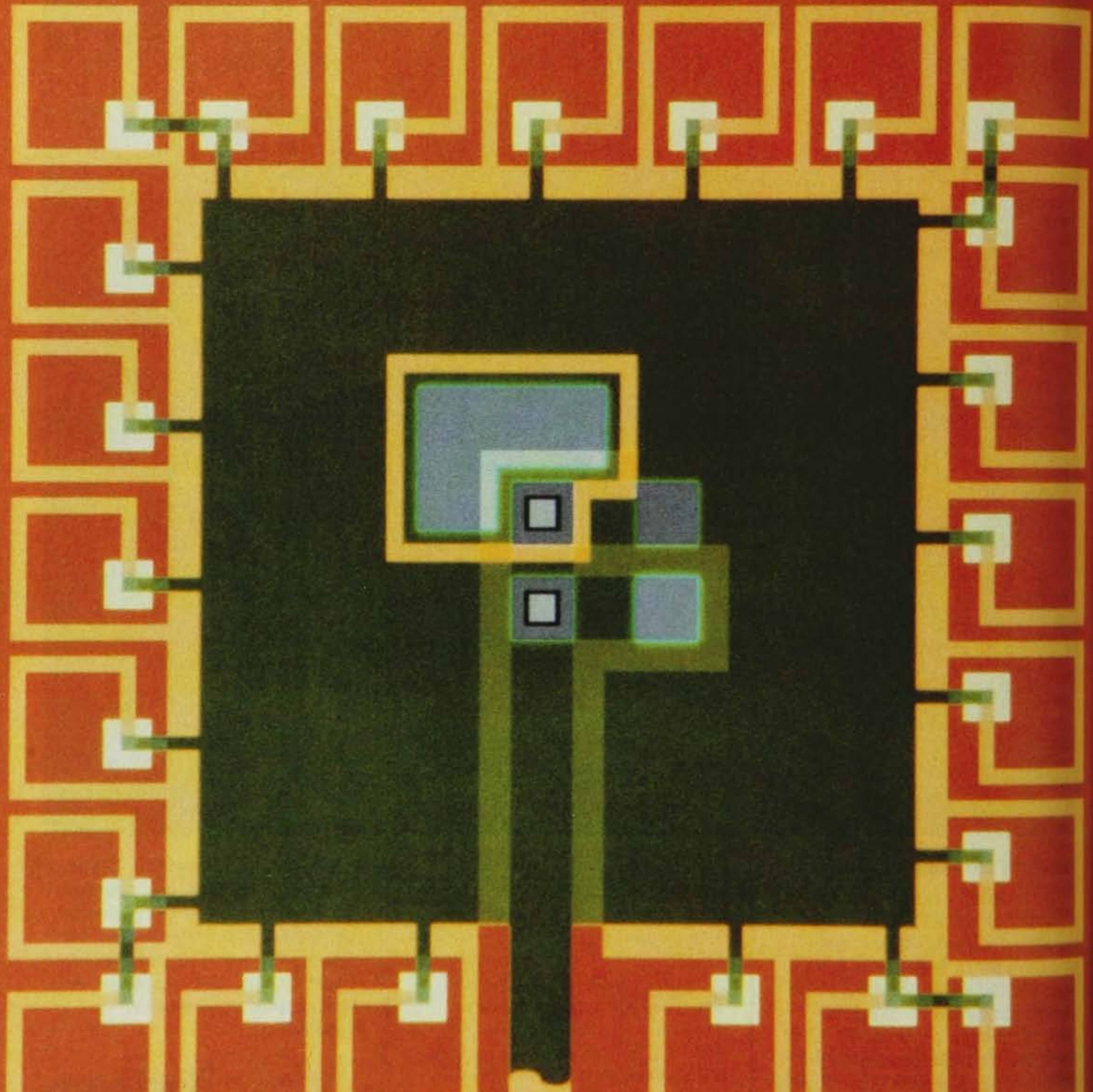
# Superconducting electronics



The extraordinary performance of Josephson-junction circuits for scientific measurements, and the suitability of similar circuits for large scale integrated electronics, presage the emergence of a new technology.

Donald G. McDonald

The pioneers of superconducting electronics are accumulating an impressive record of achievement. For example, they have now gained the high-performance lead in the important field of digital electronics. Logic delays of 13 picoseconds and switching times of 9 picoseconds have been experimentally demonstrated.[1] The same basic devices, Josephson junctions, also make the most sensitive microwave detectors, the most sensitive magnetometers (or current sensors) and the most stable voltage sources. Although each of these developments is an important independent accomplishment, the *combination* of these developments in a single technology merits special attention.

To gain a perspective of research in superconducting electronics during the past fifteen years, consider the *variety* of accomplishments beyond those mentioned above. In the lowest frequency band of the electromagnetic spectrum this research has centered on the development of current comparators of very high accuracy, on the extension of accurate thermometry to very low temperatures, on new techniques for gravitational, geomagnetic and biomagnetic measurements, and most recently, on gravitational-wave detection. In the midrange of frequencies, from the radio band through the microwave band, emphasis has been given to accurate measurements of power and attenuation, to the development of superconducting-cavity stabilized oscillators, to parametric amplifiers, to accurate waveform measurements of fast transient signals, to microwave frequency analog-to-digital converters, and (with particularly heavy emphasis) to integrated circuits for logic and memory. In the highest frequency band for which superconductivity is useful, from millimeter waves to the infrared, advances have been made in the sensitivity of millimeter-wave heterodyne detectors for astrophysical measurements, in broad-band frequency synthesis, and in the measurement of molecular constants at $CO_2$-laser frequencies. When these developments are compared with the best techniques at ambient temperatures, improvements in sensitivity, accuracy, speed, or resolution of factors of 10 to 100 have been common. Two devices, each an excellent example of modern superconducting electronics, are illustrated in figures 1 and 2.

What needs to be recognized from the foregoing is the broad significance of low-temperature electronics. Although it is not entirely evident from the discussion thus far, we will see that all of the most basic components of a general-purpose electronic technology have been developed in the superconducting realm. Thus, with some reservations, we can begin to think about making almost any critical electronic instrument or system with superconducting integrated circuits.

The availability of an accurate model for a Josephson junction, and the accurate control of circuit parameters resulting from the development of integrated circuit fabrication methods for superconductors,[2] together mean that basic circuits can be accurately modeled and, therefore, optimized. In a practical sense it is this last development (fabrication methods) that brings superconducting electronics within striking distance of the fundamental physical limits to measurements in two areas: energy sensitivity and single photon detection.

In speculating on the future of superconducting electronics one cannot ignore the fact that no liquid-helium-temperature technology, for any application whatever, has succeeded in a major way by emerging from the research environment for broader use. No one can say whether or not superconducting electronics will succeed, but we will show how this technology overcomes an important practical barrier to the continuation of long-term trends of electronics toward higher speed and increased miniaturization. Thus we see superconducting electronics becoming a significant challenge to established semiconductor electronics.

My main purpose here is to sketch the conceptual basis for superconducting electronics and to discuss the status and implications of current research. Instead of describing complex circuits I will emphasize fundamental ideas and relationships to more familiar phenomena. At the practical level superconducting electronics has a simple and elegant theory; however, it is theory unlike anything that preceded it. Testimony to its originality comes from the Nobel prizes bestowed on its creators: John Bardeen, Leon Cooper, J. Robert Schrieffer, Ivar Giaever and Brian Josephson. All but Giaever are theoretical physicists.

