would need some 10,000 tries. That's still a significant improvement, and it gets bigger with larger databases. What's more, database searching is such a fundamental computer task that any improvement is likely to have an impact on a large array of applications.

How would the Internet benefit? Right now, searching all publicly available web pages for certain key words takes a few seconds (assuming you have a good connection). But remember, the web is still in its infancy. In ten years, it might be thousands of times bigger, and growing, with far more people using it for far more chores. It's not hard to imagine all this activity bringing conventional computers to their silicon knees.

A number of theorists are struggling to come up with strategies for quantum software programs that will usefully solve still other sorts of problems. But, with many of these strategies, the process by which wrong answers are canceled out is so inefficient that they would provide only a modest improvement over conventional computers. There's a large class of problems for which quantum computers would be about twice as fast as classical computers. But physicists are after something sexier.

One possibility that physicists are taking a close look at is a quantum program that could determine whether two complex and very different-looking graphs that connect multiple points are in fact equivalent to each other. Such a program could prove invaluable to computer chip designers, for example, who often switch components around without knowing if they've actually changed anything. Another target is the "traveling salesman" problem, which essentially involves figuring out the shortest way to connect a large number of scattered points. This problem shows up in many forms, including the challenge airlines face in serving the most cities with the fewest possible planes. A nice bonus to solving either of these problems is that they're part of a large class of mathematical problems believed to be related, so cracking one of them could point the way to solving them all.

Few researchers are willing to predict whether quantum computing will ever go beyond a handful of applications. The overall trend has been encouraging, though, and despite the early suspicions of many, if not most physicists, the elusive nature of quantum mechanics would inevitably lead to the uncovering of subtle fundamental barriers to practical quantum computing. However, a deep and wide-ranging theoretical search has yet to turn up a single one.

Finally, what's the big rush? The history of computing suggests that hardware and software breakthroughs tend to occur ahead of the problems they end up solving. Maybe by the time you need to search databases so large that it takes months for an ordinary computer to get through them, quantum computers will be up and running. And that, of course, would free computer scientists to look for the next big thing.

Conclusion

These discoveries have generated intense interest among physicists, partly out of a desire to understand the basic mechanism of high-temperature superconductivity. It is known that the current carriers are Cooper pairs of holes and that conduction takes place along the copper-oxygen planes in these materials, but the mechanism that provides the attractive force within the Cooper pairs remains undecided.

The more general reason for interest in high-temperature superconductors is their possible applications. As previously explained, these include powerful magnets (for MRI, particle accelerators, etc.), lossless transmission lines for electrical power, and highly efficient motors and generators (where the resistive "copper losses" would be absent). However, all of the high-temperature superconductors are brittle ceramics; forming wires and coils from them has proved a formidable task.

Another remarkable property of superconductors is magnetic levitation: A magnet placed over a superconductor remains suspended above its surface because any vertical fall of the magnet induces circulating currents in the superconductor which oppose the motion. This has inspired designs for high-speed magnetically levitated trains, which are currently being tested.

Finally, high-temperature superconductors are currently being used to construct resonant cavities used in microwave communication equipment. Other possible applications rely on the Josephson effect: if two pieces of superconductor are separated by a thin (< 2 nm) oxide layer, Cooper pairs can tunnel through the oxide gap, even in the absence of an applied voltage. If a dc voltage V is applied across the junction, an alternating current flows whose frequency is $f = (2e/h)V = 483.6$ MHz where V = 1 microvolt. This allows small voltages to be measured reliably, since frequency can be measured with very high accuracy. A loop of superconductor which contains two Josephson junctions forms a SQUID that is sensitive to small magnetic fields, such as those produced in the heart or brain.

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