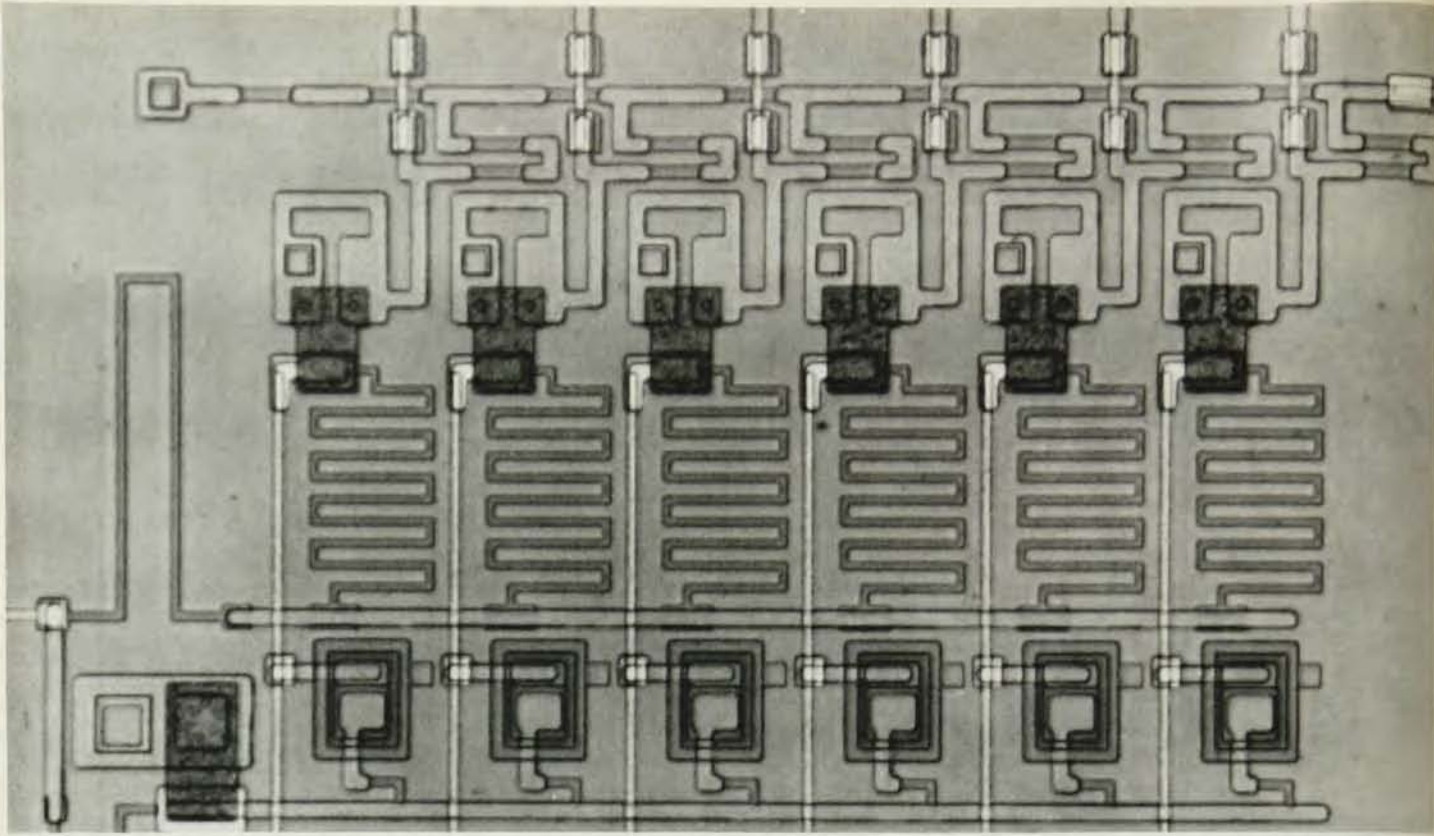
## Superconductors

The abrupt transitions of some metals (lead, tin, and niobium, for example) from a normally conducting state to a state of zero electrical resistance, or superconductivity, below a critical transition temperature $T_c$ is basic to any discussion of superconductivity. A second elementary property is the exclusion of electrical currents and magnetic flux from the interior of superconductors; they are both largely confined to a surface layer $10^{-5}$ cm thick, called the penetration depth.

In normal metals the current density $\mathbf{j}$ is related to the applied electric field $\mathbf{E}$ by Ohm's Law, $\mathbf{j} = \sigma\mathbf{E}$, where $\sigma$ is the conductivity. The conductivity is a real number for frequencies up to the

**A highly sensitive SQUID,** shown in the center, surrounded by its external coupling coils. This computer-enhanced color illustration is an artist's impression of a device made by Michael Cromer and Pasquale Carelli at the National Bureau of Standards. Figure 1

Don McDonald is a staff scientist in the Cryoelectronic Metrology Group of the National Bureau of Standards, Boulder, Colorado.



**A six-bit analog-to-digital converter** that uses six identical SQUIDs as current comparators. This device, developed by C. A. Hamilton and Frances L. Lloyd of NBS, operates at a conversion rate of $2\times10^9$ samples per second and an output data rate of $12\times10^9$ bits per second—nearly an order of magnitude faster than the fastest semiconductor devices. Figure 2

order of $10^{14}$ Hz. Thus for an alternating **E** field of modest frequency the current and voltage are in phase and, as a result, power is dissipated in the metal. For a superconductor similar logic leads to the conclusion that if the power dissipation is to be zero, the current and voltage must be out of phase by 90°, which means that $\sigma$ must be an imaginary number.

But if high-frequency currents are imposed on superconductors, small amounts of power *are* dissipated. So the general case requires a complex conductivity

$$\sigma = \sigma_1 + i\sigma_2$$

where $\sigma_1$ is characteristically much less than $\sigma_2$. The two terms for the conductivity naturally give rise to the two-fluid model of a superconductor in which $\sigma_1$ is the conductivity of a normally conducting fluid and $\sigma_2$ is the conductivity of a dissipationless fluid, or superfluid.

For normal conductors the conductivity can be used to calculate the resistance of a wire:

$$R_n = (1/\sigma)(l/A)$$

where $l$ is the length of the wire and $A$ is its cross-sectional area. If a complex conductivity is used in a similar fashion, one obtains both a resistance and a reactance. For a superconductor the phase of the reactance indicates that it is inductive in character with inductance $L_s$ given by

$$L_s = \frac{1}{\omega}\frac{\sigma_{2\omega}}{\sigma_{1\omega}^2 + \sigma_{2\omega}^2}\left(\frac{l}{A}\right) \qquad (1)$$

where $\omega$ is the angular frequency. The $\omega$ subscript on $\sigma_1$ and $\sigma_2$ implies a frequency dependence of these quantities. Equation 1 is applicable only if the transverse dimensions of the superconducting wire are small enough to ensure a uniform current density—in other words, for transverse dimensions less than the penetration depth mentioned earlier.

To gain physical understanding of this inductance we consider a simple model of the superfluid component of superconductors. The charge carriers are "superconducting electrons" with mass $m$, charge $e$, and number density $n$, all moving with velocity $v_s$. They have a kinetic energy $(1/2)nmv_s^2(l/A)$. Equating the inductive energy $(1/2)L_s i^2$ to the kinetic energy and using the usual expression for the current, $i = nev_sA$, we obtain:

$$L_s = \frac{m}{ne^2}\frac{l}{A} \qquad (2)$$

Detailed analysis shows that this expression for $L_s$ is the low-frequency limit of the more general expression in equation 1. From this simple derivation, however, we see that energy is stored in a superconductor in the form of kinetic energy of superconducting electrons. The inductance $L_s$, which we now call the *kinetic inductance*, is a manifestation of this energy storage. Thus superconductivity does not simply refer to a large conductivity; it refers to a large *imaginary* conductivity, which may be alternatively described as a kinetic inductance. Of course, any superconductor will also have magnetic inductance (determined by the detailed geometry), which must be added to $L_s$.

A piece of superconducting wire in a circuit can usually be described as having no resistance but finite magnetic and kinetic inductances. In fact the magnetic inductance numerically dominates the kinetic inductance in most situations. The kinetic inductance dominates only in conductors of very small cross-sectional area (it is proportional to $1/A$) and in Josephson junctions, both of which are important in microelectronics.

Before turning to the subject of Josephson junctions we will extend our description of superconductivity by discussing magnetic flux quantization. From a conceptual point of view the original flux quantization experiments and their interpretation are the critical link between the classical superconductivity of Kamerlingh Onnes (1911) and the modern superconductivity epitomized by Josephson's theory (1962).

## Magnetic flux quantization

Imagine taking a circular ring of superconductor, initially at a temperature above its transition temperature

$T_c$, and applying a magnetic field perpendicular to the plane of the ring. Then cool the ring below $T_c$ and remove the externally applied field. Because of Faraday's Law and the perfect conductivity of the ring, a permanently "trapped" magnetic field will exist in the hole of the superconductor. This field is produced by a permanently circulating supercurrent around the ring.

The classical (pre-quantum) analysis of this experiment predicts that the magnitude of the trapped flux should be proportional to the strength of the applied magnetic field; however, in 1950 Fritz London predicted a different result, based on quantum theory. Because the microscopic theory of superconductivity had not been developed at that time, his argument was heuristic in nature.

He postulated that superconductivity was the result of a "condensation" in momentum space such that the motion of the superfluid could be described by a single mean-value momentum vector. With this simplification the properties of the superfluid were then assumed to be the same as those of a typical single particle of mass $m$, charge $q$, and velocity $\mathbf{v}_s$. The momentum of this particle in a magnetic field of vector potential $\mathbf{A}$ is

$$\hbar\mathbf{k} = m\mathbf{v}_s + q\mathbf{A} \qquad (3)$$

in SI units. The wave function of the superfluid was taken to be of constant amplitude throughout the superconductor but of variable phase. We denote the wave function as $\Psi = |\Psi| e^{i\theta(r)}$ with the phase $\theta(r) = kr$.

London noted that if one considers the phase of the wave function at points along a circular path P inside a ring, as in figure 3a, then the basic requirement that the wave function must be single valued at each point along P is a significant constraint. In particular the change in phase for a complete trip around P must be an integral multiple of $2\pi$:

$$\oint_{\mathrm{P}} \mathbf{k}\cdot d\mathbf{r} = 2\pi n, \quad n = 0,1,2,... \qquad (4)$$

(This equation is also used in the Bohr–Sommerfeld theory of the hydrogen atom.) If the path P is chosen well inside the superconductor, then $\mathbf{v}_s$ is zero everywhere along P, because supercurrent exists only in a thin surface layer of the ring, as mentioned earlier. Consequently, equations 3 and 4 together give

$$\hbar^{-1}\oint_{\mathrm{P}} q\mathbf{A}\cdot d\mathbf{r} = 2\pi n \qquad (5)$$

Using the general result that the integral of $\mathbf{A}$ around a closed path is the flux $\Phi$ through the path, we finally obtain

$$\Phi = nh/q = n\phi_0 \qquad (6)$$

This result predicts that flux through the ring will be quantized in units of $h/q$. It was later shown that $q = 2e$ for a superconductor, rather than just $e$ as London thought, so the quantum of magnetic flux is $\phi_0 \equiv h/2e = 2.07\times 10^{-15}$ Wb.

The wave function for the superconductor with ten flux quanta through the ring is illustrated in figure 3b. It is a ten-turn helix on the surface of a torus. For a change of one flux quantum through the ring the number of turns of the helix must change by one.

In 1961, Bascom S. Deaver and William M. Fairbank, and R. Doll and M. Näbauer, showed experimentally that magnetic flux through superconducting rings was indeed quantized as discussed above. These experiments, combined with London's insightful theory, endowed superconductors with a new characteristic, a quantum phase factor for the macroscopic system. This abstract quality might well have fallen into obscurity had it not been for Josephson's discovery of the phase dependence of tunneling currents between superconductors. This discovery occurred about one year after the successful flux-quantization experiments, but apparently it was not stimulated by those experiments.[3] However, Josephson's ideas, in the hands of other physicists, rather quickly transformed the concept of magnetic flux quantization to one of practical importance.

### Josephson junctions

Without Josephson junctions superconducting electronics would be of little interest. These junctions are the essential superconducting elements for producing power gain at high speed, a vital function in electronics.

Josephson junctions most commonly take the form of two thin films of superconducting metals separated by a very thin layer of insulator, as illustrated in figure 4a. Experimentally it is found that such devices will conduct electrical current with zero voltage drop across their terminals, as was first reported by Philip W. Anderson and John M. Rowell. Above some maximum level of current, called the critical current $I_c$ (typically about 1 mA), voltage does appear across the terminals of the device.

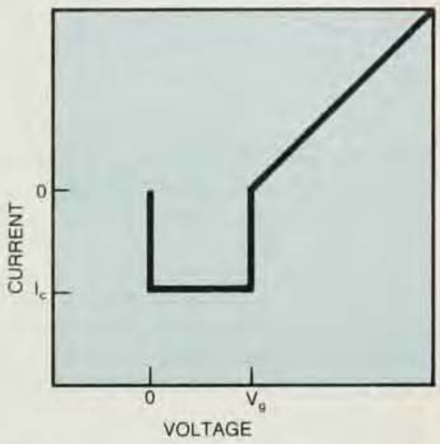
The physical basis for this behavior derives from the fact that the wave function, which describes the properties of the superconductor, extends slightly beyond the surface of the metal. Thus, if the insulating layer separating the two superconductors of figure 4 is thin enough (about 1 nm), the wave functions of the two superconductors can overlap in space, and thereby physically couple the two systems. Under these circumstances an electrical current can pass through the insulator,

## Microscopic theory

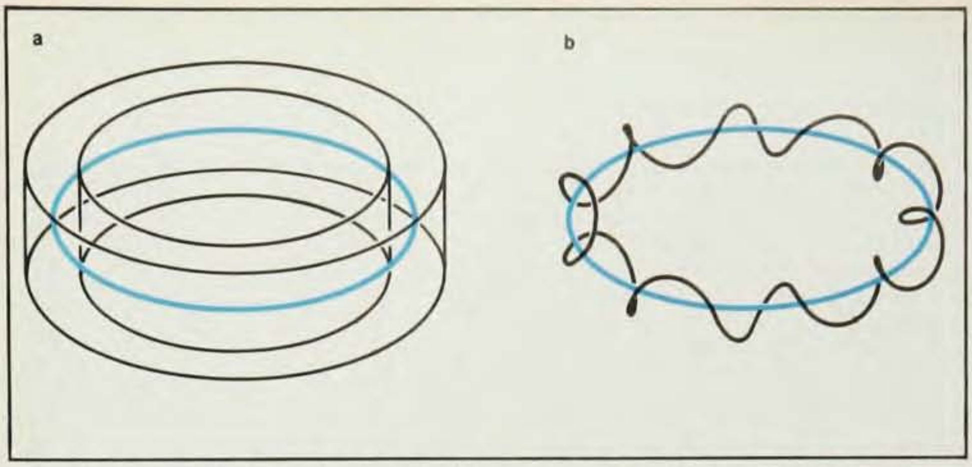
The current–voltage characteristic of a Josephson junction is a plot of the average current in a junction versus the applied voltage. It has two branches, which are conceptually separable and are derived from the components of the two-fluid model of a superconductor. In the microscopic theory of superconductivity, by John Bardeen, Leon Cooper and Robert Schrieffer, a superfluid current is described by paired electron states, or the flow of so-called "Cooper pairs." A normal fluid current is described by unpaired electrons, the so-called "quasiparticles." At $T = 0$ K all electrons are paired and there are no quasiparticles, if the superconductor is in thermodynamic equilibrium.

In the current–voltage characteristic shown above right we first consider the supercurrent, which is the current ranging from zero to a maximum value of $I_c$, all at zero voltage. For voltages greater than zero, but less than the energy-gap voltage $V_g$, the amplitude of the supercurrent is unchanged but it is rapidly oscillating, at 484 MHz/microvolt, and averages to zero. Thus the supercurrent does not contribute to the current–voltage characteristic for $V > 0$.

The remainder of the characteristic results from entirely different processes. Between $V = 0$ and $V_g$ there is no mechanism for transporting direct current at $T = 0$ K, so the device behaves as an insulator. When the applied voltage reaches the energy-gap voltage, sufficient energy is available from the electric field to break pairs of electrons and produce a quasiparticle current. Thus the righthand portion of the characteristic is referred to as the "quasiparticle branch."




A number of complicating features are omitted from this brief discussion in order to emphasize the most important concepts. An actual current–voltage characteristic at $T = 4$ K is illustrated in figure 6a.




**Superconducting ring** (part **a**), with the path of integration (called P in the text) shown in color. Part **b** shows the wave function describing the system when ten flux quanta are trapped in the ring. Allowed states must have an integral number of wavelengths around P. Figure 3

by the mechanism of quantum-mechanical tunneling, even though the insulator is not a conductor in the classical sense.

Josephson's discovery was not the discovery of tunneling between superconductors, which had already been observed by Giaever, but rather the theoretical prediction that a supercurrent could tunnel through an insulating barrier. According to the theory of superconductivity a supercurrent is a flow of paired electrons. The conventional wisdom prior to Josephson was that the correlated tunneling of a pair of electrons would be a process of very low statistical probability and, therefore, unobservable. Josephson showed that due to the special properties of the superconducting state, pair tunneling has essentially the same probability as single-particle tunneling.

The practical description of the tunneling supercurrent is in terms of two simple equations. These equations both involve $\theta'$, the difference in phase from one side of the tunneling barrier to the other, of the macroscopic wavefunction first introduced in the discussion of magnetic flux quantization. The equations are:

$$\frac{d\theta'}{dt} = \frac{2e}{\hbar} V(t) \tag{7}$$

and

$$I_s = I_c \sin \theta' \tag{8}$$

Equation 7 says that the time rate of change of $\theta'$ is proportional to the instantaneous voltage across the tunneling barrier, with the proportionality constant being 484 MHz/microvolt. Equation 8 says that the tunneling supercurrent $I_s$ is zero if $\theta'$ is zero and reaches a maximum value of $I_c$ for $\theta' = \pi/2$.

In particular we note that these equations permit non-zero current with zero applied voltage. We also note that if $V(t)$ is a constant, other than zero, then $\theta'$ increases linearly in time and produces a sinusoidally oscillating current $I_s$. Further discussion of Josephson junctions is given in the box on page 39.

Just as we described superconductors in terms of an effective inductance, we find a similar description for Josephson junctions. Combining the elementary relationship $V \equiv L_J \, dI_s/dt$ (where $L_J$ is the inductance of a Josephson junction) with equations 7 and 8, we obtain

$$L_J = \frac{\phi_0}{2\pi I_c \cos \theta'} \tag{9}$$

We recognize that this is not a magnetic inductance, because it does not depend on geometry; it is the kinetic inductance of the superfluid in the Josephson junction.

From $\int I_s V \, dt$ the energy stored in $L_J$ is found to be

$$E_J = -\frac{\phi_0 I_c}{2\pi} \cos \theta' \tag{10}$$

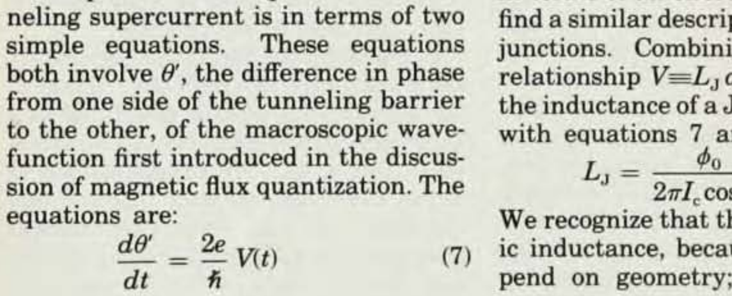
Equation 10 tells us that as the phase $\theta'$ changes, the energy stored in the Josephson junction is modulated between $\pm \phi_0 I_c/2\pi$. For a typical junction the modulated energy is approximately $10^{-18}$ J. From this property we should expect that superconducting electronics will be useful only if we are dealing with quantities of energy comparable to or smaller than this characteristic Josephson energy. Thus, superconducting electronics is intrinsically "low-power" electronics, but not impractically low.

For example, the thermodynamic fluctuation energy at room temperature is $kT \sim 4 \times 10^{-21}$ J, which is considerably smaller than the Josephson energy, and therefore not generally disruptive to superconducting electronic systems.

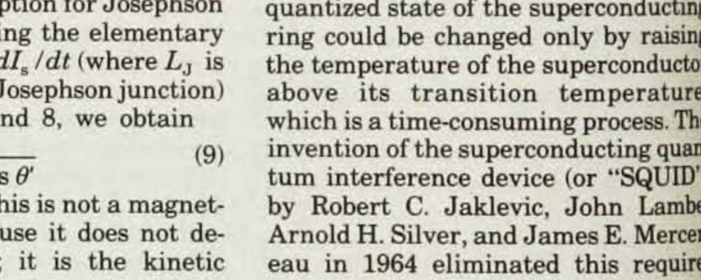
The Josephson inductance is important in determining the maximum speed of response of Josephson junctions. At very high frequencies the shunt capacitance of a junction electrically shorts $L_J$, which makes the junction ineffective in the circuit. The small size of $L_J$ (about 0.3 pH), however, gives a sufficiently low impedance compared with the capacitive reactance that full Josephson responses[1] can occur on time scales as short as 2 picoseconds.

## SQUIDs

In the experiments on magnetic flux quantization described earlier, the quantized state of the superconducting ring could be changed only by raising the temperature of the superconductor above its transition temperature, which is a time-consuming process. The invention of the superconducting quantum interference device (or "SQUID") by Robert C. Jaklevic, John Lambe, Arnold H. Silver, and James E. Mercereau in 1964 eliminated this require-




**Josephson junction** (a) and SQUID (**b**), shown very schematically. The SQUID consists of two Josephson junctions connected in parallel in a superconducting loop. Figure4




**The maximum current $I_{max}$ that a SQUID will conduct**, shown as a function of magnetic flux $\Phi$ through the SQUID loop, in the limit of small loop inductance. $I_{max} = 2I_c |\cos \pi\Phi/\phi_0|$. Figure 5 ment and also eliminated the need for a conventional magnetometer to sense the quantized state of the ring. In SQUIDs the quantized states are observed through a periodic dependence of their critical current on applied magnetic field, as we will discuss shortly.

The significance of SQUIDs resides primarily in the fact that they provide a practical means for utilizing magnetic flux quantization in a variety of applications. SQUID magnetometers, based on the theory and design of James E. Zimmerman and Silver, have been made with extremely high sensitivity—around $10^{-14}$ T. Although early work focused on this unique sensitivity, more recent developments for integrated circuit applications of SQUIDs, pioneered by Hans H. Zappe, emphasize high-speed operation of these devices—operation on a time scale of 10 to 100 ps.

A simple SQUID is illustrated in figure 4b. It consists of a superconducting loop interrupted by two Josephson junctions. In these devices the kinetic inductance of the junctions is made comparable to the magnetic inductance of the loop, so that the junctions have a major effect on the dynamics of the circuit.

If the junctions were not in the loop, that is, if the loop were just a continuous film of superconductor, then the magnetic flux inside the loop would be $\Phi = n\phi_0$, as in equation 6. The corresponding phase shift of the wavefunction around the loop in this case is

$$2\pi n = 2\pi(\Phi/\phi_0) \qquad (11)$$

With Josephson junctions in the loop this last equation becomes

$$2\pi n = 2\pi(\Phi/\phi_0) + \theta'_1 - \theta'_2 \qquad (12)$$

where $\theta'_1$ and $\theta'_2$ are the phase shifts across the respective Josephson junctions. The transport current $I$ through the SQUID is given by the sum of the currents in the two junctions:

$$I = I_c(\sin\theta'_1 + \sin\theta'_2) \qquad (13)$$

The maximum value that $I$ can have under any circumstances is $2I_c$, corresponding to equal phase shifts of $\pi/2$ in each junction. This situation occurs for $\Phi = n = 0$, for example. With flux through the loop one junction will reach its critical current before the other if the external current is increased. The maximum current through the SQUID with zero voltage drop, $I_{max}$, occurs when either junction reaches its critical current. Combining equations 12 and 13 and solving for $I_{max}$ yields the form of the essential character of SQUID response. The resulting pattern, shown graphically in figure 5, is often referred to as an "interference" pattern because of its similarity to optical interference patterns. The important result is that $I_{max}$ is a *periodic function* of the flux through the SQUID, with a periodicity of $\phi_0$.

The high sensitivity of SQUID magnetometers comes in part from the small value of $\phi_0$, which means that the interference pattern provides a finely graded measuring scale for magnetic flux. Also important is the low noise level of the device, which allows a sensitivity many orders of magnitude greater than $\phi_0$.

A fundamental way of analyzing the noise performance of a magnetometer is in terms of its energy sensitivity. The relevant quantity is $S_\Phi/2L$, where $S_\Phi$ is the spectral density of the square of the magnetic flux noise in the loop of the SQUID at low frequencies, and $L$ is the inductance of the loop. In 1977, Claudia D. Tesche and John Clarke[4] predicted theoretically that a SQUID *should* achieve an energy sensitivity of approximately $h/2 = 3.3 \times 10^{-34}$ J/Hz. This value is very close to $\hbar$, which is the maximum energy sensitivity per Hz obtainable in any quantum-mechanical system, according to the Heisenberg uncertainty principle.

This theoretical prediction stimulated experiments in several laboratories beginning with a major advance to a sensitivity of 145 $h$ by E. L. Hu *et al.* in 1978, a further advance by Mark B. Ketchen and Richard F. Voss to $5h$ in 1979, and culminating in two experiments[5] reaching very near $h$ in 1980. The swiftness of these advances attests to the skill of the researchers and the innate qualities of superconducting methods. We believe that no other technology has produced a device of comparable sensitivity.

These impressive results should stimulate further refinement of the theory regarding ultimate practical limitations. In particular a theory is needed for the rising spectrum of $1/f$ noise, which dominates at frequencies below the tens of kHz range, where the maximum sensitivity is obtained.

## Circuits

In the foregoing discussion we have described the elementary properties of the unique components of superconducting electronics: Josephson junctions and SQUIDs. The first applications of these devices were to magnetometers, radiation detectors and voltage standards. Very early however, in fact less than two years after Josephson's original publication, Rowell's patent application on logic and switching recognized the broader potential applications of Josephson junctions. In 1966 Juri Matisoo published the first experimental results with an emphasis on digital electronics. He reported measurements of the switching speed from the pure supercurrent branch to the quasiparticle branch of the current–voltage curve (see figure 6a). The high-speed switching that he observed (faster than 800 ps) stimulated a more extensive research effort, which has greatly enlarged the potential arena for applications of superconducting electronics.

We might reasonably ask what the ultimate functional scope of superconducting technology could be? In digital logic systems it is relatively easy to answer this question because a sufficient requirement for performing logic is the availability of the three functions of Boolean algebra—AND, OR and NOT—all of which have been implemented in superconducting technology. Extending this line of thought we might ask if *all* of the functional operations normally performed by electronics can also be performed by superconducting devices? Unfortunately we know of no rigorous way of answering this question but an intuitive and practical answer is that if components are available for detection, amplification, logic, and memory, then most general purpose circuits, both analog and digital, can be built.

In the table on page 42 we summarize the highlights of such basic developments. For each of the functional areas there has been a variety of developments but, for brevity, we describe only a single device or circuit in each area.

For detection we note that the device most widely used for this purpose in conventional electronics is the diode rectifier. The equivalent device in superconducting electronics is a detector biased on the quasiparticle nonlinearity of a tunnel junction's current–voltage characteristic (see the box on page 39). This device has reached its highest development in the reference given in the table. The quoted responsivity corresponds to 0.52 electrons in the output of the device for each incident photon. Thus the practical device is within a factor of two of the so-called quantum limit of one electron per photon. (One electron per photon is believed to be the maximum output a tunneling device can have.) In addition to a good quantum efficiency, the noise-equivalent power given in the table is the lowest ever published for a microwave video detector. Thus, measured against other practical devices, the performance is excellent. It is nevertheless clear that the noise performance can still be considerably improved with already developed fabrication methods that reduce the leakage current.

Although the research efforts for detectors are at microwave frequencies and above, in general electronics one is usually interested in lower-frequency detectors. Device theory says that the responsivity will be essentially the same at audio frequencies, for example, so we view this video detector as a general-purpose device.

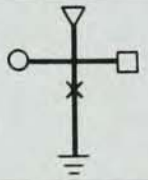
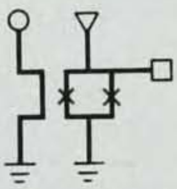
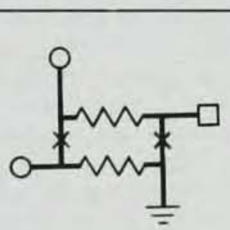
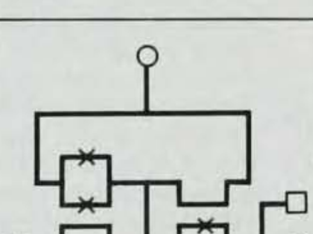
Moving on to amplification, we ask what superconducting device is most nearly equivalent to the conventional transistor? A SQUID amplifier, shown schematically in the table, plays this role. This is the same basic circuit as a SQUID magnetometer. As discussed earlier the recent trend in research on SQUID magnetometers has focused on their energy sensitivity, which implicitly recognizes that they have power gain, although they have not generally been viewed in this light. The SQUIDs designed for maximum energy sensitivity, which we discussed as magnetometers, have not had an efficiently coupled input coil. In Michael Cromar and Pasquale Carelli's work cited in the table, however, a highly sensitive SQUID was tightly coupled to a relatively large-size but low-inductance input coil, giving an energy sensitivity of around $71h$ and a power gain as listed in the table. This was an important step forward, but considerably more development is needed (related primarily to bandwidth and dynamic range of operation) before SQUIDs can routinely be used as amplifiers.

The next function of interest is logic. Logic and memory circuits are the main products of the commercial integrated circuit industry, so it is not surprising that these functions have received far more study and development than the preceding two functions.

Josephson junctions in binary logic circuits act as threshold detectors. The threshold condition for switching the circuit is that the sum of the two input currents must exceed the Josephson junction critical current. Figure 6 illustrates the simplest implementation of a logic function. As might be expected the more sophisticated implementation of superconducting logic involves more complex circuits, but the basic threshold switching idea remains.

The leading developments in this field have been by the groups at IBM Research Laboratories and at Bell Telephone Laboratories. Through the years these groups have devised a number of distinct approaches to logic circuits. However, at the present time

## Highlights of developments in superconducting electronics

| FUNCTION | SCHEMATIC | PHYSICAL MECHANISM | NOTES |
|---|---|---|---|
| **Detection** |  | Rectification by the quasiparticle nonlinearity. | Measured current responsivity[a] of 3500 amps of output current per watt of input power at 36 GHz. Noise equivalent power = $2.6 \pm 0.8 \times 10^{-16}$ W/Hz$^{1/2}$ |
| **Amplification** |  | Magnetic modulation of the SQUID critical current by the input signal. | The energy sensitivities per unit bandwidth of SQUID amplifiers are approaching the quantum-mechanical limit for this quantity (at audio frequencies). Power gains of the order of $6 \times 10^5$ have been achieved in single devices.[b] |
| **Logic** |  | Switching produced by drive currents exceeding the junction critical current. | The fastest superconducting logic produced so far is a two-input OR gate with a switching delay of 13 ps when fabricated with 2.5-micron linewidth lithography.[c] Designs emphasizing simplicity of fabrication and improved miniaturization properties yield an estimated 40 ps switching delay for fully loaded circuits.[d,e] The power dissipation per gate is about 3 microwatts. These circuits provide a basis for a computer with a 2 nanosec logic cycle time.[f] |
| **Memory** |  | Information stored by flux trapping in the large superconducting loop. | Memory compatible with the above high-speed logic utilizes the quantized flux state of a superconductor. Two flux quanta are inserted for a 1 and no quanta for a 0. In present design work a one-bit memory cell is expected to have a current transfer time of about 35 ps (time to go from a to b in figure 7) when fabricated with 2.5-micron minimum linewidths. Overall memory access time for reading one bit is no more than about 500 ps on a 4K-bit chip having 6 mW of dissipation per chip.[g] |

Symbols used in the schematics are:
- O input terminal
- ▽ bias terminal
- □ output terminal
- X Josephson junction


**References**

a. P. L. Richards, T. M. Shen, R. E. Harris, F. L. Lloyd, Appl. Phys. Lett. **36**, 480 (1980).

b. M. W. Cromar, P. Carelli, Appl. Phys. Lett. (to be published). Also see J. M. Jaycox, M. B. Ketchen, Proc. 1980 Applied Spectroscopy Conference, to be published in IEEE Transactions on Magnetics.

c. T. R. Gheewala, IEEE J. Solid-State Circuits **SC-14**, 787 (1979).

d. T. A. Fulton, S. S. Pei, L. N. Dunkleburger, Appl. Phys. Lett. **34**, 709 (1979).

e. T. R. Gheewala, A. Mukherjer, Int. Electron Devices Meeting, Washington, D. C. (1979).

f. W. Anacker, IBM J. Res. Develop. **24**, 107 (1980).

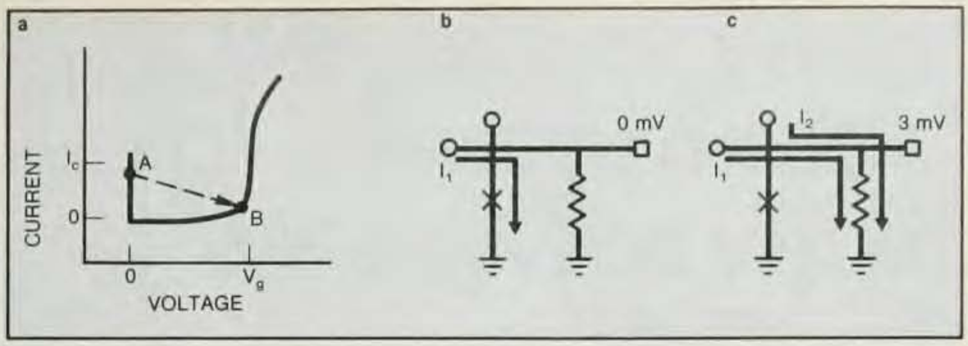
g. S. M. Faris, W. H. Henkels, E. A. Valsamakis, H. H. Zappe, IBM J. Res. Develop. **24**, 143 (1980).

there is a convergence of approaches that have considerable similarity. The latest results are summarized in the table. The schematic shown there for logic (and also for memory) is a simplification of the actual circuit.

Finally we turn to the memory function. We will briefly discuss only the present form of the highest speed random-access memory (cache memory) that is being developed as large-scale integrated circuits. The storage of binary information is conveniently accomplished with the flux-trapping phenomena discussed earlier. Two features of this form of information storage are the zero power dissipation in memory when no reading or writing is occurring and the fact that it is "nonvolatile," which means that the stored information is not lost if the computer is turned off. In addition it operates at sufficient speed to be compatible with the very high-speed Josephson logic circuits. Some details of memory-cell operation are described in figure 7.

In the table we have identified the unique physical mechanism used in each of the functional areas. Because the mechanisms are different in each case we begin to get a feeling for the richness of phenomena available in superconductivity. The practical importance of these effects becomes clear when we note that in all four functional areas superconducting electronics has extraordinary performance, in fact performance beyond that of any other technology.

To appreciate the broader picture more fully, however, we must briefly take up one additional topic: miniaturization in electronics. This topic is put in perspective by the present situation in commercial electronics, in which circuit power dissipation is seen to be of major importance. The highest-speed large-scale computer of today has 400 000 logic gates. To avoid overheating in this system there are only two gates in each integrated circuit package; so there are 200 000 separate integrated circuits for logic. Compare this situation with the other extreme of miniaturization, which is a microprocessor with about 20 000 logic gates in a single miniature package. To make a microprocessor system roughly comparable in complexity to the high-performance logic unit would require 20 microprocessors or just 20 integrated circuits. (The emphasis here is on a crude comparison of levels of integration; no suggestion is intended that it is practical to interconnect 20 microprocessors for the required logic of the large computer.) The cost of these 20 circuits is only a few thousand dollars, whereas the cost of the higher-performance logic system is on the scale of millions of dollars. To a significant degree this difference comes from differences in costs of packaging and assembling a miniaturized system as compared with one that could not be miniaturized because of high power dissipation. Part of the cost difference also arises from the volume of production, which favors microprocessor technology over that for high-speed logic systems. It is fully expected that there will be reductions in the power requirements for semiconductor logic in the future. On the other hand, as computers get faster there is a natural need for increased memory size, which produces increasing problems of power dissipation.




**Switching of a simple AND gate.** Initially only one current $I_1$ is present. It has a magnitude less than $I_c$; also the Josephson junction is a state A of the current-voltage characteristic shown in part **a**. The path of this current in the AND circuit, shown in color in part **b**, is entirely through the junction, and the result is a zero voltage output. If a second current, $I_2$, of comparable magnitude is also applied, the critical current of the junction is exceeded and it switches to the energy gap voltage $V_g$. In this situation the current in the junction after switching depends on the value of the load resistance. If the resistance is properly selected the junction will switch to point B of the characteristic (**a**), where the junction current is much less than in the zero voltage state. Thus, to a good apporximation, both input currents are directed to the load resistance, as in part c, resulting in a 3-mV output. The circuit is reset to zero voltage by reducing $I_1$ and $I_2$ to zero. Figure 6

One of the virtues of superconducting technology is that it achieves high speed without high power dissipation in either logic or memory. In fact, the speed of superconducting technology exceeds the speed of the fastest conventional technology and simultaneously dissipates orders of magnitudes less power.[6] Thus the principal barrier to miniaturization of high-speed electronics is eliminated in this technology. In what follows we will consider the physical reasons for this performance.

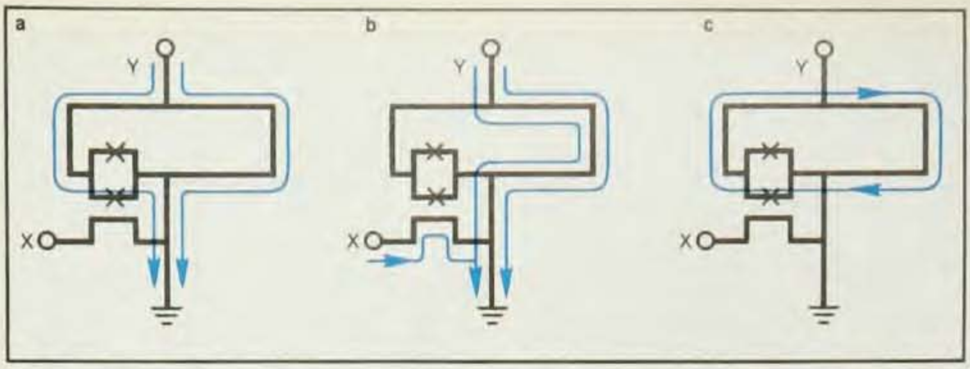
### Basis for performance

Is it simply an accident that superconducting electronics has outstanding performance in *all four* of the functional areas of electronics, or is there a basic reason why this should be so? We might say that superconductivity is the reason for the good performance, but that would be a rather nebulous response because superconductivity has many facets. The role of superconductivity in superconducting electronics is to provide the physical mechanism for making things happen. The specific question we will address is why does it work so well? To discuss this question we will examine the features of the technology that are of the greatest practical importance, namely the low power dissipation, the high speed, the high sensitivity and the low noise.

Detection, amplification, logic and memory all utilize nonlinearities for their practical realization. By nonlinearity we mean a nonlinear relation between an input parameter and an output parameter. The simplest case is for a two-terminal device in which there is a nonlinear relation between the input current and the resulting voltage, as in a Josephson junction.

The fact that the nonlinearities of superconducting devices occur at very low energy, generally below 5 meV, is of fundamental practical importance, producing both low power dissipation and, to a substantial extent, the high speed of these devices. It is important to recognize that such low-energy nonlinearities are effective only at low temperatures.

Electrons in solids have fluctuations in their energies of the order of a few $kT$. If this fluctuation energy is substantially greater than the range of energy over which a nonlinearity exists, then the nonlinearity will in effect be averaged out by the fluctuations. A basic requirement for a nonlinearity to be physically effective with a change in terminal voltage from zero to $V$ is that $eV$ should not be less than $kT$. (As an example note that the large quasiparticle nonlinearity in a Josephson junction occurs over an energy range around 8 $kT$ for $T = 4$K). This relationship is a restriction on the minimum voltage at which an electronic technology can operate and, consequently, sets the scale for power dissipation.[7] For devices with the same impedance but operating at different temperatures $T_1$ and $T_2$, the ratio of the *minimum* power dissipations is




**Operation of a memory cell** consisting of a superconducting loop with an inserted SQUID. If flux is trapped in the loop it is interpreted as "1," and the absence of trapped flux is a "0." Consider the writing of a 1 in a cell initially in the 0 state. The writing sequence begins with the application of a Y current as shown in part **a**. This current naturally divides itself between the two sides of the superconducting loop according to their relative inductances. The current in the SQUID in the left-hand branch of the main loop is arranged to be less than the SQUID critical current. Next, an X current is applied. It is inductively coupled to the SQUID and reduces the SQUID's critical current below the level of the applied Y current. This causes the SQUID to switch temporarily to the voltage state, which diverts its current to the other side of the loop, as in **b**. If the X and Y currents are now turned off, a persistent current is established in the loop as shown in **c**, resulting in a 1 state. Reading of the 0 or 1 states is done with a nearby second SQUID on the right-hand side of the memory cell (see table, page 42), which simply detects whether or not there is flux in the loop. Figure 7

$P_1/P_2=(V_1/V_2)^2=(T_1/T_2)^2$. According to this formula a reduction in power dissipation by a factor of about 5000 is achievable on going from 300K to 4 K, if optimal devices are used in both cases.

Lower power dissipation implies less heating of the substrate, the importance of which has already been emphasized. To complete this argument one must also consider heat transfer from the substrate to the surrounding medium as Robert Keyes[7] has done. This process is about a factor of 20 less favorable at low temperatures, so the effective decrease in power dissipation is about a factor of 250 rather than 5000. Nevertheless it remains an important factor for electronics, and it illustrates the importance of a low-temperature environment.

A primitive model for the speed of typical electronic devices reveals how low-energy nonlinearities also contribute to higher-speed operation. Consider a model in which the terminals of a device must make an excursion in voltage across its intrinsic nonlinearity. The time that this will take is given approximately by $CV/i$, where $C$ is the capacitance between the output terminals, $V$ is the necessary voltage change, and $i$ is the current available to drive the change in voltage.

In superconducting devices the voltage change is typically 3 mV. For contrast we note that for room-temperature devices, even in unsaturated semiconductor logic, the corresponding voltage is about 600 mV. Thus, low-voltage operation gives an intrinsic speed advantage to superconducting devices. Such operation is possible only at low temperatures.

The high sensitivity of SQUID magnetometers depends upon the small size of the flux quantum. As we have already discussed, flux quantization is a manifestation of a coherent quantum-mechanical state extending over macroscopic distances. Superconductivity is not the only such state. The coherence of lasers and the long-range order of magnetic materials may be similarly described.[8] Thus we cannot assert that a low-temperature environment is required for a macroscopic quantum state. What we can assert is that a low temperature is required for the observation and use of macroscopic quantum states with small spacings between energy levels. It is the small energy spacing between the quantized flux states (or actually the small barrier between states) that produces the high sensitivity of SQUIDs. An additional factor is the low noise level of Josephson junctions. There is nothing conceptually extraordinary about the noise in Josephson junctions; both the usual Johnson noise and electronic shot noise are present as in other devices. But of course the low-temperature environment reduces the Johnson noise by a factor of 100 below that of ambient temperature devices. Thus we find that both factors responsible for the high sensitivity of SQUIDs are in fact made possible by the low-temperature environment in which they operate.

We conclude that the basis for the good performance of superconducting electronics in the four functional areas is primarily the low temperature of operation.

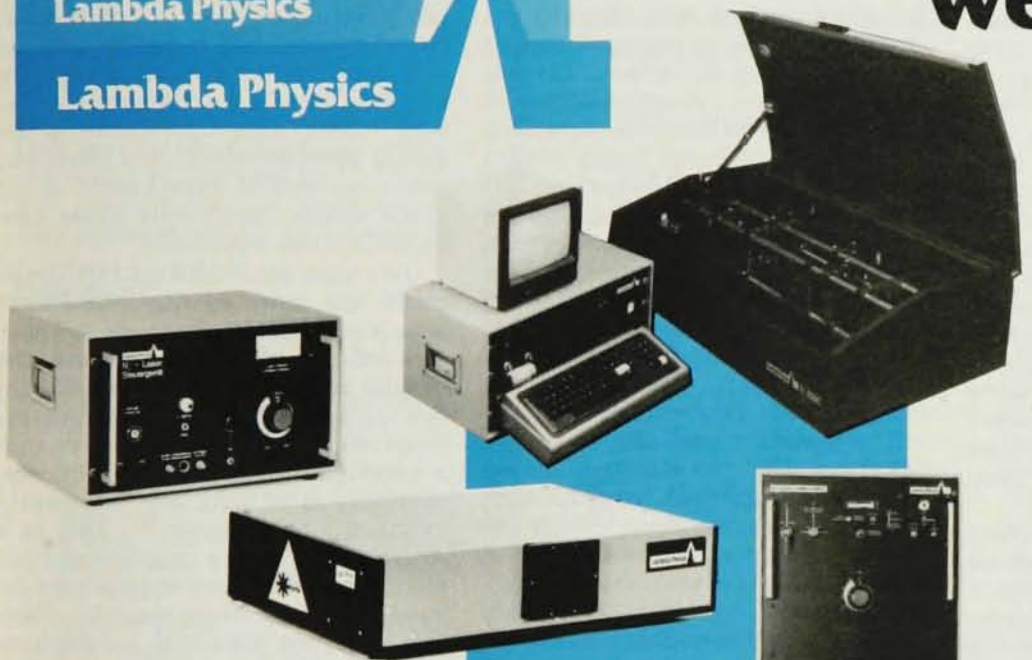
### Future prospects

Superconducting electronics should be viewed as a technology potentially applicable to any critical instrumentation problem that requires the highest possible performance in either speed or sensitivity. Considering the sophisticated and relatively mature development of conventional electronics, we should all be impressed with the result that superconducting technology, even in its present immature form, has the best performance in the most fundamental areas of both analog and digital electronics.

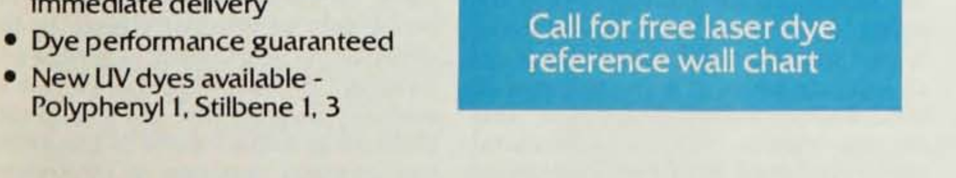
We have attributed the good performance of this technology to its low-temperature operation. On this basis it seems likely that if superconducting electronics is optimally implemented then no ambient temperature technology will give comparable performance. A critical question, however, is: How closely can ambient temperature circuits approach the performance of superconducting circuits? No one knows what the ultimate answer will be because both technologies are still advancing. A related question is: Can the performance of other electronic technologies be greatly improved by cooling? This is a complex issue to discuss, but Keyes[7] has addressed the question for electronics based on semiconductors and on magnetic and optical materials. His general conclusion is that reduced operating temperatures are beneficial in many ways. Whether the performance of these systems can be made comparable to that of superconducting electronics remains an open question.

Perhaps foremost among the practical questions about superconducting integrated circuits are those relating to reliability of fabrication processes and durability of the devices after fabrication. There is a tendency for the very thin tunneling barriers in Josephson junctions to change with time when stored at room temperature and a tendency for the mechanical stresses of temperature cycling to 4 K to cause electrical changes in junctions. Most of the circuits discussed here were made of lead-alloy superconductors. The successful fabrication and operation of a 2048-bit main memory development chip was the most severe test of these methods thus far.[9] Competing with lead-alloy circuits are more recent developments with niobium. A report on junctions with niobium base electrodes and lead-alloy counter electrodes[10] gives failure probabilities of less than $2\times10^{-8}$ failures per Josephson junction per thermal cycle to 4 K. Advances in this area look promising.

Another problem, unique to this technology, is magnetic flux trapping at inhomogeneities in the superconducting films. Such flux can greatly alter the performance of superconducting circuits. Flux trapping occurs spontaneously as superconductors are






Watts
η[%]
1.0
0.5
BM-Terphenyl
PTP
Polyphenyl 1
Stilben 1
Coumarin 102
Rhodamin 6G
DCM
Oxazin 1
Hexacyanin 3
Dibenzocyanin 45
TMQ
350 400 450 500 550 600 650 700 750 800 850 900 950 λ[nm]

cooled in a magnetic field, even in very small fields. It can also be produced by thermal gradients that develop as the circuits are being cooled to 4 K. Efforts are underway to solve this problem.

Miniaturization, which is of great importance for integrated circuits, poses interesting questions. Superconducting circuits are presently being developed mostly with 2.5-micron minimum linewidth lithography, much the same as commercial semiconductor circuits. As the linewidth is reduced, performance is expected to improve significantly[11]. However, as the geometry becomes sufficiently small (films about a tenth of a micron thick), new effects become significant. The basic description of Josephson tunnel junctions is not expected to change but the kinetic inductance of the circuit external to the junctions will become increasingly significant—both in transmission lines and in SQUIDs. Physically this means that energy storage in SQUIDs, for example, shifts away from magnetic energy toward kinetic energy of the electrons. How important this will be has not been worked out.

When devices are made smaller there will be a tendency to want an increase in the junction critical current density so as to maintain the Josephson coupling energy and ensure stability against thermal fluctuations. Increased current density increases the importance of nonequilibrium between the quasiparticle and pair distributions. The effect of nonequilibrium on device performance has not been quantitatively explored. It is perhaps most interesting for noise performance.

Of course semiconductor technology also encounters new problems with increased miniaturization. A specific area where miniaturization decidedly favors superconductivity is in the properties of the microstrip transmission lines that interconnect high-speed devices. Richard L. Kautz[12] has shown that, within the context of high-density integrated circuits, further miniaturization of normal metal lines will produce poor transmission properties for pulses having widths of 100 ps or less. The superior properties of superconducting transmission lines may be of decisive importance in the competition between very high speed technologies.

For large-scale integrated circuits the prospects for superconductivity are sufficiently promising that the design of prototype superconducting computers is underway. Matisoo has recently summarized this work.[13] There are reasonable prospects for a superconducting machine about fifty times faster than the general-purpose machines of today.

Many opportunities for further developments exist in analog superconducting electronics, but the importance of these developments is more difficult to summarize because the possibilities are so varied. We will therefore focus somewhat arbitrarily on the interface between analog and digital circuits, that is, on analog-to-digital converters, which are circuits of technological importance in many areas of work.

In figure 2 we illustrate an advanced superconducting analog-to-digital converter design that emphasizes high-speed performance. Equally important is the development of designs for high-accuracy converters. The precision of the best commercially available devices is limited by the instability of their semiconductor based voltage references, which is a few parts in $10^6$. In superconducting technology one can use the Josephson voltage reference, initially developed by Donald N. Langenberg, William H. Parker and Barry N. Taylor, which is known to be at least a factor of 100 better than its semiconductor counterpart. If this reference is combined with a superconducting current comparator and the necessary digital circuitry, the resulting analog-to-digital converter can have the same precision as the Josephson voltage reference. Thus an improvement by a factor of 100 over conventional technology is feasible, but as physicists are prone to say, the engineering details have not been worked out.

What is perhaps more fascinating to physicists is that the maximum achievable precision of the Josephson voltage reference is simply unknown. This is significant not only for the physics involved but also for practical reasons as well. Measurement systems of the highest precision commonly operate on the basis of observing changes between a reference level and the quantity of interest. Thus an improved reference would allow one to observe physical effects that are presently unobservable, in phenomena as varied as solid-state physics and geophysics, for example.

Recent work by Kautz[14] on the Josephson voltage reference is notable in this connection. He showed that the basic mechanism of phase lock between the Josephson self-oscillation and the external drive-oscillator can be maintained without a significant break for at least six hours at a frequency of 25 GHz, which corresponds to $5 \times 10^{14}$ continuous cycles. This experimental work, combined with the accompanying theory, suggests that essentially perfect phase lock is achievable with a Josephson junction. This in turn implies that, barring the intervention of other effects, it should be possible to define voltage as precisely as frequency, the most accurately measurable physical quantity. The real problem that remains is the possible "other effects." No such effects have been identified, although there is evidence[15] that thermodynamic nonequilibrium processes may necessitate a correction factor for the Josephson voltage reference.

It is clear that basic SQUID systems are still not adequately understood and should be more thoroughly explored. The status of the most sensitive energy detector is unique and of fundamental importance to experimental science. Within the framework of Claude Shannon's celebrated ideas for information transfer one should recognize that the most sensitive energy detectors are also the most sensitive *information* detectors. Thus, since information is the goal of all experiments, it is clear that the most critical experiments of all kinds should incorporate these new SQUIDs when applicable.

Over what bandwidth can SQUIDs be made the most sensitive detectors? How should direct feedback (without conventional electronics) around the SQUID be used? No one knows. In fact these questions lead us to mention recent work in which it was shown that a superconducting heterodyne mixer, operating at 36 GHz, can very nearly detect a single photon.[16] This is a second area where superconducting electronics closely approaches a fundamental limit for measurements. Since this work was done with a Josephson junction (which is thought of as an electric-field detector) and not a SQUID (which is thought of as a magnetic-field detector), it raises the interesting problem of determining the best spectral region for using SQUIDs and for using Josephson junctions as sensors. No definitive answer can be given yet.

In concluding this discussion it is fitting to broaden the perspective and to consider the development of electronics from a more philosophical point of view. I shall ignore such technical details as the different materials used in producing electronics devices and consider somewhat more generally what is happening in electronics. Since the 1950's conventional electronics has progressed dramatically, largely by advances in miniaturization, which has many ramifications but which we describe only as a major change in the dimensional length scale of devices and circuits. Because this change was so useful it suggests that one should consider other radical shifts in the primitive physical variables of electronics. The two radical changes that have been most extensively studied in the last two decades are changes in frequency and in temperature. The shift in frequency, to the optical region, has resulted in fiber optics and associated optical circuits, for which the main broad application appears to be communications over medium and long distances. On the other hand the shift in temperature to the cryogenic regime has led to superconducting electronics, a technology best adapted to the microscale world of miniaturized integrated circuits. Thus the major radical alternatives to conventional electronics are seen to be functionally complementary. Maybe at some time in the future these radical technologies will be joined.

But regardless of the course that future commercial technology takes, it should be abundantly clear that superconducting electronics presents a demanding challenge to the technology of semiconductors. It is reasonable to claim, at least for the foreseeable future, that superconducting electronics will be the pre-eminent technology for high performance—for high speed, for high precision, and for high sensitivity.

### References


1. For a review with emphasis on high-speed measurements, see D. G. McDonald, R. L. Peterson, C. A. Hamilton, R. E. Harris, R. L. Kautz, IEEE Trans. Electron Devices, **ED-27**, 1945 (1980).
2. J. H. Greiner, C. J. Kircher, S. P. Klepner, S. K. Lahiri, A. J. Warnecke, S. Basavaiah, E. T. Yen, John M. Baker, P. R. Brosious, H. -C. W. Huang, M. Murakami, I. Ames, IBM J. Res. Develop. **24**, 195 (1980).
3. B. D. Josephson, Science **184**, 527 (1974).
4. C. D. Tesche, J. Clarke, J. Low Temp. Physics **29**, 301 (1977).
5. R. F. Voss, R. B. Laibowitz, M. B. Ketchen, A. N. Broers, Conference Digest, Second International Conference on Superconducting Quantum Devices, Berlin, May 1980, page 94; M. W. Cromar, P. Carelli (to be published in Appl. Phys. Lett.).
6. T. R. Gheewala, IEEE Trans. Electron Devices, **ED-27**, 1857 (1980).
7. R. W. Keyes, Proc. IEEE **63**, 740 (1975).
8. M. O. Scully, in *Coherence and Quantum Optics* (L. Mandel, E. Wolf, eds.) Plenum, New York (1973); page 69.
9. R. F. Broom, P. Gueret, W. Kotyczka, Th. O. Mohr, A. Moser, A. Oosenbrug, P. Wolf, IEEE J. Solid-State Circuits, **SC-14**, 690 (1979).
10. R. F. Broom, S. I. Raider, A. Oosenbrug, R. E. Drake, W. Walter, IEEE Trans. Electron Devices, **ED-27**, 1998 (1980).
11. H. H. Zappe, Proceedings of NSF Workshop on Opportunities for Microstructure Science, Engineering and Technology, Arlie, Va. (1978); page 209.
12. R. L. Kautz, J. Research NBS **84**, 247 (1979).
13. J. Matisoo, Scientific American, May 1980, page 50.
14. R. L. Kautz, Appl. Phys. Lett. **36**, 386 (1980).
15. J. Clarke, M. Tinkham, Phys. Rev. Lett. **44**, 106 (1980).
16. T. M. Shen, P. L. Richards, R. E. Harris, F. L. Lloyd, Appl. Phys. Lett. **36**, 777 (1980); see also PHYSICS TODAY, August 1980, page 19. □